NORDISK HYDROLOGISK KONFERANSE 1992

Arrangert av Nordisk Hydrologisk Forening

Alta, Norge, 4. - 6. august 1992
Redigert av Gunnar Østrem

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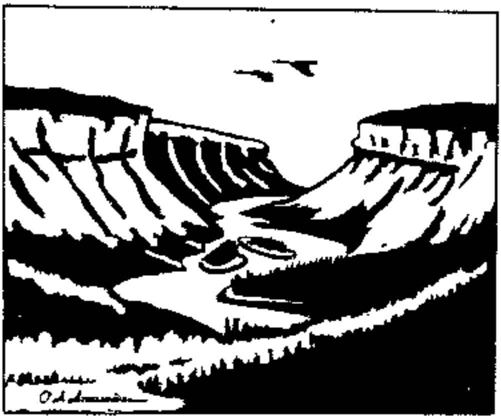
FORORD



Nordisk Hydrologisk Konferanse 1992 (NHK-92), som denne gang avholdes i Alta, arrangeres av Nordisk Hydrologisk Forening. Konferansen er den 17. i rekken siden det første møtet i Sverige i 1955. Fram til 1970 ble konferansene arrangert hvert tredje år, deretter hvert annet år.

Tema for NHK-92 er "Nordisk hydrologi i en internasjonal sammenheng", idet vi gjerne vil markere at det internasjonale samarbeidet innenfor fagfeltet blir stadig tettere. Det er invitert en foredragsholder fra British Hydrological Society for å utdype dette nærmere.

De anmeldte foredragene er inndelt i følgende sesjoner:

Klimaforandringer og vannressurser
Hydrologiske prosesser
Flerbruk
Observasjoner og data
Polar hydrologi

Denne publikasjonen inneholder manuskriptene til de fleste av innleggene til Nordisk Hydrologisk Konferanse i Alta. Noen av manuskriptene var ikke ferdig tidsnok til å komme med i publikasjonen og vil derfor bli distribuert separat på konferansen. For lett å kunne ta kontakt med forfatterne i etterkant av konferansen, er det utarbeidet en adresseliste bakerst i boken der også telefonnummer og telefaxnummer er oppgitt.

Originalene til manuskriptene forelå i A4-format og er i publikasjonen nedfotografert til A5-format. Redaktør for boken har vært Gunnar Østrem, NVE.

Arrangementskomitéen har hatt følgende sammensetning: Marit Lundteigen Fossdal, Vassdragsregulantenes forening, NHF, Sven Erik Hetager, Statkraft, Randi Pytte Asvall, NVE, Ola Kjeldsen, NVE, Bjørn Moltzau, Arendals Vasdrags Brukseierforening, Einar Berntsen, Norsk Hydrologisk Komité, samt Åse Berit Fjell, Vassdragsregulantenes forening.

Konferansen har fått støtte fra følgende institusjoner og firmaer:

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SINTEF-Strømningsmaskiner

Arrangøren vil få takke alle som har støttet konferansen med midler og/eller ved arbeidsinnsats. Videre vil vi takke redaktøren for denne publikasjonen, Gunnar Østrem, og hans medhjelper, Arnhild Gjøtterud, for iherdig innsats for å lage en publikasjon av god teknisk kvalitet innenfor de budsjettrammer som forelå.

Til slutt vil vi rette en takk til alle forfattere og deltagere for deres innsats for å fremme NHK-92 og håper at alle positive forventninger til konferansen vil bli oppfylt.

Marit Lundteigen Fossdal
Formann i Nordisk Hydrologisk Forening

INNHOLD

GJESTEFORELESNINGER

KLIMAENDRINGER OG VANNRESSURSER

Innledningsforedrag

HYDROLOGISKE PROSESSER

Innledningsforedrag

AVLØP

FORDAMPNING

SNØ

MARKVANN OG GRUNNVANN

VANNKVALITET

FLERBRUK

Innledningsforedrag

PLANLEGGING

DRIFT

VIRKNINGER AV VASSDRAGSINNGREP

OBSERVASJONER OG DATA

Innledningsforedrag

DATAINNSAMLING

MÅLEMETODER

ANALYSER OG BEARBEIDING

POLAR HYDROLOGI

Innledningsforedrag

AVSLUTNING

NORDIC HYDROLOGY - AN INTERNATIONAL PERSPECTIVE

Dr James S G McCulloch **Great Britain**

ABSTRACT

The origin of the British Hydrological Society in relation to its Nordic counterpart is outlined and its association with the European Geophysical Society is commended. The historical development of British, and links with Nordic, hydrology is discussed, as are the various approaches to hydrology as a science, the engineering approach, the systems approach and the processes approach. While the importance of the other approaches is appreciated, it is considered that the leading edge of hydrological science lies with physical (and chemical) process studies. Hydrology, which is only now becoming less local and regional and more global in its approach, must develop with more international involvement and collaboration than hitherto. All the international development banks are keen to support environmental investigations as essential components of aid and loan projects. Demand for hydrology will increase. Hydrological measurements, formerly considered irrelevant by global modellers, are now an essential prerequisite to use of the latest global climatic models (GCMs)

INTRODUCTION

I am honoured to have been invited to address the Nordic Hydrological Society for at least two reasons. The first is the long relationship that has existed between the Nordic Hydrological Society and the British Institute of Hydrology (IH), of which I was the founder Director. There have been many meetings and many exchanges of personnel between Britain and the Nordic countries and I have participated in and enjoyed previous Nordic Hydrology conferences. Indeed on one such occasion, I proposed to your conference that extension of the Nordic Hydrological Society to include Britain and Ireland would reflect past history (!), and strengthen the impact, internationally, of our many capable scientists. While nothing came of this proposal at the time, I was able, to support the creation, in 1985, of the British Hydrological Society which I represent here to-day.

Up to that time, the scientific basis of hydrology in Britain had been largely fragmented among other disciplines, such as geography, geology, meteorology and soil physics; the focus of hydrological aspirations, (other than the societies relevant to the component disciplines) in terms of learned societies, lay within the Royal Society. Of course, the greatest number of practising hydrologists were civil engineers, who looked to the Institution of Civil Engineers for support in the shape of a Hydrological Group. Although this Group was not exclusive to civil engineers, it was not considered appropriate by non-engineers as the societal basis for hydrological science. During the 1st IAHS Scientific Assembly at Exeter in 1982, a truly multi-disciplinary British Hydrological Society (BHS) was proposed; by 1985, the preparatory work was done and the BHS was formed as a learned society in its own right, with the blessing of the Royal Society and of the Institution of Civil Engineers. The BHS has flourished and now has upwards of 600 members. Irrespective of their previous professional training, all British hydrologists now meet at the BHS on an equal basis. Indeed, when, as an economy measure, the Royal Society abolished all its subject committees, hydrology, represented by the BHS, has proved to be well able to stand alone. More recently, the British Hydrological Society has become formally associated with the European Geophysical Society,

Of course, in much of the civilised world, national frontiers are breaking down and the meetings of the European Geophysical Society are perhaps a better and certainly a wider forum than my previously proposed combination of British and Nordic hydrological scientists. So I hope that my Nordic colleagues will strengthen their links with the EGS. It was at the Copenhagen EGS meeting that enthusiastic support was given for hydrology to be granted full section status within EGS in its own right. At Copenhagen also, the proposal was made for EGS to adopt the Journal of Hydrology (JH) as the house journal for the EGS hydrological sciences section. This has resulted in European hydrological research papers having more immediate access to a major international journal, subject to the normal peer reviewing process.

Although I am well aware of the merits of Nordic Hydrology as an international journal, citation analyses suggest that JH is the only European journal with a prospect of competing successfully with the North American Water Resources Research (WRR). Indeed, a study of the distribution of authors and subscribers to the various international hydrological journals indicates that JH is more truly an international journal than WRR.

HISTORICAL DEVELOPMENT OF HYDROLOGY

In an address to the British Hydrological Society, this year, I could not resist being somewhat philosophical, natural philosophical no less. My Scottish university qualifications are in mathematics, statistics and natural philosophy; in Scotland this description is synonymous with physics although the Scottish term now seems rather more appropriate for an environ- mentalist. In that talk, I considered the development of hydrology as a science, with a view to placing, in an international context, the British contribution to the subject. Historically, Plato (428-348 BC) accepted the ancient Greek (Empedocles of Agrigentum) theories about the primary elements of matter, air, water, earth and fire but added a fifth element; Aristotle (385-322 BC) subsequently explained this as heaven! The karst geology of Greece and the Greek interest in argument rather than measurement, may well excuse Plato for accepting the Tartarus (huge subterranean reservoir) explanation for the origin of rivers and springs; Aristotle derided this concept and suggested that air was converted into water in the ground, just as cold changes air into water above the earth. Mankind had to wait nearly 1000 years for the first correct measurement of streamflow as a function of velocity, by Hero of Alexandria. The first Briton to write on any hydrometeorological matter was the Venerable Bede (673 - 735). Clearly, until theory and description gave way to measurement and experimentation, progress in hydrology, as opposed to hydraulics, was very limited.

The most notable British contributions to hydrology as a science, have been in the study of physical processes and instrumentation. Many names might be mentioned from the seventeenth century onwards but Halley (1656 - 1742) and Dalton (1766-1844) are particularly associated with evaporation and Wren and Hooke with rainfall measurement. Progress, in these early days, was generally reported to the Royal Society. It is tempting to include Manning's (1806 - 1897) work on velocity of flow in pipes and open channels but sadly, like Professor Dooge of Dublin and Professor Nash of Galway, both frequently thought to be British hydrologists, Manning was Irish! Recently, the U S National Research Council, in a publication entitled "Opportunities in the Hydrologic Sciences", included some biographies of eminent hydrologists. Inevitably Americans predominated; the two

Britons included were Penman, a physicist rather than a hydrologist, whose equation for estimating potential evaporation and transpiration is perhaps the most significant recent contribution to hydrology, and Hurst for his lifetime's study of the River Nile.

In commenting on the international perception of Nordic hydrologists, I concentrate likewise on natural philosophers and environmentalists. Many eminent Nordic scientists and meteorologists have contributed much, internationally to the science, with development of meteorological models, as long ago as the 1920s and 1930s, somewhat before my time! It may be more interesting for me to recall contacts and interactions from my own experience and to indicate how the activities of IH interdigitated with those of Nordic scientists and engineers. Before doing so, I would like to explain and define the various approaches to hydrology, the engineering or applied, the systems exploring the hydrological cycle over complete catchments and the processes studies, which examine the movement of water between the various phases of the hydrological cycle.

HYDROLOGY - THE ENGINEERING APPROACH

Hydrology has always been an applied, indeed problem-oriented science and hydrological investigations have been local, or at most regional. From the earliest times, engineering techniques have dominated the subject; indeed, since engineers had to reach hard decisions on the hydrological boundary conditions to be applied to particular schemes, many earlier developments in the science, which some consider more appropriately described as a technology, such as the Rational Method or Unit Hydrograph approaches to flood estimation, were the product of engineering requirements, as were many of the "black box" modelling studies. In these days, tackling hydrological and water resources problems involved mainly the two component phases of the hydrological cycle that were directly measurable, the input, rainfall and the output, runoff. Little consideration was given to the evaporation and storage phases of the hydrological cycle, other than to the calculation of evaporation "by difference" or to the use of a diversity of evaporation pans or tanks with empirical "pan factors". Additions to soil moisture storage and ground water were calculated, also "by difference", after assuming a value for actual evaporation derived from some empirical equation, probably derived in a totally different environment.

HYDROLOGY - THE "SYSTEMS"* APPROACH

After completing my doctorate studies with Penman at Rothamsted in England, I became an agricultural meteorologist in East Africa, where hydrology was dominated by the engineering approach as outlined above. Whatever the limitations of the technology at the time, the East African countries had a tremendous attraction for a physically-inclined hydrologist. The rainfall was markedly seasonal and the soils in the important catchment areas were deep and porous; so deep and porous indeed that a whole season's streamflow could be stored within the soil profile, without ever reaching the water tables which tended to be at great depths. Seasonal water balance studies could be undertaken and, with no more sophisticated instrumentation than a soil sampling tool, a balance and a drying oven, soil moisture storage, a previously unmeasured component of the hydrological cycle could be determined in experimental catchment studies. In an era before reliable soil moisture neutron gauges or similar capacitance gauges were available anywhere in the world, in East Africa such routine soil sampling every 10 days at three sites within each catchment was entirely feasible. This was the basis of the East African Catchment Area Research project, 1957 - 1974. Initial results were published in 1961 (Pereira et al), a data volume in 1976 (Edwards et al), full results in 1979 (Blackie, Edwards and Clarke) and finally, the results wete summarised by Edwards and Blackie (1981). In general, fully vegetated catchments adequately supplied with water use similar amounts of water but there can be considerable savings in water use when plants are seasonal, small and shallow-rooted. While exceptions prove every rule, forest has a unique capacity for preventing rainfall runoff and hence for increasing infiltration into the soil, as well as a particularly substantial requirement for water for evaporation and transpiration.

The first results of East African Catchment Area Research into complete changes of land use in important upland catchment areas had been published before the advent of the International Hydrological Decade (IHD), initiated by UNESCO. The Nordic response to the IHD was commendable; enthusiastic support was given for many components of the programme. In Britain, where after 9 years in East Africa, I was now directing the hydrological research programme at the Institute of Hydrology (IH) at Wallingford, no specific funding was provided for participation in the international programme but catchment area research was a principal part of the IH

Programme of Research. While the IHD was an all-embracing programme with many inter- connected parts, benchmark, representative and experimental basins were the component which was most memorable (and perhaps, the least successful, except for providing good outdoor laboratory facilities and opportunities for studies of physical processes and for development of instrumentation). All over the world, hydrologists were encouraged to instrument and monitor such representative basins and innumerable publications of data eventuated with, until the co-operative Northern European venture FREND, relatively little scientific advance, (other than in the accumulation of basic data) for the massive expenditure of effort and expense. The exceptions to this criticism were certain of the experimental catchment studies; in Britain, IH operated linked systems and processes studies in experimental catchments at Plynlimon in Wales and at Balquhidder in Scotland.

All these catchment studies are <u>systems</u> studies of the whole of the hydrological cycle in discrete and, inevitably, limited catchment areas.
Each hydrological experiment envisaged a number of catchments, chosen in the belief that they were watertight and from which one would be chosen, at random, for "treatment", in respect of a change in land use in the catchment to be "treated". A reasonably long "calibration" period would be available to compare the hydrological performance of the different basins, before the land use change was initiated. All these experiments involved clear-cut (in both senses!) comparisons of one treatment with another in complete, albeit relatively small catchments. Initially, the principal hydrological concern was the compaarative water use of different crops in similar catchments; only later was the importance appreciated of a better understanding of the chemistry (cf acid rain) as well as of the physics.

In effecting these catchment experiments in East Africa and in Britain over the years, many problems were resolved, more or less successfully. The most difficult of solution (and impossible of rectification!) was the question of the water-tightness of the catchments selected. Only over periods of measurement lasting for many years, can one be reasonably certain that no measurable input or output has been overlooked. Another possible problem may be that an experiment, envisaged to run for 20 years, may outlive the socio-economic considerations which gave rise to it in the first place. In fact even the East African projects were sufficiently well conceived for their results to be of real value to the countries, after the changes which followed independence.

HYDROLOGY - THE PROCESS APPROACH

However successful the systems approach, however randomly selected and watertight the catchments, however continuous the data set and however thorough the analyses of all the measurements from the experimental catchments, doubt remains on the propriety of applying the results to other catchment areas, in apparently similar environments. Extrapolation of the results from a small headwaters catchment to the whole of the extensive river basin of which it is a component part involves problems of scaling. In conventional situations, clearly-defined changes in land use over large basins are frequently impossible to achieve. Indeed, in few of the experimental catchments described above, was the land use cover complete over the whole of the even relatively small catchments. Even in Kenya, the indigenous vegetation at higher altitude (bamboo forest with montane outliers) differed from that lower in the catchment (montane forest).
This, then, is the justification of the physical process approach. It does not obviate the requirement for research in complete catchments but, by study of the physical (and chemical) processes involved within the catchment, it leads to an understanding of the reasons for the catchment behaving as it does. When the results of a systems investigation (complex, long-term and costly in effort and equipment) are inconsistent with previous experience, only process studies offer a possible solution to the dilemma. Hence, when the programme of IH was being established, I argued the necessity to complement the systems studies (to which IH was committed as part of its original Terms of Reference) with studies of all the physical processes involved. That I was successful is proven by the fact that the physical processes division of IH became the largest of the four divisions of IH; it encompassed evaporation flux studies, vegetation- atmosphere interactions, process modelling, fluvial geomorphology, soil hydrology, groundwater and chemical hydrology.

Just as British hydrologists concentrated their research interests and priorities on gaining an understanding of certain of the physical processes (such as evaporation, transpiration and interception measurement) underlying the behaviour of hydrological systems, I consider that Nordic hydrologists have contributed most effectively to research into the particular aspects of hydrology which are of greatest relevance to their environment, namely soil moisture, nuclear techniques, snow and ice and, above all, acid precipitation. Indeed, throughout my 24 years at IH, this emphasis on physical (and chemical) understanding of the processes within the hydrological cycle was mirrored by the attitude of Nordic hydrologists and scientists. There were detailed interactions with Danish scientists (Drs Somer and Olgaard) over development and calibration of neutron soil moisture gauges in the late 1960s, collaboration with the International Atomic Energy Agency (IAEA) in preparing a monograph on Nuclear Techniques in Hydrology in association with Dr E Eriksson and others and studies of stable isotopes in precipitation (Dr D Dansgaard); collaboration continued in the 1970s when parties of Nordic scientists visited Wallingford and exchanged presentations and ideas.

In the meantime, I or one of my colleagues from IH, attended meetings in Norway, in Sweden, in Denmark and in Finland. Indeed, there have been so many meetings and discussions and fairly long term exchanges of staff between Wallingford and Nordic scientists that it would be impractical to document them all here. Many were undertaken as part of the International Hydrological Decade (IHD) or the subsequent International Hydrological Programmes (IHP) of UNESCO or the WMO Operational Hydrological Programme (OHP). More recently, Northern European (including Nordic) collaboration on catchment research in FREND has brought together national data bases thus enabling mathematical modelling and analyses on a wider regional basis, particularly relating to floods and low flows. Thus, a widening of areal coverage and a measure of understanding previously lacking in the results of these expensive inter-national programmes has been achieved as well as some positive results from the disparate mass of material collected in response to IHD, IHP and OHP.

However, I feel that the principal concern of Nordic hydrologists in recent years has, very understandably, been with the phenomenon of acid rain. The response to the serious losses of fish because of freshwater acidification in Scandinavia was substantial, since the late 1950s and the Norwegian SNSF project bagan in 1972. In this acid rain debate, Prof Rosenqvist argued the importance of forest development in acidifying catchments; changing the vegetation and hydrological routing can affect the environment adversely. Indeed, in a wider setting it is the effects of land use change which may well provide the major environmental threat on a global scale.

The British Royal Society Surface Water Acidification Programme (SWAP), begun in 1986, proposed funding of shared research between academic bodies in the UK and in the Nordic countries; in the event, some Scandinavian scientists declined to participate until IH was equally involved. Indeed Prof Nils Christopherson spent a year working with Dr Colin Neal at Wallingford and Prof Hans Martin Seip was one of the key advisers to the programme. In the meantime, meetings associated with the European Geophysical Society at Barcelona in 1987 began a process which led to the production of one of the most successful Special Issues of the Journal of Hydrology; Guest Edited by Colin Neal and Mike Hornung, Volume 116 was entitled "Transfer of Elements through the Hydrological Cycle" and the list of Nordic contributors testifies to the close and continuing Anglo-Nordic relationship. I am confident that, despite the sometimes rather emotional approach of the acid rain lobby, the truly scientific understanding which has resulted from these collaborative efforts, building on the pioneering work of Nordic scientists over the last 20 years, is impressive testimony to what can be achieved by the combined efforts of the hydrological scientists of Northern Europe. However, the research must be more expansive in outlook and not restricted to themes of immediate political, parochial scale; broadening the research will give a wider perspective on global and regional, as well as on local affairs.

The international, political, role of the Nordic countries, on matters of the environment and on aid to less developed countries is so well acknowledged that it need not be mentioned here. The Stockholm conference, twenty years ago, led to the creation of UNEP, in Nairobi and, ultimately to the Rio Earth Summit in June 1992. At a less political level, through my position (on leaving IH) as the International Commissioner for NERC environmental consultancy services, I have learned much about the generous overseas aid programme of some of the Nordic countries; indeed, on occasions of staff shortage by Nordic aid agencies, I had previously actually seconded IH staff to work on Nordic aid programmes! Since most European countries provide assistance to most developing countries, in Africa for instance, it is rational for the various national aid agencies to agree to allocate sectors of aid requirement to particular donor countries. Thus in Kenya, I learned that British aid is concentrated on projects in the infrastructure, mainly on roads and power generation while Nordic aid has addressed water and sanitation, through the various Scandinavian aid agencies. I commend this excellent solution, which avoids different national aid agencies becoming involved in what can only be described as inappropriate and unseemly competition; sadly, this situation is frequently exacerbated by the less developed country's staff charged with coordinating diverse donor aid! Through the international development banks, such as World Bank (WB), Inter-American Development Bank (IDB), Asian Development Bank (ADB), African Development Bank (AfDB) and European Bank for Reconstruction and Development (EBRD), very substantial funding is available for environmental impact studies and for water resources investigations, among other things. Following some unfortunate misdirection (to environmentally unfriendly projects) of international finance in the past, the programme of all the international development banks has been amended so that environmental considerations have high priority in the assessment of the viability of any project; indeed, unlike the other banks which have become aware of the environment in retrospect, the EBRD has environmental awareness written into its terms of reference.

THE FUTURE

Over the years, crises of public confidence in environmental matters have stimulated, or discouraged advances in the hydrological sciences. In Britain, the disastrous floods and fatalities at Lynmouth in 1952 resulted in funding being provided for the IH Floods Studies Team; their Floods Studies Report (NERC 1975) has determined British hydrological procedures in relation to floods planning. The major drought in 1975 was immensely inconvenient to the populace. One popular newspaper's front page picture showed a dry and cracked reservoir. The headline read "Will it ever rain again?" However, the drought caused no human fatalities; thereafter, since a 1 in 200 year drought event had been survived, water resources studies were restricted and promising research into evaporation and transpiration failed to attractfunding. Twenty years ago, a new ice age was thought to be approaching and the Club of Rome caused equally great concern with their "Limits to Growth" study. These panics are overlooked and, indeed, are largely superseded by the present concern about global warming. Such crises can lead to improvements in measurement techniques and networks, provided these are tied to reasonable scientific requirements and associated with demand management. Under no circumstances should they be used as scientific blackmail, to compel governments to spend more and more on collecting data for data's sake, without a clear requirement for the data. Too much of this may have occurred under the IHD, the IHP and the OHP. To a developing country, the cost of dealing with all the data from ever-increasing networks, coupled with greater frequency of observation from improved, automated, instruments may well prove prohibitive! In many developing countries, the principal aim of water resources studies in the past has been Water Master Plans, almost invariably comprehensively (and expensively) prepared by expatriate teams and often destined to remain for ever on the shelf because of their inherent inflexibility and because of the lack of awareness of the political, social and economic context. Hence, there is a need to communicate priorities to decision makers, to convey the need for urgent action. Growing international awareness of the need for greater consideration to be given to the economic and social implications of water resources schemes leads to the requirement for hydrologists to think more as economists in specifying requirements for measurements. The marginal cost of each %age point in the quest for greater precision may far outweigh the benefit. On the other hand, the economist's emphasis on short-term expediency versus long-term planning must be restrained; the maximum time span for an economist is 10 years, as compared with the 40-50 year plan of a water engineer. Even more than at present, hydrologists must become globally-oriented. The days of hydrologists considering in detail only limited catchment areas of the earth's surface are long since past, other than aslimited open air laboratories or as local or regional applied investigations, which are technological rather than scientific. A more synoptic, more international approach is now needed to tackle problems of:

(1) pollution, which is no respecter of national boundaries
(2) global climatic change
(3) sustainable development, where there is a need for planning data to maximise benefits at minimal cost

This change of scale of operations is illustrated by the programme of IH, which was established, originally, to resolve a pressing political problem of the comparative water use of forested versus grassed catchments in Britain. Now, small scale hydrological modelling has been extended to regional and global modelling. Similarly, close collaboration between hydrologists world wide will be needed if the extent of global climatic change is to be measured and more accurate predictions of its effects are to be made. Not only may this prove to be a major threat to civilisation as we know it but it may invalidate the 30 or 50 year record on which much hydrological credibility is based. Even on a local scale, in East Africa and more recently in China, substantial but apparent (because of the difficulty of statistical "proof") regional discontinuities in the hydrological responses to precipitation have been attributed to changes in land use in the headwaters catchment areas. Hence, all such phenomena must be investigated, taking into account all possible changes in the underlying physical processes.

While remote sensing, use of satellite data collection platforms and other esoteric instrumental developments have added much sophistication to the hydrologist's repertoire, something can still be learned from detailed observations of nature as indeed was demonstrated by our British and Viking ancestors' siting of settlements in Britain with such close attention to flood risk and water supply that most of the village sites have survived to the present day. As world-wide demand for water increases, the value and importance of hydrology is appreciated by the aid agencies and the "experts" have much to learn from local experience and folk memory. Planning for sustainable development must exploit all existing knowledge, so as to maximise benefits at minimal cost. International collaborative studies are a priority, with emphasis on involving hydrologists and scientists from the developing world in hydrological studies in their own countries. In Europe, drought is an inconvenience; to peasants in Africa, it is a matter of life and death. May British and Nordic hydrologists, who have achieved so much in mutual collaboration in Northern Europe, lead the way forward by applying their science to the pressing hydrological and water resources problems of the less developed countries.

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OM ALTAUTBYGGINGEN

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ABSTRACT

The Alta watercourse is located in the county of Finnmark, in the norternmost part of Norway. Most of the catchment area is located on the Finnmark plateau, and the main river runs northwards toward the Altafjord. Among several ecological aspects, the superb salmon fishing in the Alta river was the most important.

The Alta Power Plant is a run-of-the-river plant. A 110 m high dam has been built in a narrow gorge 5 km downstream the natural outlet of the original lake, and the reservoir obtained is 135 mill m^3, or about 6 %.

During the planning stage, before, and after regulation several environmental investigations have been performed.

The plant has very strict flow regulations, and due to uncertainties about the influence on ice conditions and fish, these regulations were made temporary for 5 years. The manoeuvring regulations are now being reconsidered.

Never have the environmental questions connected to a Norwegian hydropower project aroused such public interest as with the Alta scheme. The project was put before the Norwegian Parlament three times, and also taken to the Supreme Court. Actions from demonstrators influenced the government to halt construction work for one year.

In connection with the Alta scheme great focus was placed on the Sami culture, which led to the establishment of the Sami parlament.

KORT BESKRIVELSE AV VASSDRAGET

Altavassdraget ligger i Vest-Finnmark og har sitt utspring ved grensen mot Finland. Hovedelva renner nordover mot Altafjorden gjennom Kautokeino og Alta kommuner. Vassdraget kan deles i en øvre og en nedre del ved innsjøen Vir'dnejav'ri, og nedslagsfeltet til Virdnejav'ri dekker ca 6000 km^2.

Den øvre delen ligger på Finmarksvidda mellom 360 moh og 265 moh. Selve vidda når stedvis opp i ca 600 moh, og mesteparten av Finmarksvidda består av metamorfe bergarter dekket av løsmasser av varierende tykkelse. Hovedelva som her kalles Kautokeinoelva har lite fall, og består delvis av lange, smale innsjøliknende partier. Landskapet er flatt og rolig med avrundede høydedrag inni mellom. Over hele vidda finner en større og mindre vann omkranset av myrområder som bl a er berømte for multeforekomster.

Vir'dnejav'ri, som er utbyggingens eneste magasin, ligger i nordkanten av vidda, og det er bratte dalsider opp til viddenivået. Størstedelen av sjøen er relativt grunn, 5-10 m, med enkelte dypere partier.

Fra det naturlige utløpet av Vir'dnejav'ri (normalvannstand 250 moh) falt elva nesten 200 m på 7 km og gikk delvis i en trang dal og delvis i et bratt gjel. Omtrent 5 km nedenfor det naturlige utløpet er det bygd en 110 m høy dam, og det etablerte magasinet har en høyeste regulert vannstand på 265 m. Laveste regulerte vannstand er 245 m ovenfor det naturlige utløpet av Vir'dnejav'ri, i delmagasinet nedenfor er laveste regulerte vannstand 200 m. Kraftverket utnytter fallet mellom magasinet og dalbunnen ved Savco, ca 80 moh og ca 2 km nedenfor dammen.

Nedenfor utløpet av Vir'dnejav're heter elva Altaelva. Fra utløpet av kraftstasjonen renner elva 5 km delvis i stryk og så gjennom en ca 2 km lang grunn innsjø som ligger i den etter hvert velkjente Alta canyon. Dalen er trang og dalsidene meget bratte. Videre nedover renner elva skiftevis i stryk og roligere partier gjennom Altadalen og ut i Altafjorden ved Alta. Nedbørfeltet ved utløpet i fjorden er ca 7500 km^2.

På den nordre delen av Finmarksvidda er grunnfjellet dekket med lag av sandstein og skifer. Disse lagene kommer ut i dagen enkelte steder langs dalsidene, og en finner her den berømte Altaskiferen. Brudd av denne utgjør en betydelig industri.

Langs Altaelva fra Kista til utløpet i sjøen domineres landskapet av løsmasseavsetninger fra den siste istiden. Avsetningen fant sted i sjøen som på den tiden sto ca 75 m høyere enn i dag. Etter hvert som landet steg har elva funnet seg veg gjennom avsetningene under stadige forandringer av elveløpet. Under denne prosessen har elven gravet og transportert løsmassene ut i Altafjorden hvor et stort delta har bygget seg opp. Samtidig som elva har gravet seg dypere har store grus- og sand terrasser blitt dannet, og disse er meget karakteristiske for landskapsbildet i den nordre delen av dalen.

ØKOLOGISKE SÆRTREKK

Den øvre delen av vassdraget ligger på Finmarksvidda i et område med arktisk innlandsklima med lange og kalde vintre. Selve Altadalen er påvirket av kystklimaet, og Altaområdet med Altadalføret er kjent som et frodig distrikt. Man finner bl a furuskog som ikke er vanlig så langt mot nord. Nær kraftstasjonsområdet er det et område med ospeskog - denne er fredet. Masimjelten er en særegen blomst som bare er funnet få steder. Forekomster av denne er blitt spesielt beskyttet.

Selve Altaelva er særlig kjent for sitt laksefiske. Hvert år er fiskerettighetene raskt utleid og elva har på denne måten vesentlig økonomisk verdi samtidig som den har sosial og rekreasjonsmessig betydning.

Altavassdraget, som en del av Finnmarksvidda, utgjør vinterbeitegrunnlaget for rein. Både i Alta og Kautokeino kommuner bor mange samefamilier som driver reindrift. Like øst for Altaelva går sentrale trekkruter for flytting av reinen mellom vinter- og sommerbeitene. I nærheten av utbyggingsområdet for Alta kraftverk finner en også kalvingsområder for reinen.

PLANHISTORIE, STATKRAFTVERKENES SØKNAD OG UTBYGGING

I 1966 og 1968 utarbeidet henholdsvis Studieselskapet for Norges vannkraft og NVE's avdeling for vasskraftundersøkelser (VU) to ideskisser for vannkraftutbygging i Altavassdraget. Studieselskapets skisse hadde to kraftstasjoner med en samlet produksjon på 480 GWh. VU's plan var mest omfattende, den medførte neddemming av Masi, og hadde en samlet produksjonskapasitet på snaue 1200 GWh. Denne skisseplanen var et uttrykk for vannkraft-potensialet i vassdraget og ikke noen reell plan.

Statkraftverkene startet arbeidet med en plan for kraftutbygging i Altavassdraget i 1970. Neddemming av Masi var aldri med i Statkraftverkenes planer fordi dette ville føre til store konsekvenser for bosettingen i Masi og for is- og erosjonsforholdene nedstrøms kraftverket.

I 1973 vedtok Stortinget varig vern av Masi og at Altavassdraget skulle konsesjonsbehandles.

Statkraftverkenes søknad ble fremmet i 1974 og bestod av en kraftstasjon i Savco med en produksjon på 860 GWh. Neddemmet areal utgjorde 9 km^2. Planen omfattet ellers regulering og overføring av Iesjav'ri, regulering av Joat'kajav'ri, og overføringer av deler av Tverrelva. Vir'dnejav'ri ble regulert og fallet utnyttet til noe nedenfor Joat'kajåkkas samløp med Altaelva. Fallet fra Joat'kajav'ri ble utnyttet i samme kraftstasjon.

I 1976 sendte Statkraftverkene inn en revidert søknad hvor regulering og overføring av Iesjav'ri var tatt ut. Produksjonen i Alta kraftstasjon var redusert til 710 GWh. Hovedstyret i NVE innstilte 21. desember på utbygging av Altaelva og Joat'kajåkka.

Under konsesjonsbehandlingsprosessen gikk både Alta og Kautokeino kommuner mot utbyggingen, mens Finnmark fylkesting var for utbygging av Altaelva med regulering av Vir'dnejav'ri, men Joat'kajåkka ble foreslått varig vernet.

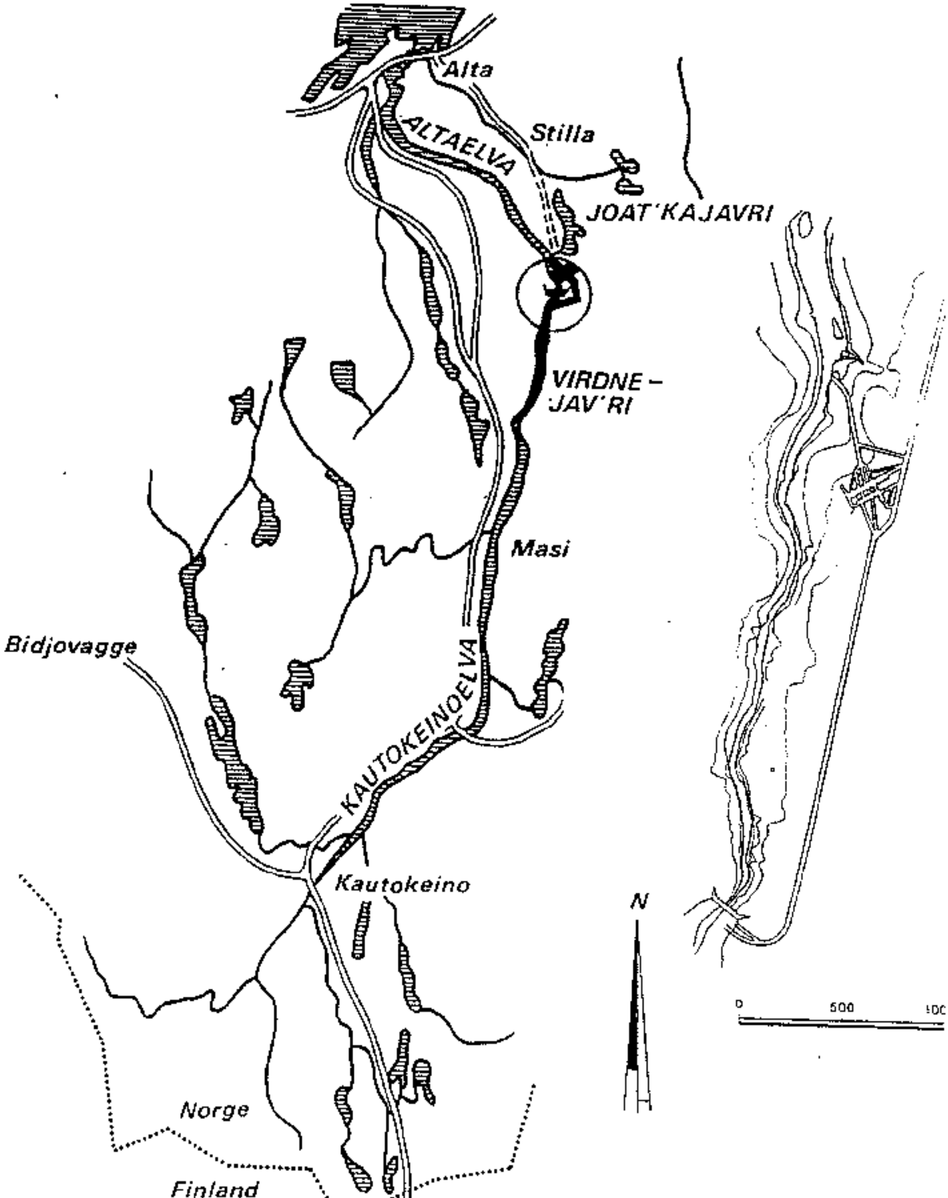

Fig 1. Skisse over Altavassdraget og utbyggingen.

I 1978 vedtok Stortinget en utbyggingsplan med Vir'dnejav'ri som eneste magasin. Fallet i Altaelva utnyttes til oppstrøms samløp Joat'kajåkka for å unngå tørrlegging av den øverste lakseførende strekningen i Altaelva. Neddemmet areal rundt Vir'dnejav'ri utgjør 2.8 km^2 og midlere produksjon ble 625 GWh (fig 1). Stortinget vedtok samtidig varig vern av bl a Iesjåkka og Joat'kajåkka.

DEMONSTRASJONER OG ANLEGGSARBEIDE

Det ble fremsatt krav om ny behandling i Stortinget basert på feilaktig behandling og manglende utredninger. Dette sa Stortinget nei til i juni 1979 og 15. juni fastsatte regjeringen utbyggingsplanen for Alta kraftverk ved Kongelig resolusjon.

Anleggsarbeidet ble startet opp og dermed ble en omfattende motstand ledet av Folkeaksjonen mot utbygging av Alta-Kautokeinovassdraget utløst. De mest omfattende demonstrasjonene fikk en i Alta med hundretalls demonstranter, og hvor navn som Stilla og 0-punktet har brent seg fast. Det var også aksjoner i Oslo, og endog statsministerens kontor ble okkupert for et kortere tidsrom.

Saken kom pånytt opp i Stortinget, som i mai 1980 igjen fastslo at utbyggingen skulle finne sted. Gyldigheten av utbyggingsvedtaket ble prøvet for Alta herredsrett som stadfestet lovligheten av vedtaket. Alta herredsretts avgjørelse ble anket og saken vedtatt sendt direkte til høyesterett. Høyesterett behandlet saken i plenum, og avsa 26. februar 1982 enstemmig dom for at utbyggingsvedtaket var gyldig.

Store politistyrker var stasjonert i Alta fram mot høyesteretts avgjørelse for å holde demonstrantene vekk og sørge for at arbeidet med anleggsveien kunne gå sin gang.

Det ble hevdet fra demonstranter at myndighetene ved å bygge ut Altavassdraget ikke viste respekt for samekulturen og krenket samenes rettigheter. Dette skyldtes nok mye misforståelser og mangel på konkrete opplysninger om utbyggingen og virkningene av denne. Dette bidro imidlertid til at samenes interesser og rettigheter kom i fokus.

Et av kravene var at det snarest måtte etableres et demokratisk valgt sameparlament. Altakonflikten viste at det ikke fantes noe representativt organ som kunne tale samenes sak. De samiske organisasjonene hadde forskjellige oppfatninger om de spørsmål som reiste seg i forbindelse med utbyggingen. Konflikten bidro til at norske myndigheter for alvor innså sine manglende kunnskaper om samiske forhold. Samenes historie, deres kulturelle og rettslige stilling var til da ikke viet særlig oppmerksomhet, hverken faglig eller politisk. Sametinget ble opprettet i 1989.

I Alta gikk det videre anleggsarbeidet meget raskt og uhindret, og i mai 1987 kunne kraftstasjonen settes i kommersiell drift.

MANØVRERINGSREGLEMENTET

Manøvreringsreglementet for Alta kraftverk ble gitt ved Kgl.res av 15. juni 1979. Dette var et prøvereglement gjeldene for de fem første driftsårene av kraftverket pga usikkerhet omkring virkninger av utbyggingen på fiske- og isforhold. Manøvreringen skulle derfor utføres i samråd med en fiskerisakkyndig oppnevnt av Miljødepartementet og med Iskontoret i Norges Vassdrags-og Energiverk.

Om sommeren etter at magasinet er oppfyllt skal vassføringen være mest mulig nær den naturlige og ikke avvike mere enn 10 % fra denne. Utover høsten avtrappes vassføringen gradvis fram mot isleggingstiden til maksimalt 30 m³/s 15. desember. Denne vassføringen holdes eller reduseres utover vinteren. Om våren når elva åpner seg kan vassføringen gradvis økes (fig 2).

Prøvereglementets funksjonstid er nå over og i Statkraft er arbeidet med forslaget til et endelig manøvreringsreglement i full gang. I prøveperioden har det foregått omfattende forsøk særlig med mer fleksibel vinterdrift.

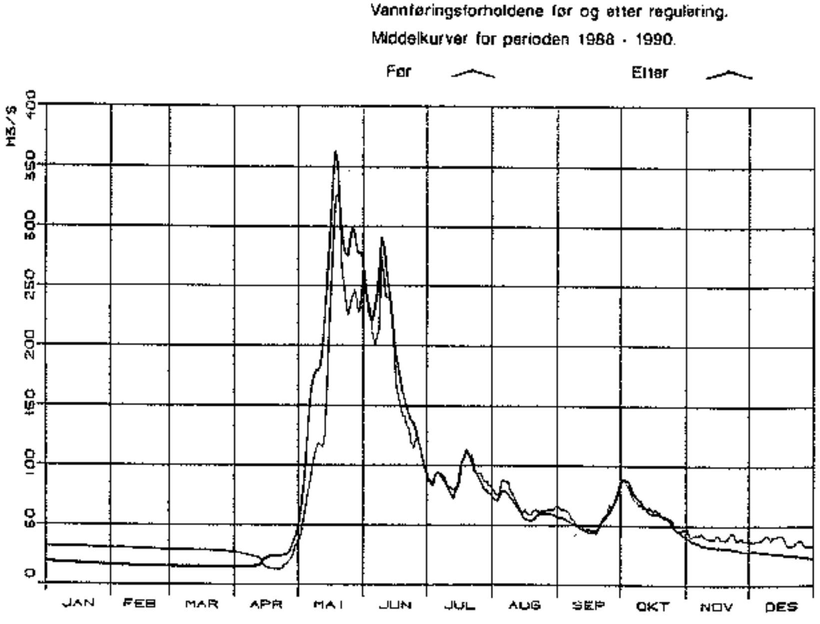

Fig 2. Naturlig vassføring i perioden og vassføring etter utbygging i perioden

MILJØUNDERSØKELSER

Parallelt med den tekniske planleggingen av utbyggingen ble det satt i gang en rekke miljøundersøkelser, og resultatene fra disse ble løpende vurdert i planleggingsarbeidet. Enkelte undersøkelser var av typen kartleggingsarbeid mens andre i større grad har gått på å dokumentere forskjellige virkninger av utbyggingen. I en del tilfeller er nødvendige undersøkelser for skjønnet kommet i tillegg.

Hydrologiske undersøkelser har vært utført i vassdraget siden 1915 som ledd i Hydrologisk avdelings generelle undersøkelser. I forbindelse med planleggingen av kraftutbygging i området ble undersøkelsene utvidet og en del kraftverksrettede spesialundersøkelser er utført.

Isundersøkelser har pågått i vassdraget fra 1960-årene. Mulige virkninger av utbygging på isforholdene blir vurdert ved alle utbygginger i landet, og var særlig viktig ved denne utbyggingen. I det midlertidige manøvreringsreglementet stod mulige virkninger på isforholdene sentralt. Isforholdene er derfor undersøkt i prøveperioden med henblikk på å finne hva vassdraget tåler i denne sammenheng.

Vanntemperaturmålinger om sommeren ble satt i gang i 1972. De omfatter målinger både i den regulerte og uregulerte delen av vassdraget, og virkningene av reguleringen på vanntemperaturen nedstrøms utløpet av kraftverket er vurdert. Resultatene viser en temperaturreduksjon første del av sommeren og en økning siste del av sommeren, høsten og vinteren (fig 3).

Vanntemperaturen er viktig for fiskeundersøkelsene, og i den sammenheng er også vanntemperaturen i elvebunnen målt før og etter reguleringen på utvalgte gyteplasser.

Da en temperaturreduksjon som følge av reguleringen ble forutsett, ble det satt i gang undersøkelser for å finne om et øvre inntak i magasinet ville kunne redusere virkningene av reguleringen på temperaturforholdene i elva. Det ble i denne sammenheng laget en fysisk modell av magasinet (Norges Hydrodynamiske Laboratorium). Etter disse forsøkene ville det bare være korte perioder når et øvre inntak ville ha merkbar effekt på temperaturforholdene, men det øvre inntaket ble likevel bygget.

Altaelva er en av landets beste lakseelver, og mulige skadevirkninger på laksen stod meget sentralt både under planleggingen og ved fastsettelsen av reglementet. Fiskeundersøkelser ble satt i gang i forbindelse med planleggingen og undersøkelsene inngår også som en viktig del for det kommende fiskeskjønnet i vassdraget. Resultatene av undersøkelsene er under bearbeiding. Det har vært store variasjoner i fangstmengden i Altaelva etter regulering, men det har det også vært i andre lakseelver i området. Det ser foreløpig ikke ut til at reguleringen har hatt så store virkninger på fisket som det ble fryktet.

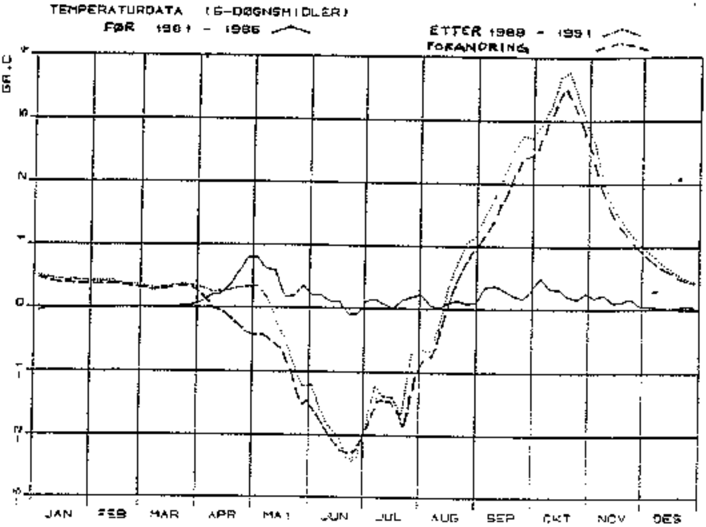

Fig 3. Temperaturforskjell oppstrøms og nedstrøms reguleringsområdet før regulering, etter regulering og forandring som følge av reguleringen.

Det har vært foretatt grunnvannsundersøkelser i Altavassdraget før og etter utbygging. Virkningene på grunnvannsforholdene er marginale.

Det er foretatt erosjonsundersøkelser i vassdraget og disse pågår fortsatt. Det er stadig noe erosjon i elvemælen, delvis på faste steder og av og til på nye steder. Forholdene blir overvåket og det blir vurdert om dette skyldes reguleringen eller ikke. En del strekninger er blitt forbygget i forbindelse med reguleringen.

Sedimenttransporten er undersøkt, og ytterliger undersøkelser pågår som del av de hydrologiske påleggene for å kartlegge eventuelle endringer i elveleiet som følge av reguleringen.

Allerede under planleggingen ble det hevdet at Vir'dnejav'ri-magasinet og dammen ville kunne føre til klimatiske endringer, spesielt med lavere temperaturer oppstrøms dammen og endog påvirke klimaet i Masi. Klimaundersøkelsene i dette området ble derfor intensivert. Undersøkelsene er nå avsluttet, og resultatene viser bare ubetydelige klimapåvirkninger.

Botaniske og zoologiske undersøkelser er foretatt i reguleringsområdet særlig i form av kartlegginger. Ved de botaniske undersøkelsene ble den skjeldne planten Masimjelt funnet, og som nevnt tidligere er forekomster av denne i øvre del av magasinet sikret. En viktig del av de botaniske undersøkelsene var å vurdere mulige endringer i for-tilgangen for reinsdyr.

Mulige virkninger av reguleringen på reinsdyrnæringen ble også undersøkt. Neddemmingen har ført til noe reduksjon i beiteland, og anleggsveien med økt ferdsel i området kan ha innvirkning på trekk av rein, på den annen side er veien også til nytte for rein-næringen. Statkraftverkene er pålagt å betale kr 30 000 hvert år via reindriftsagronomen i Vest-Finnmark til de reinbeitedistrikter som blir berørt av reguleringen.

Under planleggingen ble det utført omfattende kulturminneundersøkelser langs veitraseen, i magasinområdet og andre arealer som ble berørt av utbyggingen. Det ble gjort mange verdifulle funn, særlig i anleggsområdet, som er av stor betydning for kulturminneforskningen Finnmark.

LANDSKAPSPLEIE

Ved planleggingen av Altautbyggingen ble det lagt stor vekt på at utbyggingen skulle bli så skånsom som mulig, og at alle anlegg skulle gli best mulig inn i terrenget. Plassering og utforming av veier, dam, tipper o a ble derfor gjort i nært samarbeid med Natur- og Landskapsavdelingen i NVE. Alle utendørsanlegg er redusert til et minimum. Resultatet er blitt meget tilfredsstillende og sår i terrenget er stort sett rehabilitert.

VIRKNINGER AV REGULERINGEN

Altautbyggingen er en liten utbygging, og fungerer om sommeren som et elvekraftverk. Magasinet er relativt lite. Som det fremgår ovenfor er det bare små virkninger av utbyggingen på miljøet. Manøvreringsreglementet som er avgjørende for virkningene på fisk- og isforhold blir tilpasset for å minimalisere også disse virkningene.

Selv om Altautbyggingen i en tid forårsaket store lokale problemer har lokalsamfunnet etter hvert også oppdaget at reguleringen har sine fordeler. Kraftverket har tilført samfunnet aktviteter og arbeidsplasser. Selve kraftverket og dammen er etter hvert blitt et betydelig turistmål. Inne i fjellet ved dammen blir det nå gjort ferdig et informasjonssenter for publikum. Gjennom et panoramavindu er det flott utsikt over dammen og magasinet.

Det er også organisert båtturer på Ladnatjav'ri og Vir'dnejav'ri helt ut til dammen. Disse starter i Masi.

Anleggsveien til kraftstasjonen er stort sett åpen for offentlig ferdsel til Joat'kajav'ri, og benyttes av lokalbefolkningen store deler av året.

Det er også grunn til å stille spørsmål ved hvilke miljøvirkninger disse sekundæraktivitetne har.

HYDROLOGICAL MACRO-REGIONALIZATION AND CLIMATIC CHANGE

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EXTENDED ABSTRACT

One of the most important consequences of future climate change may be an alteration of the surface hydrological balance, including changes in stream flow, soil moisture and ground water recharge. Climate model experiments demonstrate the great sensitivity of the hydrological cycle to climate change and to a set of specific forcing factors. These experiments, at present, establish first order relationships governing the hydrological cycle. However, they imply large and complex variability of the hydrological cycle as a part of the total global transfer and exchange of energy and matter. Much effort is now directed at better understanding of these complex relations and in particular, at the problem of parameterization of hydrological processes to a scale corresponding to the one used in climate models, as well as at the problem of disaggregation (aggregation) of the results from such models to scales suitable for analyses of the implications for water resources.

Ideally, the simulations from climate models could be used directly to drive hydrological models. These, in their turn, could be used to evaluate the hydrological and water resources effect of climate change. An obstacle is the incompatibility of space (and, to a lesser extent, time) scales between hydrological processes, that account for variations at the small to medium catchment scale, for example, hundreds of meters to tens of kilometers, and the climate models that operate at scales of hundreds to thousands of kilometers. In spite of current improvements in computers' power, it is likely that climate models will continue to use the spatial scales of this order in the foreseeable future. Improvements are rather to expect in the parameterization of processes characterizing the interaction of climate, vegetation and hydrology and other processes that are of importance for climatic feedbacks and critical in defining climate change.

There are two aspects of the problem originating from the fact that output data from climate models represent grid cells with large areas. To evaluate the parameterization of hydrological processes' representation there is an urgent need in hydrological ground truth against which the predictions of climate models could be validated. This implies the development of procedures to transfer hydrological information from the individual catchment to a regular grid. Hydrological characteristics of interest include average annual and seasonal runoff, mean monthly runoff, inter annual variability and its relationship to annual rainfall. Such gridded estimates of hydrological characteristics are also very useful in the derivation and presentation of water balance components. It is also necessary to define the degree of variability across a grid box. This knowledge is fundamental for disaggregating the results derived for grid boxes to individual sites and catchments. While for temperature the relative variations compared to long term means are almost the same over large areas, precipitation and runoff show considerable variability for an area of 100000 km or larger in this respect. Also the hydrological regime, at least in Europe, can vary substantially over such areas.

Studies of macro scale variability of hydrological variables across national boundaries require access to regional data bases. The FRIEND (Flow Regimes from International Experimental and Network Data) data base, compiled recently within the frame of UNESCO International Hydrological Programme IV H-5-5, offers a possibility of such studies for northern and western Europe.

The characterization of large scale variations in river flow is one of the subjects studied within the framework of the FRIEND project. Gridded estimates of hydrological characteristics are being developed using a variety of procedures, ranging from simple averaging through interpolation applying objective methods to the application of simple water balance models over grids. These methods are shortly presented and discussed. Special attention is put to the problem of interpolating runoff with objective methods. There are two principle approaches to this problem. The most straightforward method is to relate the interpolation to the existing river network. In this case all runoff to or from a certain grid cell must be calculated. The second approach is based on the assumption that runoff is a continuous process in space. The runoff, observed in different catchments, must, in this case, be transformed to a point process, after which it can be interpolated in the same manner as precipitation or evaporation. Procedures for interpolation with both approaches are developed and tested in this study. These procedures follow two steps: first long term means are calculated and then values for individual years. An area of 400*400 km in southern Norway is used as a test area. The data consist of observations over runoff, precipitation and actual evaporation and digital map information on topography, river networks and catchment boundaries. The grid networks used are 5*5 km, 50*50 km and 2.00*2.00.

For a grid mesh of 4 x 5 covering the Nordic countries the internal variability of temperature, precipitation and runoff within a grid box has been analyzed. The study confirms the spatial stability in the temporal variations of temperature. Precipitation and runoff, on the other hand, show considerable variability across grids in this respect. A probable scenario for the Nordic countries is an increase in average temperature by 2.5 and an increase of precipitation by 10%. When these values are taken as representative for a grid box, knowledge about the variability within a grid box allows us to evaluate in statistical terms the possible range of changes for individual sites and catchments. The assumption is, of course, that the spatial variation pattern will remain the same.

KLIMAENDRINGER OG ENERGIPRODUKSJON
STATUS OG PLANER

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ABSTRACT

Climate change will affect the Nordic energy system directly, through changes in runoff (total runoff and seasonal distribution) and thereby hydropower production, and through changes in energy consumption for heating.

Through the support of the Nordic Council of Ministers, a research program has been launched to investigate the effect of climate change on energy production, focusing on hydropower. The project period is 1991 to 1994, with participation from the power industry, research institution within water resources and energy systems, and governmental institutions.

The main parts of the program are:

A. Testing and improvements of hydrological models, with especial emphasis on evapotranspiration, snowmelt and glacier mass balance submodels.
B. Improvements of the energy planning models; better representation of reservoir inflow, coupling of inflow and consumption pattern, improved representation of snow storage.
C. Estimation of runoff, including regional scenarios for meteorological variables.
D. Analysis of climate change impacts on electricity consumption.
E. Analysis of impacts on the hydropower system; on local, national and regional scale. Also included are effects on floods and dam safety issues.
F. Analysis of climatic variability and climatic trends of hydrological records, on regional (Nordic) level. Analysis to include annual, seasonal and extreme values.

The paper presents the present status of the project.

BAKGRUNN

Det nordiske programforslaget "Klimaendringer og vannressurser", utarbeidet av CHIN og KOHYNO i 1989/90, fikk som kjent ikke midler fra Nordisk Ministerråd som samlet program. Programmet vakte imidlertid interesse, og et av programområdene, det som rettet seg mot vannkraft, har i modifisert utgave fått støtte fra Energi og miljøgruppen i

Nordisk Ministerråd, med 800 000 DKK for 1991 og 1992. Det er i tillegg betydelige nasjonal innsats knyttet til prosjektet. Denne oversikten omhandler først og fremst de fellesnordiske delene av prosjektet.

PROSJEKTETS MÅLSETTING

Hovedmålsettingene ved prosjektet er:

1) Å oppgradere planleggingsverktøyene for nordisk energiforsyning slik at de kan bidra til en optimal planlegging ut fra
    - den mest sannsynlige tilsigsutvikling i Norden i planleggingsperioden
    - usikkerheten i tilsigsutviklingen

2) Utarbeide prognoser for tilsigsutvikling og produksjonspotensial for en tidshorisont på 40 år, basert på den beste tilgjengelige kunnskap om klimautvikling og det beste modellerings- og analyseverktøy

De primære brukergruppene for resultatene vil være:

- de forvaltningsorganer som driver energiplanlegging i Norden
- sentrale bransjeorgan innen energiforsyningen
- vannkraftprodusentene

PROSJEKTETS INNHOLD

Hovedpunkter i prosjektet er:

A. Forbedring og verifikasjon av hydrologiske modeller
    - fordampningssimulering
    - snøsmelting
    - breakkumulasjon og -smelting

B. Forbedre planleggingsmodeller
    - bedre representasjon av tilsig og forbruk

- introdusere kobling mellom tilsig- og forbruksmønster
- mulighet for å håndtere scenarier og usikkerhet

C. Vurderinger av tilsigsutvikling
  - tilsigscenarier for Norden (inklusiv brefelt)
  - usikkerhetsanalyser for tilsig

D. Analyser av forbrukets klimaavhengighet

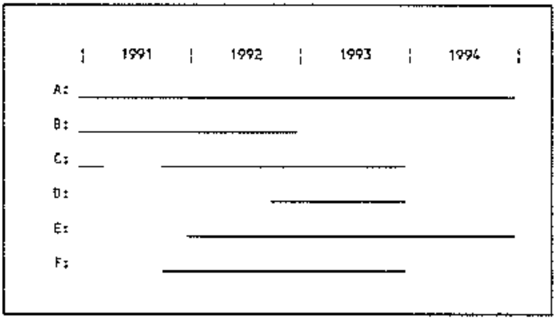
E. Analyse av totaleffekter på energiforsyningen i Norden
  - effekter på vassdragsnivå
  - regional effekter på energiforsyningen
  - fysisk sikkerhet; flommer, damsikkerhet mm

F. Analyse av historiske tidsserier for tilsig, vannstand og vassføring på nordisk basis:
  - årsverdier
  - sesongverdier
  - ekstremer

Prosjektrekkefølgen er gitt i tabell I.

Programmets tidshorisont er på fire år; start med moderat innsats i 1991, hovedinnsats i 1992 og -93; sluttberegninger og sluttrapportering i -94.

Tabell I Prosjektrekkefølge



FAGLIGE FORUTSETNINGER

Programmet tar i første omgang utgangspunkt i erfaringer fra nasjonale analyser av effekter av klimaendringer. Det foreligger i dag ikke omforenete klimascenarier for Norden, symposiet *"Nordic hydrology and the greenhouse effect"* i Reykjavik i april 1991 var første skritt på veien mot å utarbeide slike scenarier.

FoU-arbeid på klimamodellering er ikke tatt inn i programmet; det forutsettes at oppfølging av det internasjonale klimamodellerings-arbeidet regionalt i Norden ivaretas av FoU-program innen miljø- og almenvitenskaplige sektor, siden dette er grunnleggende arbeid av sentral interesse for mange brukerinteresser. Prosjektet ønsker imidlertid å bidra til nordisk samarbeid på dette området, og har avsatt betydelige midler til å bidra til klimascenariearbeidet. Det er derfor tatt inn i programmet en satsning for å få etablert de beste regionale scenariene basert på de nyeste resultater fra lokale og internasjonale klimastudier pr 1. halvår 1992.

På samme måte er grunnleggende prosessforskning i liten grad tatt inn i programmet. Dette betyr ikke at klimascenarier og modeller er "gode nok", men at vi har valgt å gjøre et gjennomført nordisk konsekvensanalyse basert på på den beste tilgjengelige kunnskap i 1992, med den usikkerhet det måtte medføre. Det vil være av vesentlig betydning for å forbedre det framtidige beslutningsgrunnlaget på energisektoren at prosessforskningen ivaretas og at det kanaliseres tilstrekkelig med midler til grunnforskningsprogrammer og utvikling av integrerte modellsystemer med forbedret prosessbeskrivelse for konsekvensanalyser. De naturlige koordinatorene for det mer grunnforskningspregete FoU-arbeidet innen hydrologi er på nasjonal basis de hydrologisk komitéene; på nordisk basis KOHYNO.

KLIMASCENARIEKOMITE

Det er nedsatt en nordisk komité for vurdering av sannsynlige klimautvikling for Norden, med særlig vekt på de klimatologiske variabler som er av størst betydning for hydrologi/vannressurser. Komiteen ble nedsatt i 1991 av styringsgruppen for "Klimaendringer og vannressurser", og hadde sitt første møte i mars. Komiteens formann er fagsjef Bjørn Aune, DNMI.

SEMINARER OG EKSPERTMØTER

Prosjektet støttet symposiet "Nordic Hydrology and the Greenhouse Effect" i Reykjavik, april 1991. I tillegg er det arrangert tre nordiske seminarer og ekspertmøter, med 10 til 25 deltakere, om snømodeller (Helsinki, oktober 1991), evapotranspirasjonsmodeller (Asker, mars 1992) og energiplanleggingsmodeller (Asker, mars 1992). Disse har hatt flere formål:

- gjøre opp kunnskapsstatus
- knytte kontakt mellom fagmiljøene i Norden
- gjøre prosjektet kjent
- få innspill til utarbeidelse av prosjektplaner fra en bred faglig gruppe

Møtene har gitt prosjektet et meget godt utgangspunkt for det videre arbeid.

HYDROLOGISK SIMULERING OG KLIMAENDRINGER

I utgangspunktet er det naturlig å anta at de mest kritiske delene av de hydrologiske modellene for å simulere virkninger av klimaendringer er simulering av snøsmelting og evapotranspirasjon. To ekspertmøter/seminarer har tatt for seg disse problemstillingene.

Snømodeller

Hovedkonklusjonene fra snøseminaret i Helsinki var:

- For nedbørfelt fungerer graddagmodeller i hovedsak like godt som energibalansemodeller.

- Graddagmodeller er utprøvd i svært varierte klimaregimer, og viser nokså stabile graddagfaktorer, stort sett rundt 3 - 4 mm/døgn grad. Et unntak er Island, der graddagfaktorene ligger betydelig høyere - sannsynligvis på særlig på grunn av høye vindhastigheter.

- Med den usikkerhet som ligger i prognosene for endringer av de klimatiske variabler som påvirker snøsmelting, er det derfor grunn til å anta at de eksisterende graddagmodellene er tilfredsstillende for simulering av snøsmelting under endrete klimaforhold.

Simulering av evapotranspirasjon

Simulering av evapotranspirasjon under endrete klimaforhold står i en særstilling innen hydrologisk simulering. For det første vil deler av det hydrologiske systemet -

vegetasjonen - kunne endre seg betydelig, og for det andre vil direkteeffekter av CO_2 på plantene føre til betydelig endring, størrelseorden 50 % økning for C_3-planter, av plantenes vannforbruk-effektivitet (biomasse produsert pr volumenhet vann). For denne effekten finnes det ingen analoger fra dagens klima.

Momenter fra diskusjonene på seminaret om evapotranspirasjonsmodeller i Asker var:

- Utslaget i vannbalansen av endringer i plantenes vannforbruk-effektivitet er avhengig av hva som er begrensende faktorer for plantevekst: vanntilgang, klimafaktorer eller næring.
- De begrepsmessige modellene (HBV, NAM) har en utilfredsstillende separasjon mellom intersepsjon, barmark-evaporasjon og transpirasjon.
- De mer spesialiserte atmosfære/vegetasjon/jord-modellene er i liten grad verifisert på nedbørfeltskala.
- Man bør ser på mulighetene for å kombinere de begrepsmessige modellene med elementer fra de spesialiserte evapotranspirasjonsmodellene.

På sikt (men neppe innen dette prosjektet) vil sannsynligvis de distribuerte modellene med data fra nasjonale databaser på topografi, arealbruk, vegetasjon, jordtyper osv bli nyttige verktøy for simulering av klimaendringer.

Modellering av massebalanse og bredynamikk

Dette delprosjektet fokuserer på tre relaterte tema:

1. Effekter av klimaendringer på breenes massebalanse
2. Effekter av endring i massebalanse på brevolum (stasjonær situasjon)
3. Breenes transiente respons på endringer i massebalanse, og endringer av avrenningen

Man er i gang med å kartlegge og dokumentere eksisterende massebalansemodeller, og tar sikte på å rapportere dette arbeidet medio 1992. En oversikt over modellene - svar på utsendt spørreskjema - er gitt i referat fra et arbeidsmøte i København i november 1992. På grunnlag av de eksisterende modellene tar man sikte på å etablere en felles massebalansemodell for det videre arbeid. Prosjektledere er Tómas Jóhannesson, Orkustofnun, og Tron Laumann, NVE.

ENERGIPLANLEGGINGSMODELLER

Konklusjonene fra ekspertmøtet om bruk av energiplanleggingsmodeller til simulering av effekter av klimaendringer på vannkraftproduksjonen var i hovedsak:

- NORDEL-modellen er generelt akseptert som et verktøy for analyser av behov for nye overføringslinjer osv på nordisk basis. Med den detaljeringsgrad modellens datasett har i dag er det sannsynligvis mulig å få tillatelse til å benytte datasettet (som tilhører NORDEL)

- Det er betydelig skepsis til å utvide datasettet til å kunne utføre detaljerte nasjonale simuleringer. De nasjonale organisasjonene foretrekker å gjøre simuleringer under egen kontroll med egne modeller (KAPAS, POP, Samkjøringsmodellen). De vil være interessert i å gjøre slike simuleringer dersom det kan skaffe fram tilsigsgrunnlag. NORDEL-modellen kan så benyttes til overordnete nordiske beregninger, med grunnlag i de nasjonale beregningene.

- Et passelig tilsigsgrunnlag er ca ti serier, med inndeling i forskjellige høydenivå, i Norge, Sverige og Island, tre serier i Finland og to på Grønland. Dataperiode 1960-90.

- To alternativer for kraftmarked er:
  1) Skandinavisk marked stadium år 2000.
  2) Ubegrenset marked, ingen overføringsbegrensninger - altså beregning av rent produksjonspotensial.

- Det synes ikke være nødvendig å ta hensyn til forbruksendringer pga klimaendringer i selve simuleringene. I et ubegrenset marked er dette selvsagt heller ikke av betydning.

- Det er mest naturlig å konsentrere seg å beskrive energiproduksjon framfor økonomi.

- Et naturlig valg av produksjonsystem vil være det nordiske systemet stadium år 2000, dette er i hovedsak kjent. Det synes også naturlig å gjøre beregningene uten hensyn til organisatoriske/nasjonale begrensninger.

PLAN FOR DET VIDERE ARBEIDET

Den videre framdrift av prosjektet vil være:

Forbedring av de hydrologiske modellene (A4). Status etter ekspertmøtene er at nedbør-avløpsmodellene (HBV/PULSE og NAM) er godt egnet til simulering av klimaeffekter på avløp, men at fordampningsdelen må analyseres videre. 1992.

Utarbeidelse av klimascenarier for Norden (C1). (Scenariekomitéen). 1992

Tilsigsscenarier(C2). Med utgangspunkt i klimascenariene foreslås det utarbeidet av størrelseorden tre tilsigsscenarier (sannsynligvis tredveårsserier) for ca ti vassdrag i Norge, Sverige og Island, tre vassdrag i Finland og to på Grønland.

Tabell II Kosmadsoverslag for prosjektperioden (NMR-midler)

	1991	1992	1993	1994	91-94
A1 - evapotransp.	10	90			100
A2 - snømodeller	50	50			100
A3 - bremodeller	10	360	200	200	770
A4 - integrasjon		200			200
B - planleggingsmod		100			100
C1 - klimascenarier	100	250			350
C2 - tilsigscenarier		80	300		380
D - forbruk	0	0	50		50
E1-3 produksjonsber.			50	400	450
E4 - damsikkerhet				150	150
F - historiske ser.		50	100		150
Administrasjon	100	150	100	100	450
Sum; NMR	270	1.330	800	850	3.250

For Norge og Sverige vil seriene bli beregnet for flere høydenivå, for Grønland, Island og Norge for brefelt og brefrie felt. 1993.

Klimaeffekter på forbruk (D). Frittstående analyse av forbrukets følsomhet for klimavariasjoner. En rapport med oversikt over nordiske erfaringer. 1993.

Nasjonale produksjonsberegninger (E). Med utgangspunkt i tilsigscenariene foretas det beregning av endringer i de nasjonale produksjonspotensialene, på nasjonalt plan og ved hjelp av de nasjonale beregningsmodellene (KAPAS, POP, Samkjøringsmodellen osv). 1993/94.

Nordiske produksjonsberegninger(E). Med utgangspunkt i tilsigscenariene og de nasjonale beregningene foretas det nordiske simuleringer ved hjelp av NORDEL-modellen. Rammebetingelsene vil være produksjonssystemet stadium år 2000, og et eller begge av følgende markedsalternativer: marked stadium år 2000 eller fritt marked, ubegrenset etterspørsel. 1994.

Flommer og damsikkerhet(E4). Undersøkelser av hvordan økt usikkerhet i flomberegninger kan ivaretas operasjonelt. 1994.

Analyse av historiske avløpsserier(F). Regionale trendanalyser på fellesnordisk datasett for vassføring - årsverdier, sesongverdier og ekstremer. 1992/93.

Budsjett for delprosjektene er gitt i tabell II (NMR-finansiert del), under forutsetning av at Nordisk Ministrråd opprettholder sin bevilgning til prosjektet.

KONFERANSER OG SEMINARER ARRANGERT ELLER STØTTET AV PROSJEKTET

Nordic Hydrology and the Greenhouse effect. Reykjavik 3-5. april 1991. 63 deltakere.

Seminar om snømodeller for simulering av klimaendringer. Helsinki 24.-25. oktober 1991. 10 deltakere.

Fagseminar om evapotranspirasjonsmodeller for beregning av effekter av klimaendringer på vannbalansen. Asker 16.-17. mars 1992. 25 deltakere.

Ekspertmøte om energiplanleggingsmodeller - klimaendringer. Asker 23.-24. mars. 15 deltakere.

KOORDINERINGSKOMITE

Perttu Aittoniemi, Imatran Voima OY
Sten Bergström, SMHI
Kristinn Einarsson, Orkustofnun
Marit Lundteigen Fossdal, Vassdragsregulantenes forening
Per-Eric Ohlsson, Vattenregleringsföretagen
Nils Roar Sælthun, NVE
Thorkild Thomsen, Grønlands Energiforsyning
Bertel Vehviläinen, Vesi-ja ympäristöhallitus (Vatten och Miljöstyrelsen)

PUBLIKASJONER OG RAPPORTER

K.Einarsson & O. Sigurðsson (eds):
Nordic hydrology and the greenhouse effect. Conclusions & Recommendations of the Reykjavik Symposium. Nordic Hydrological Programme, NHP report no 28, 1991, ISBN 9979-827-00-9.

Climate changes and energy production. Project A3: Glacier Models. Minutes from a work group meeting in Copenhagen 11-13. November 1991. Orkustofnun VOD/VM, Minutes TJ-91/04 Inneholder en kartlegging av bremodeller i bruk i Norden. 6 pp.

S.Bergström,, C.E.Bøggild, K.Einarsson, Y.Gjessing, N.R.Sælthun, T.Thomsen, B.Vehviläinen, K.Sand (ed):
Snow modeling, water resources, climate change. Norwegian Hydrotechnical Laboratory 1992, STF60 A92023, 15 pp. ISBN 82-595-7030-0.

Flere forfattere:
Climate change and evapotranspiration modeling. Red: Lena Tallaksen. Nordic Hydrologic Program, NHP report (under utarbeidelse).

Flere forfattere:
Klimaendringer og energiplanleggingsmodeller. Red: Marit Lundteigen Fossdal, Nils Roar Sælthun. NVE-rapport (under utarbeidelse).

FREQUENCY OF EXTREMES AND ITS RELATION TO CLIMATE FLUCTUATIONS

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L.Gottschalk University of Oslo Norway

ABSTRACT

Possible consequences of climate change concern both changes in long term mean values of runoff and changes in frequency and magnitude of extreme runoff events (low flows and floods). The physical safety of dams and protection against floods as well as effects of dry spells are not sensitive to the moderate changes in mean values but to the frequency and magnitude of extremes. This study presents the results of the analyses of the changes in the behavior of the extreme runoff values due to observed changes of temperature and precipitation. Statistical parameters of floods as well as the intensity of flood events have been studied. An attempt is also made to establish regional probability distribution curves for the frequencies of the extreme floods for different patterns of changes in the climatic variables considered.

1.INTRODUCTION

An analysis of the stability of flow regimes (Krasovskaia & Gottschalk, 1992) has shown that rather moderate fluctuations in the mean annual temperature and precipitation cause changes in flow regime patterns, i.e. the timing and magnitude of the average high and low flows. These noted changes of average patterns could be expected to be still more pronounced in the behavior of individual extreme events, their intensity, magnitude and probability of occurrence. These latter three characteristics of extreme floods and their sensitivity to increase/decrease in mean annual temperature and precipitation have been investigated for different flow regimes on the example of Norway.

Two independent approaches for the analysis of extremes have been used. The first one is based on partial duration series and the theory of Poisson processes. In this case the the intensity and magnitude of extremes over some given threshold level is compared for warm/cold and wet/dry years, respectively. The second one is based on annual maximum series and regional frequency curves.

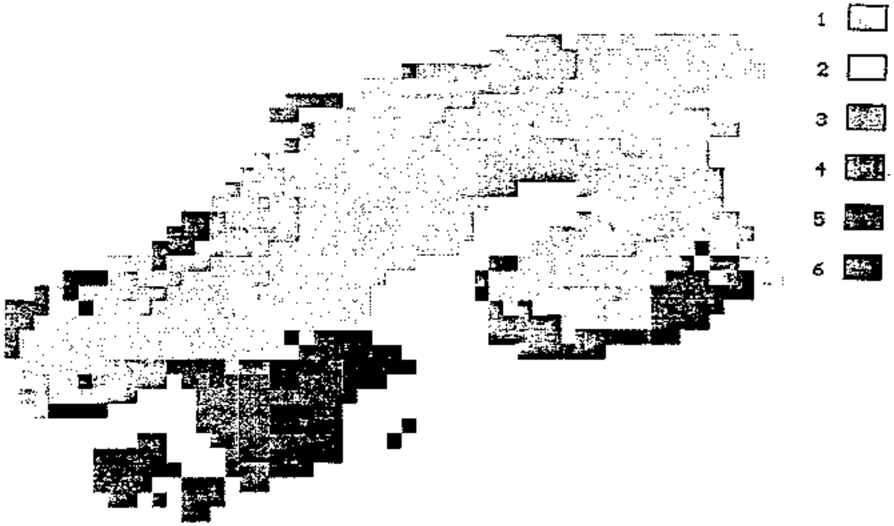
2.DATA USED

Flow regime regions, which form the background for the present analyses, originate ~~from~~ our previous study of flow regime stability (Krasovskaia & Gottschalk,1992) based on monthly river flow data for a total of 81 gauging stations in the Nordic countries. Most of the basins have an area of less than 2000 km^2. For the analysis of extremes, daily values from 24 Norwegian stations were used, all 66 years long.
Temperature and precipitation observation series were taken from climatic stations situated in the vicinity of flow gauging stations and having a common observation period with them. A total of 31 temperature and 50 precipitation series (66-years long) for the whole Scandinavia have been used. These series have been split into two sub series, respectively : one for years with the annual values above the long term mean and the other for years below. The years corresponding to these respective sub series are in the following named "warm" and "cold" and "wet" and "dry". For the "warm" years the mean annual temperature was 0.9°C above the long term mean (the average across all the stations) and for the cold years it was 0.8°C lower. For the "wet" years the mean annual precipitation was 122.4mm higher than the long term mean and for the "dry" years it was 103.2mm lower. Runoff series have been split accordingly: one sub series for the "warm" and the other for the "cold" years and then one sub series for the "wet" and the other for the "dry" years.

3.FLOW REGIME REGIONS

Flow regimes synthesize underlying processes involved in runoff formation and present seasonal patterns characteristic for certain climatic and physiographic conditions. In the context of possible climate change flow regime classification has the twofold role. On one hand it can be used in the process of validation to check that the correct seasonal patterns are reproduced by climate models. On the other hand, flow regimes, reflecting climate and environment in the basin, indicate the proper choice of hydrologic model formulation.

Flow regime classification for the Nordic countries, suggested by Gottschalk et al (1979) and modified and applied for the Nordic countries by Krasovskaia and Gottschalk (1992) have been used. This classification is a quantitative one, based on the time of occurrence of high/low flow, which reflects the role of the genetical sources in flow formation. For the Nordic countries these are snow-melt and rain water. Classification is performed automatically on monthly flow series and the resulting regions are presented on a grid network (0.5°* 0.5°). Six flow regime regions, named after the flow regime types, have been distinguished: North-Scandinavian, Northern-Inland,



1 - North-Scandinavian 2 - Northern-Inland 3 - North-Atlantic
4 - Southern-Inland 5 - Inland-Baltic 6 - Baltic

Figure 1. Flow regime regions.

Southern-Inland,Baltic, North-Atlantic and Inland-Baltic, of which the first five can be found in Norway. Figure 1 shows the geographical location of the regions.

4.CHANGES IN THE INTENSITY AND MAGNITUDE OF FLOODS

Dealing with partial duration series (PD) we are interested only in the extreme events above a certain chosen threshold. In this study this threshold was set equal to

$$x_0=m+3s \tag{1}$$

where m is the long term mean and s is the standard deviation. A convenient mathematical modeling of the partial duration series is obtained by using the well-known theory of Poisson processes. There is a large experience of applying this method to floods also for Scandinavian conditions (see, for example Rosbjerg,1985 , Rasmussen & Rosbjerg, 1989).

If our series satisfy the criteria for a Poisson process it can be shown that the number of events n(t) within a time interval t is a stochastic variable which has Poisson distribution, i.e.:

$$P[N(t)=n]=\frac{(\lambda t)^{n}}{n!}\,e^{-\lambda t} \qquad (2)$$

with the mean and variance given by:

$$E[N(t)]=Var[N(t)]=\lambda t \qquad (3)$$

where λ is the average number of events per a time unit (intensity of flood events). We further assume that the extreme flood event X at time i is a stochastic variable which has an exponential distribution function:

$$F_{x}(x)=1-\exp(-x/\alpha) \qquad (4)$$

where α is the mean of X. Let z(t) be the first exceedance of the threshold x_0 in the time interval [0,t]. The process z(t) can be defined as:

$$z(t) = \sup_{i<t} X_i \qquad (5)$$

We can now use the assumption of independence together with equation 2 to derive the following expression for the cumulative distribution function for z(t):

$$F_{X(t)}(z)=P[X(t)<z]=\exp(-\lambda t[1-F_X(z)]) \qquad (6)$$

If we set t=1 and with X having an exponential distribution (eq.3) we get:

$$F_X(z)=\exp(-\lambda\exp(-z/\alpha))=\exp(\exp(z-\alpha\ln\lambda)/\alpha) \qquad (7)$$

where for simplicity we denote $\lambda(1)=\lambda$.

The values of λ and α have been estimated for each of the flow regime regions for the two sub series: one for the "warm" years and the other for the "cold" years. Table 1 shows the results of calculations, where λ and α are given in the relation to the mean values for the whole series.

It can be seen from the table that the intensity of the floods λ is higher for the series for "warm" years in all the regions. The difference is the largest for the North- Atlantic, Southern-Inland and Baltic regions. These results coincide with the conclusions made in our previous study of the stability of flow regimes (Krasovskaia & Gottschalk, 1992). As far as the magnitudes of floods are concerned, it can be seen from the table that they remain almost unchanged for the PD for the "warm" and "cold" years. However, taking into account the tendency for the increased intensity of flood events during the

Table 1. Values of λ and α for the different flow regime regions for "warm" and "cold" years

Parameters	λ		α	
Years	"warm"	"cold"	"warm"	"cold"
Flow regime region				
North-Scandinavian	1.118	0.858	1.000	1.020
Northern-Inland	1.115	0.922	1.011	0.989
North-Atlantic	1.208	0.791	0.998	1.006
Southern-Inland*	1.344	0.706	1.009	0.979
Baltic	1.124	0.850	1.032	0.960

*based on limited data

"warm" years, the probability to observe floods of large magnitudes anyway increases.

The estimated values of λ varied between ≈1 and ≈4 and no systematic patterns in their fluctuations were found like, for example, dependence on the catchment area. In order to demonstrate the influence of the flood intensity λ on the magnitude of floods we have calculated hundred year floods for different λ. Table 2 offers the results of this calculation, given in relation to those for the whole series.

Table 2. The influence of the intensity of flood events λ on floods during "warm" and "cold" years.

	Deviations					
Years	"warm"	"cold"	"warm"	"cold"	"warm"	"cold"
Flow regime region	λ=1		λ=2		λ=3	
North-Scandinavian	1.073	0.918	1.050	0.950	1.042	0.960
Northern-Inland	1.083	0.936	1.060	0.953	1.057	0.958
North-Atlantic	1.122	0.852	1.083	0.900	1.070	0.916
Southern-Inland *	1.204	0.756	1.143	0.826	1.122	0.849
Baltic	1.111	0.858	1.086	0.890	1.078	0.900

*based on limited data

It can be seen from the table that the largest deviation is observed for Northern- and Southern-Inland regions, both with the climate having more pronounced temperature amplitudes than in other regions. In general, the percentage of deviation seems to reduce with growing λ .

To investigate the influence of the changes in the precipitation on the intensity and magnitude of floods, the analyses have been repeated for the two precipitation sub series: one for the "wet" and the other for the "dry" years. Table 3 presents the values of λ and α obtained in relation to those for the whole series.

Table 3. Values of and for the different flow regime regions for "wet" and "dry" years.

Parameters	λ		α	
Years	"wet"	"dry"	"wet"	"dry"
Flow regime region				
North-Scandinavian	1.047	0.909	1.009	0.992
Northern-Inland	1.154	0.782	1.007	0.980
North-Atlantic	1.110	0.811	1.011	0.969
Southern-Inland*	1.450	0.576	1.014	0.955
Baltic	1.180	0.787	1.029	0.963

*based on limited data

The results show that during "wet" years the intensity of floods can increase from about 5% up to 45% compared to the whole period. The decrease during "dry" years seems to be approximately the same. The magnitude of floods is only slightly influenced by the precipitation variation, being around ±1-4%.

5. REGIONAL EXCEEDANCE PROBABILITIES

In a sample of regional data of extremes the probability to observe an extreme value with a return period larger than the number of observation years is much greater than that for the individual series. The probability of exceedance p_i of the largest value for a certain year i in regional sample of independent data has been given by Gottschalk (1989):

$$p_i = \frac{1}{Mk+1} + \frac{Mk}{Mk+1}\,\frac{1}{M(k-1)+1} + \ldots + \frac{Mk}{Mk+1}\,\frac{M(k-1)}{M(k-1)+1}\ldots$$

$$\ldots\frac{M(k-i+1)}{M(k-i+1)+1}\,\frac{1}{M(k-i)+1} \qquad (8)$$

where M is the number of observation stations in the regional sample and k the number of common observation years (note that in the original paper M and k by mistake has been interchanged). The probabilities p_i can be regarded as the plotting positions for the regional extremes corresponding to Weibull's formula for individual series. As data series are not independent, we have calculated an equivalent number of independent series M_e for each region from the relation (Gottschalk, 1989):

$$M_e = \frac{1}{1+(M-1)\rho} \qquad (9)$$

where ρ is the mean regional spatial correlation.

Figure 2 shows the plotting diagrams for the regional exceedance probabilities calculated for "warm" and "cold" years. The difference in the curves for "warm" and "cold" years is largest for the Baltic region and Southern-Inland region, while for the North-Scandinavian and North-Atlantic regions the difference is very small. For the Northern-Inland region the difference lies somewhere in between. Table 4 illustrates the changes giving the results of calculation of the magnitude of the extreme flood with the return period of 100 years for "warm" and "cold" years in relation to that for the whole period.

Table 4. Magnitude of the extreme flood with return period of 100 years for "warm" and "cold" years in relation to that for the whole period.

Years Flow regime region	"warm"	"cold"
North-Scandinavian	1.014	0.988
Northern-Inland	1.017	0.985
North-Atlantic	1.003	0.997
Southern-Inland*	1.111	0.902
Baltic	1.151	0.888

* based on limited data

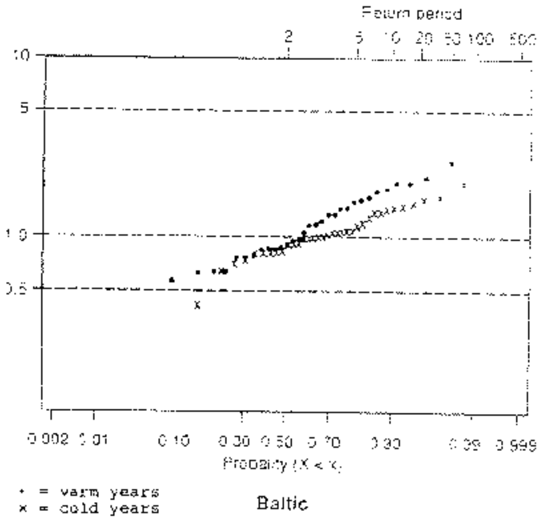
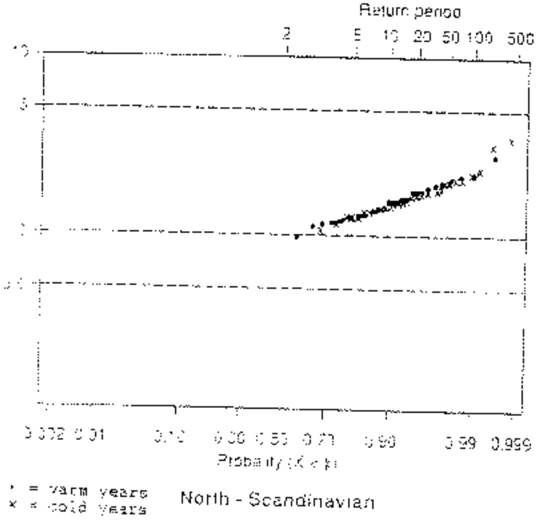
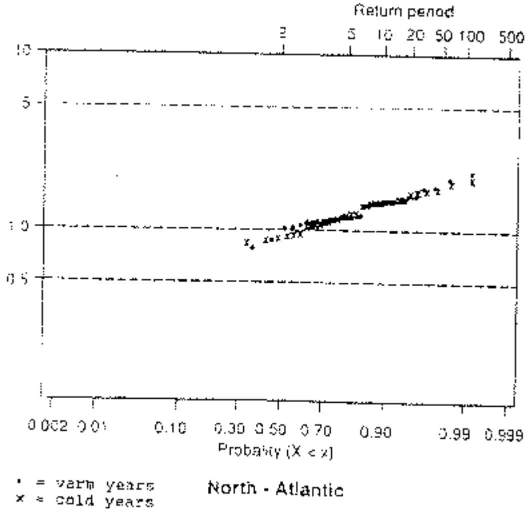


Figure 2. Regional exceedance probability curves for different flow regime regions

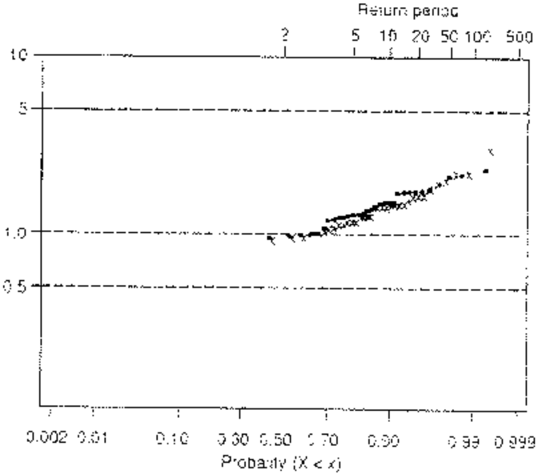


North - Scandinavian



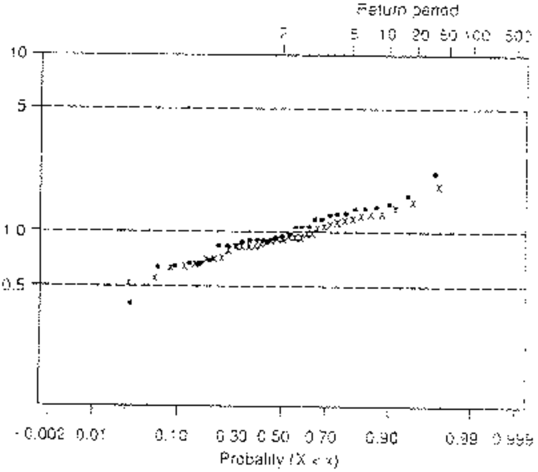
North - Atlantic

Figure 2. (continued)



• = warm years
x = cold years

Northern - Inland



• = warm years
x = cold years

Southern - Inland

Figure 2. (continued)

It can be seen from the table that, for example, for Baltic region the extreme flood with the probability 1/100 is more than 15% higher for the "warm" period than that for the whole one, while it is about 11% lower during the "cold" period. The figure in the table demonstrate again that the greatest difference is observed for for the southern part of the studied territory (Baltic and Southern-Inland regions). Both of them have previously showed the largest difference between the parameters of the partial duration series. If we compare the deviations from the average for the whole series given in Table 4 to these of a given in table 2, we can see that the tendency is the same, i.e. the ~~largest~~ largest difference can be observed for Southern-Inland and Baltic regions.

6.CONCLUSIONS AND DISCUSSION

A possible consequence of climate change concerns change in frequency and magnitude of extreme floods. Some ideas of the sensitivity of extreme floods to variations in temperature and precipitation can be obtained from observed flood data records by splitting them into sub series for warm/cold years and wet/dry years, respectively, which has been demonstrated in this study. To allow generalizations the data have further been grouped in accordance with river flow regimes. Two independent approaches were used - partial duration series and regional exceedance probabilities.

The results of the study are most clearly demonstrated by investigating calculated design floods for a certain return period, here the 100-year flood. The analysis shows that this estimated flood is higher when calculated with observations from "warm" years, for which the mean annual temperature was about 0.9C° higher than for the whole period. The analysis of the extreme flood events based on partial duration series demonstrated that this increase seems to be a result of the increased intensity of the flood events during the warm years (by 10-15% on the average), while the volumes of floods varied only slightly. Due to this increased number of flood events, the probability to observe floods of large magnitudes increases during the "warm" years. During the "cold" years the situation was the opposite, i.e. the intensity of the extreme flood events has decreased.

The results of both the analyses of partial duration series and regional exceedance probabilities revealed the same tendency, namely that the changes are the largest for the southern part of the region. This conclusion supports the one made in our previous study of the stability of river flow regimes (Krasovskaia & Gottschalk, 1992), which also showed that the greatest changes in the flow regimes during "warm" (or "cold") years occur in the southern parts of the Nordic countries.

For the "wet" years the number of extreme floods increases between 5%-20% compared to the whole period. The decrease during the "dry" years is of the same range. The magnitude of the extreme floods even in this case seems to be only slightly influenced by the variation of precipitation, being around 1-4%. Again it is in the southern part that the changes are the largest.

Studies of the sensitivity of extreme floods to the changes in temperature and precipitation have been undertaken for Norway by Saelthun et al. (1990) and for Finland by Vehviläinen & Lohvansuu (1991). It is difficult to directly compare the results of the present study to those presented in these two investigations for several reasons. In both these studies conceptual models have been used to investigate the sensitivity of flow to climate change. Thus, the results rely heavily on the accuracy and relevance of the models used (Vehviläinen & Lohvansuu, 1991). Besides, the hydrological model used has not been calibrated with special attention to extremes for optimal fit. In both studies referred to, the stress has been put on the changes in the magnitude of the extreme flood events and their seasonal distribution, while the eventual effects on the intensity of the flood events has not been treated. Studies that are based on some assumed constant changes in temperature and precipitation show very distinct effects of these changes. The results are in many cases obvious without going into model simulations. The impression is that such assumed constant changes highly oversimplify the real situation and the effect of natural variability in time and space. The present study based on observed regional data sets demonstrates much more complicated variation patterns. Eventual effects are in this case not that clearly revealed.

This study is first of all to be considered as a test of different methods for analyzing changes in extreme floods due to the observed changes in temperature and precipitation. In order to be able to draw any definite conclusions about the behavior of extreme floods in the context of climate change, it is necessary to repeat the analyses for more complete data sets for the Nordic countries as a whole.

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FLUCTUATIONS OF LONG DISCHARGE TIME SERIES IN FINLAND

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ABSTRACT

Because discharge integrates several climatic factors over the basin (as precipitation, evaporation and temperature) and because there exist long (70-150 years) measurement series, the analysis of these series can give valuable information of climatic and human induced fluctuations and trends. The preliminary analyses of the longest series show about the same features for mean discharge in different parts of the country: in this century decrease until 40's and thereafter relative steep increase. In the last years the winter discharges have increased still very rapidly except in the northernmost Lapland, where the winter discharges have diminished. The analysis of spring flood show that the flood beginning and the flood peak have become earlier. The winter low flow before the flood beginning has been increasing, in Lapland, however decreasing. The maximum spring discharge is increasing in most basins.

LONG-TERM FLUCTUATIONS OF ANNUAL DISCHARGE

The location of observation sites as well as some basic information of the drainage basins are shown in table 1. and in fig. 1. An examination of long-term discharge time series reveals that discharge has been fairly large in Finland in the beginning of the twentieth century. Then the average flow has diminished until around 1940-50, and after it discharge has increased fairly strongly all over the country (see fig. 2). The steep increase of discharge during the last 15 years resamples some fluctuations in the past; similar discharge increase occurred in second and fifth decade of this century.

The corrected precipitation series are not yet available. In 1980's the precipitation has been heavy in southern and central Finland. The evaporation values measured by Class A pan show no notable change except in Lapland, where evaporation seems to be decreasing.

This is in accordance with observations made in the northern Atlantic and Fennoscandia regions of the drop of temperature: as a result of weather process, there has been heavy rainfall on the borders of cold regions themselves. This also explains qualitatively the difference in winter discharge trends observed in southern and northern Finland after about 1950.

CHANGES OF SEASONAL VARIATION

Changes in seasonal runoff can be significant even if the annual discharge remains practically unchanged. By studying the date and height of spring flood by daily discharge values different regional patterns could be recognised. Examples of typical regional features are shown in fig. 4. The flood beginning and the flood peak have become earlier. Winter low flow and flood peak flow have increased in southern and central Finland. In northern Lapland the maximum discharge is increasing and the minimum flow is decreasing.

There has been a clear increase in winter discharges, with the exception of northern Lapland (see figs. 3 and 4). Similar results have been obtained earlier as well by Hyvärinen (1988) as by Hyvärinen and Leppäjärvi (1989).

CONCLUSIONS

The analysis of discharge time series showed, on one hand, that some features, as long term fluctuations (10-30 a) of annual discharge, have wide areal coherence. On the other hand, areal differences and tendences appear, especially in development of seasonal variation.

The origin and mechanism causing long period fluctuations or trends is to be searched by analysing simultaneous precipitation and evaporation series and also information about human activities (as ditching and forest drainage). The comparison of the development in neighbouring regions (in Scandinavia and Estonia) will shed more light on the areal scale of climatic fluctuations.

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Table 1. The discharge observation sites, drainage areas, lake percentances, coordinates, starting years and value type K (d = daily values, y = yearly MQ).

No	Name	F km^2	L %	N	E	Start	K
0400600	Ruunaa	6165	12.3	6326	3028	1931	d
0408087	Konnus+Karvio	16270	15.3			1931	y
0410410	Partak.+Kärnäk.	890	24.7	6117	2739	1971	d
0411450	Imatra	61265	19.9	6113	2847	1959	y
1402900	Äyskoski	2160	18.1	6301	2640	1896	d
1405000	Petäjävesi	665	5.4	6212	2511	1910	d
1600110	Pyhäjärvi	455	6.1	6042	2601	1954	d
1800500	Vakkola	1135	1.7	6028	2537	1963	d
2101700	Oulunkylä	1680	2.5	6014	2459	1937	d
2800300	Hypöistenkoski	385	0.0	6039	2236	1948	d
3504800	Kituskoski	565	9.2	6216	2402	1911	d
3509800	Sääksjärvi	660	9.8	6123	2228	1922	d
3510450	Harjavalta	26025	11.8	6121	2207	1948	y
5100200	Lestijärvi	380	20.2	6335	2442	1921	d
5901320	Änättijärvi	420	12.2	6424	2951	1931	d
5901900	Lammasjärvi	3480	11.1	6408	2930	1901	d
6101950	Raasakka	14315	5.8	6519	2526	1911	y
6503000	Ounasjärvi	335	8.0	6824	2344	1950	d
6503200	Köngäs	4523	3.4	6752	2451	1941	d
6700800	Muonio	9515	3.7	6756	2340	1959	d
7100800	Saukkoniva	5250	4.1	6853	2655	1921	d

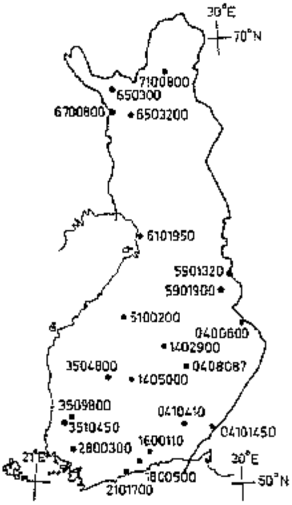

Fig. 1. The location of observation sites. See Table 1.

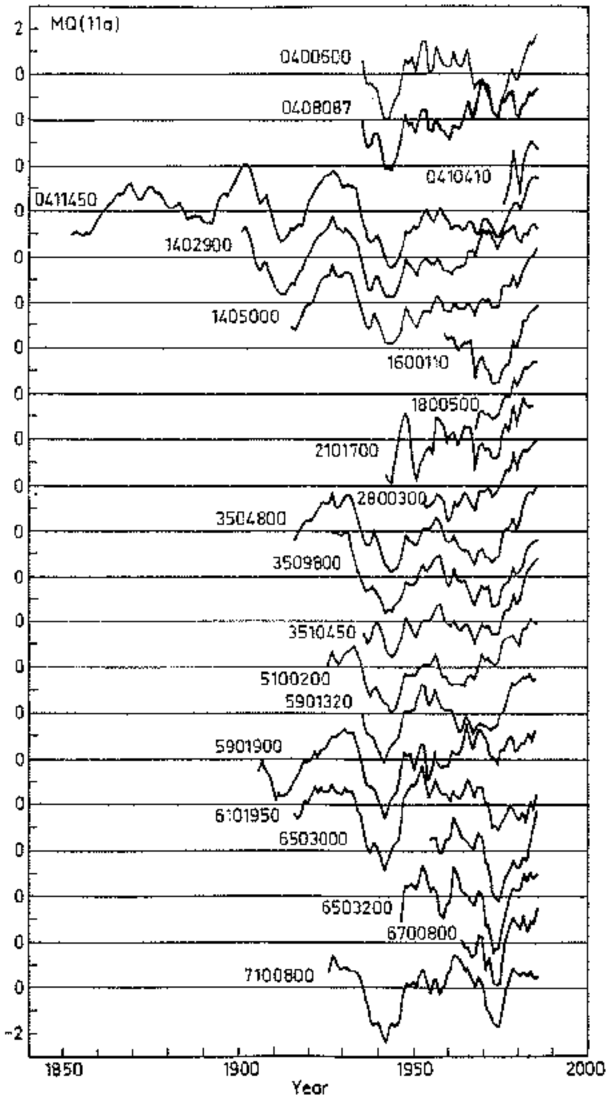

Fig. 2. Discharge time series for 21 basins in units of standard deviation. The discharges have been smoothed with a 11 year gliding average and standardised (mean value = 0, standard deviation s = 1).

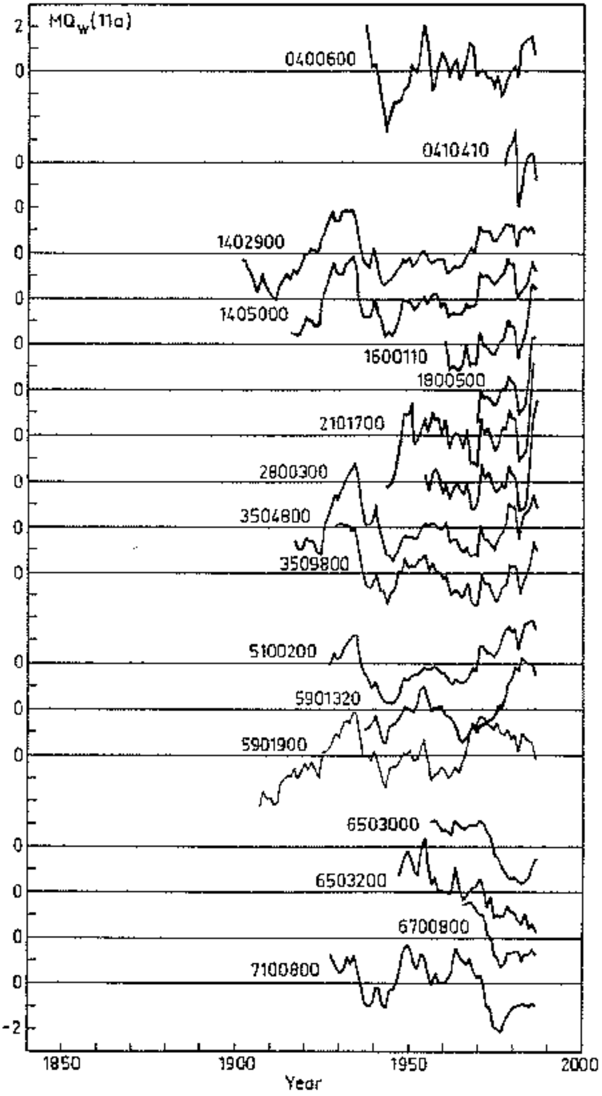

Fig. 3. Winter (months XII - III) time series for 17 basins. See the explanation of Fig. 2.

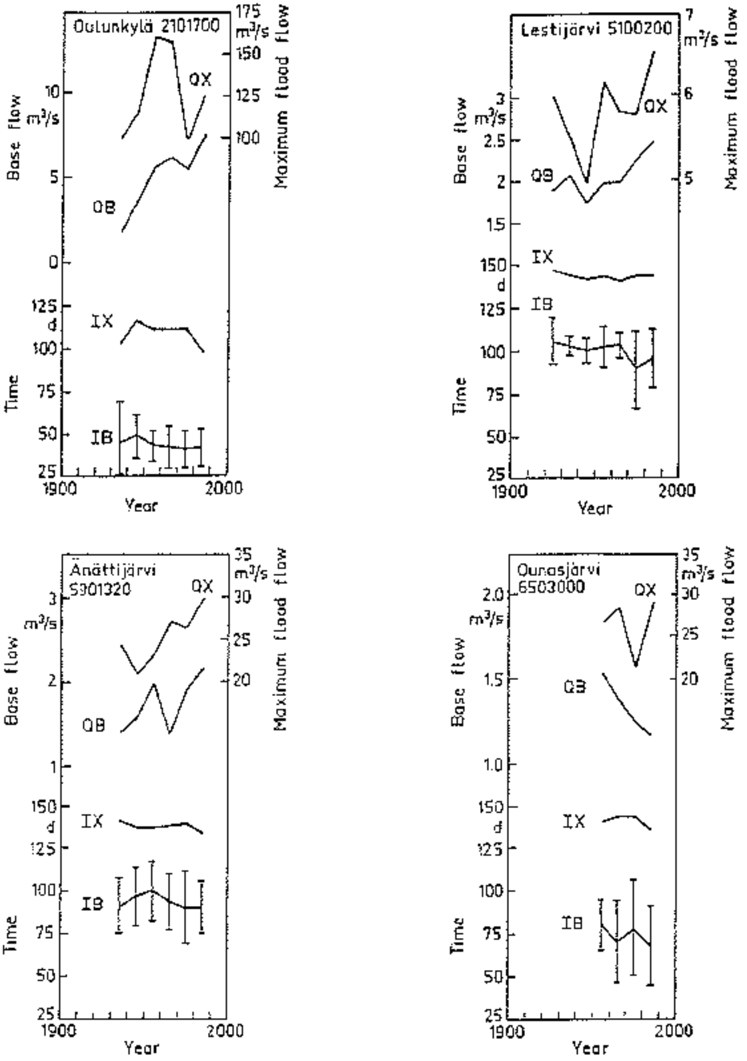

Fig. 4. Some features of spring flood described as decennial averages for 4 stations. The starting point of flood rise, IB, with 95 % confidence interval and the moment of the flood peak flow, IX, are measured in days from the beginning of the year. The basic discharge (14 days average), QB, immediately before IB and the maximum flood discharge, QX, are expressed in m³/s.

FLOODS IN SWEDEN - OCCURRENCE AND TRENDS

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ABSTRACT

Sweden has experienced a number of floods in the 1980-ies, the most notable in September 1985 when the Noppikoski dam failed. This has raised the question on whether floods have become more frequent in recent years. A systematic study on floods in unregulated rivers is now being carried out in Sweden. Preliminary results show no trends when sufficiently long records are studied. The 1980-ies had unusually many large autumn floods, and the 1970-ies had unusually few. This may have led to the impression of a trend. No convincing evidence of autocorrelation in time has been found.

INTRODUCTION

A large number of high floods occurred in Sweden during the 1980-ies. The most notable one was the September flood in 1985 in Voxnan and Dalälven, which caused the failure of the Noppikoski dam. The large number of floods raised concern in the society. Usually, the spring flood is the largest flood during the year, but many of the floods in the 1980-ies were caused by rainfall. The possible links between extreme floods and changes in land use, e.g. clearfelling, or climate were discussed. The objectives of this paper are to study trends in, and occurrence of floods.

METHODS

Trend analysis was made by two techniques: a non parametric test (Hansen, 1971), and regression. An advantage of the non parametric test is that no assumption is needed about independent and normally distributed observations. Regression, on the other hand, implies the assumption of a normal distribution. Extreme values are non normal, but the normal distribution of logarithms is often used for hydrological extremes (see e.g. Cunnane, 1989). With logarithmic flood data the regression equation reads:

$$\ln Q = a + bt \tag{1}$$

$$dQ/Q = b\,dt \tag{2}$$

The slope parameter b is then the relative increase per time, i.e., the trend. The significance of this trend was tested as given by Hansen (1971). To allow a weighted analysis of all stations, the series were standardized, by subtracting by the mean and dividing by the standard deviation. The average of the standardized series was computed for each year.

The persistence, P_E, was calculated as:

$$P_E = q/N \tag{3}$$

where N is the total number of data, and q is the number of observations followed by another observation on the same side of the median. The non parametric run-test (Hansen, 1971) was used to test the significance of P_E. The autocorrelation function $\rho(\tau)$ was estimated as (see e.g. Hansen, 1971):

$$\rho(\tau) = \frac{1}{N-\tau}\sum_{i=1}^{N-\tau} Q_i Q_{i+\tau} \quad ; \tau = 1,2,...,N/2 \tag{4}$$

in which the series Q_i has been standardized. Two tests for significance were used (Hansen, 1971 and Box and Jenkins, 1979). The autocorrelation was considered significant if indicated by at least one of the two tests. Periodogram analysis together with the Fischer test of significance (see Hansen, 1971) was used to search for periodic variations.

It is sometimes felt that flood frequency analysis underestimates the risk for extreme floods. The probability that the N year flood is not exceeded during N years is:

$$P(Q_N \geq Q_{max}) = (1-\tfrac{1}{N})^N \approx 1/e \approx 37\% \tag{5}$$

This means that the true N year flood should exceed the largest flood Q_{max} in N years in only about 37 % of all records. In many countries studies have been made on the fitness of different distributions for flood frequency analysis. An overview was given by Cunnane (1989). In Sweden, Gottschalk (1975) studied various distributions for monthly river runoff. However, there seems to be a lack of a comprehensive investigation of methods for extreme floods. Bergström et. al. (1989) found that the Lognormal 2 distribution could be rejected fewer times by χ^2 goodness of fit test, than could the Gumbel and Lognormal 3 distributions. The χ^2-test is, however, usually considered as a weak test. It covers the whole probability range, and not only the upper extreme. Frequency analysis was made for annual, spring and autumn maximum values. The parameters were estimated using the method of moments for some commonly used distributions. Sample statistics, e.g. coefficient of variation and skewness were computed.

Mean values for the whole observation period and for the 1980-ies were plotted to discern any change in the seasonal distribution of runoff, together with maximum values as an envelop.

RUNOFF RECORDS

All series were divided into hydrological years to avoid false dependence between years. The beginning of the hydrological year was for convenience set at a date when low flow usually prevails. The following criteria were used in the selection of series: - the station should be unaffected by regulation, - at least 40 years of continuous data should be available, and the station should still be in operation, - there should be no overlapping of areas, i.e., no basin area should be used twice, - the series should include a minimum of interpolation or relations with other stations. All series were plotted and visually inspected. Periods with dubious data were excluded. Eight records from different parts of Sweden have been chosen until now, covering a total of 595 station years (Table 1). The series were divided into spring and non spring periods (called autumn in the text). An example of a plot of the longest record is given in Fig. 1, in a compressed time scale.

Table 1 Data series used in the analysis.

River	Gauging station	Area (km^2)	Obs. years	Spring	Start of hydrol year
Torneälven	Kukkolank.	34063	1911-90	Jan-Jun	1 Jan
Råneälven	Ytterholmen	1004	1924-91	Jan-Jun	1 Jan
Umeälven	Solberg	1067	1911-90	Jan-Jun	1 Jan
Harmångersån	Hassela	658	1919-91	Jan-Jun	1 Jan
Ljusnan	Ljusnedal	340	1925-90	Jan-Jun	1 Jan
Dalälven	Ersbo	1101	1912-90	Jan-Jun	1 Jan
Lagan	Rörvik	162	1907-91	Mar-May	1 Aug
Fylleån	Simlången	262	1928-91	Mar-May	1 Aug

RESULTS AND DISCUSSION

Selected results from the trend tests are given in Tables 2 a and b. The tests indicate trends for example for Rörvik (cf. Fig. 1), for some subperiods but not for the whole sample. The average of all standardized series (Fig. 2), illustrates the low autumn floods during the 1970-ies, followed by the larger floods in the 1980-ies, both in spring and autumn. Individual years stand out in the analysis, for example the dry summers of 1959 and 1976, and the large spring floods in 1966 and 1967. This would have to

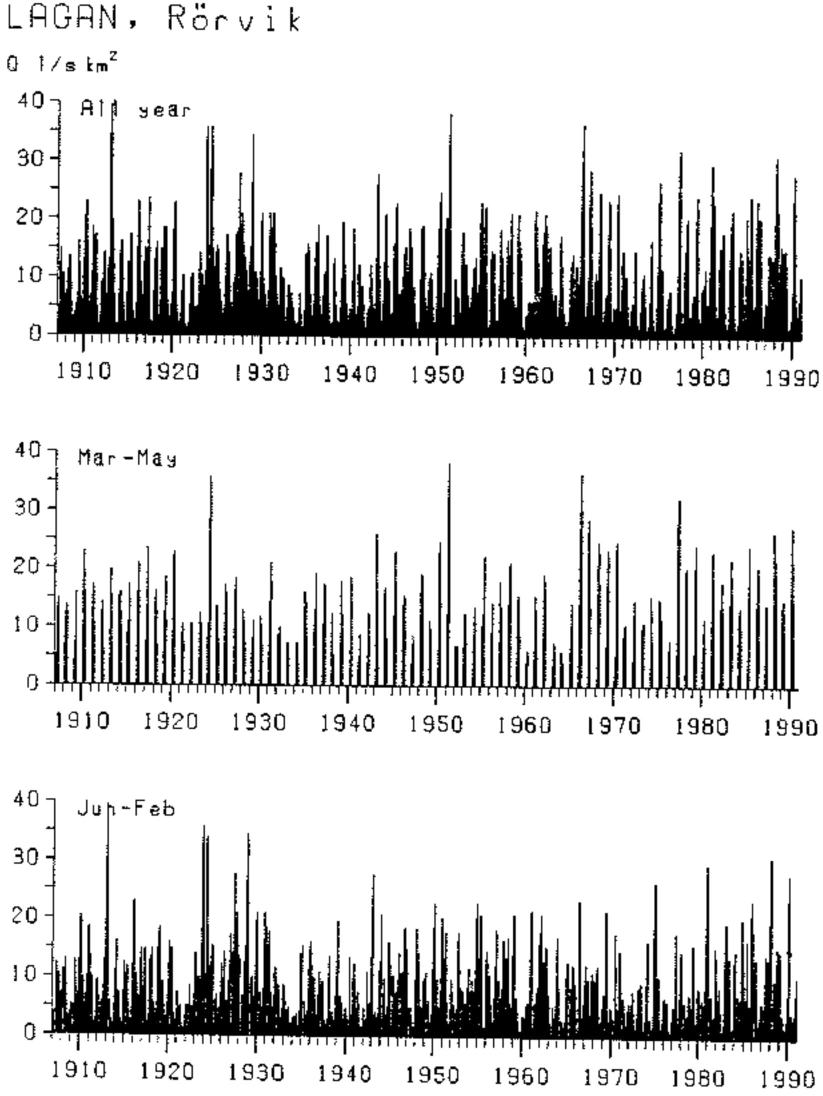

Fig. 1. Recorded runoff at Rörvik, Lagan, 1907-1990.

be taken into consideration in a regional flood frequency analysis.

Some results from the time series and frequency analysis for largest annual floods are shown in Table 3. No significant persistence by the run-test was found, except for autumn floods at Rörvik, at the outlet of a large lake. The only significant periodic cycle was, likewise, found for Rörvik. The seasonal distribution of flow is given for some stations in Fig. 3. In general, there were some signs of earlier snowmelt during the 1980-ies than in the complete records. It can also be noted that at none of the 8 stations did the largest recorded flood occur in the summer, when precipitation intensities are highest. The results for largest annual floods therefore to a large extent correspond to the results for spring floods.

For all annual maximum series the lognormal 3 distribution predicted larger floods than the highest recorded for the return period N+1 years, the Weibul plotting position (cf. Fig. 4). This is far from the expected 37% from eq. (5), and seems to indicate overestimation rather than underestimation. The skewness coefficient was positive for almost all samples, whereas the skewness for logarithms was usually negative (Table 3). This suggests that the lognormal distribution with 2 parameters in most cases may not be appropriate for extrapolation to low probabilities. Neither does the Gumbel distribution appear suitable in general as it has a fixed skewness of 1.14.

*Table 2.a. Trend tests for largest annual floods, 1911-1990. * denotes 95 % significance, and - denotes no significance on the 95 % level.*

Station	Trend test				Regression slope (%/yr)			
	11-90	31-90	51-90	71-90	11-90	31-90	51-90	71-90
Kukkolankoski	-	-	-	-	0	+1	+2	-6
Ytterholmen		-	-	-		+3	+5	* -11
Solberg	-	-	-	*	+2	+2	+2	* -16
Hassela[1]	-	*	*	-	+5	* +9	* +14	+28
Ljusnedal		-	-	-		0	0	+6
Ersbo[2]	-	-	-	-	-1	0	-2	+7
Rörvik	-	*	-	-	+1	* +6	+7	+18
Simlången		-	-	-		0	0	+3

[1] 1919-1990, [2] 1912-1990

Table 2.b. As Table 2.a., autumn floods.

Station	Trend test				Regression slope (%/yr)			
	11-90	31-90	51-90	71-90	11-90	31-90	51-90	71-90
Kukkolankoski	-	-	-	-	-2	-1	-3	+7
Ytterholmen		-	-	-		-6	-5	+30
Solberg	-	-	-	-	+1	+1	+5	+15
Hassela[1]	-	-	-	-	+2	+4	+2	+46
Ljusnedal		-	-	-		-6	-8	+27
Ersbo[2]	-	-	-	-	-2	-2	+5	+26
Rörvik	-	*	-	-	+1	* +6	+7	* +37
Simlången		-	-	-		0	0	+10

[1] 1919-1990, [2] 1912-1990

*Table 3. Time series analysis, and sample statistics of largest annual floods. * denotes 95 % significance for autocorrelation ρ(1) and for the largest periodic component.*

Station	ρ(1)	Largest period (years)	Mean (l/s km²)	Var. coeff.	Skew. coeff.	Skew. coeff. for log.
Kukkolankoski	-0.08	4.7	63	0.23	+0.52	-0.08
Ytterholmen	+0.06	2.3	123	0.25	+0.21	-1.14
Solberg	-0.02	4.7	200	0.23	-0.16	-0.75
Hassela	+0.16	10.3	70	0.48	+0.60	-0.14
Ljusnedal	-0.07	2.4	211	0.23	+0.49	-0.30
Ersbo	-0.06	2.3	181	0.34	+1.02	+0.34
Rörvik	-0.10	* 3.8	20	0.36	+0.72	-0.35
Simlången	-0.15	3.9	128	0.30	+0.63	-0.62

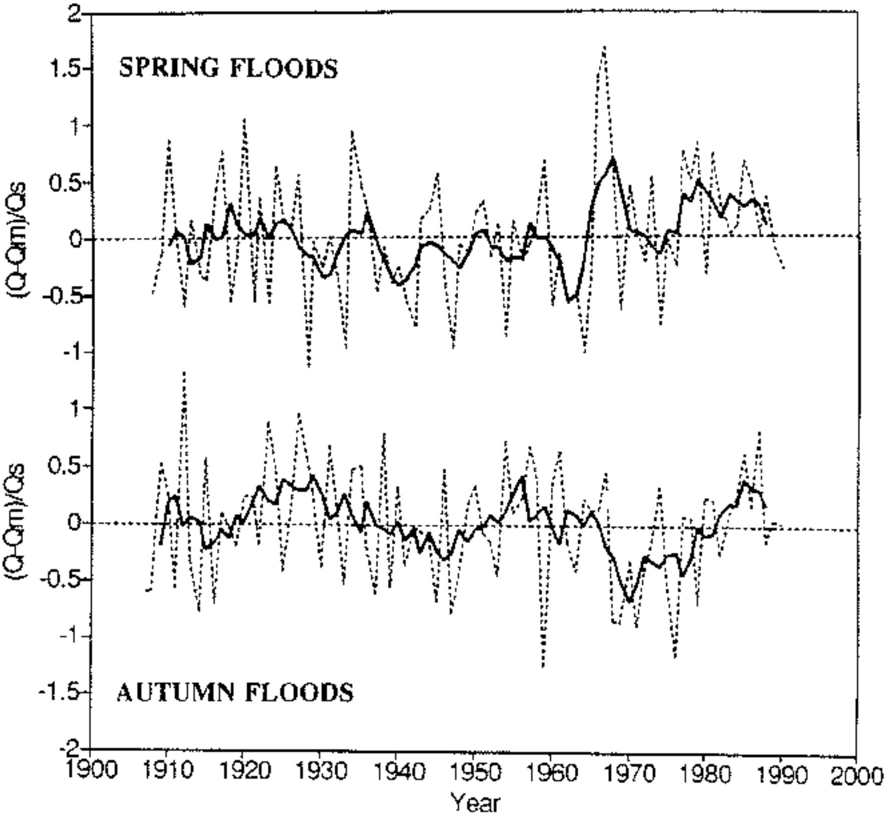

Fig. 2. Average of all 8 standardized series, dotted line = individual years, solid line = centered 5 years moving average.

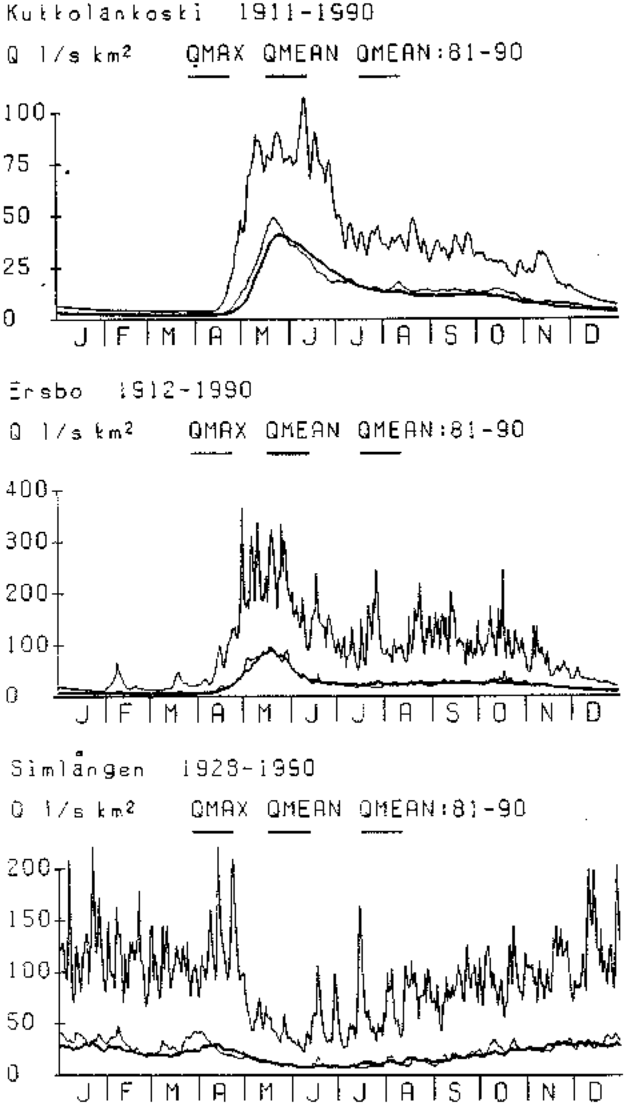

Fig. 3. Seasonal distribution of flow, with maximum recorded as the envelop. Thick curve = mean for the whole period, thin curve = mean for 1981-90.

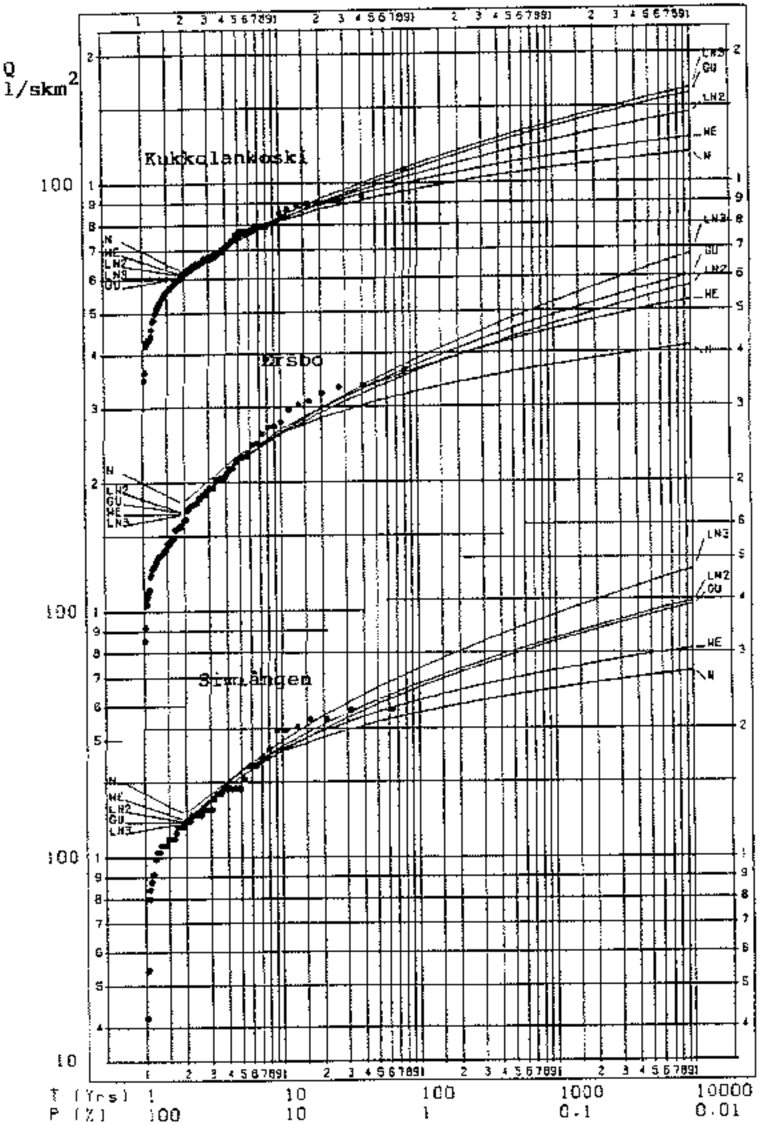

Fig. 4. Example of flood frequency analysis of annual extremes, Lognormal 2 and 3, Gumbel, Weibul and Normal distributions.

CONCLUSIONS

The presented results are prelimary, and the work is continued. The following tentative conclusions are nevertheless suggested: No significant trends in extreme floods were found, when studying sufficiently long records. This agrees with the results by Jutman (1991), who found very weak, if any, trends in yearly mean runoff in Sweden. The 1980-ies had an unusually large number of high floods, whereas the 1970-ies were drier than normal, especially when it comes to autumn floods. This probably led to the impression of a trend in floods.

There were some indications of snowmelt occurring earlier in the year in the 1980ies, than in the complete records. Other than that no changes in the seasonal distribution of runoff could be seen. Time series analysis of annual, spring and autumn extremes did not reveal any convincing signs of autocorrelation, persistence, nor periodic variation. It appears difficult to select one probability distribution as appropriate for all records, but the fitness of different distributions will be studied further.

ACKNOWLEDGEMENTS

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INFLUENCES OF CLIMATE CHANGE ON THE FINNISH ENERGY ECONOMY

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Finland

ABSTRACT

The direct influences of the greenhouse gas-induced climate change on the Finnish energy sector by the year 2025 are studied. On the basis of the literature study, three climate change scenarios have been constructed. The annual mean temperature and precipitation increase from the present in all scenarios. The annual mean hydropower production in the Kemijoki river basin in northern Finland with existing power plants, calculated with a run-off model, increases considerably, by 12% - 41%. The annual total electricity consumption in Finland decreases by 1.2% - 4.4%, according to the changes in heating degree days. The aggregate effect on the whole of electricity production is estimated with an electricity generation system model. The variable costs of the separate condensing power are found to drop by 5% - 15% annually. The study shows that the possibility of the climate change should be considered when long-term investments in energy operations dependent on climate are made.

1. INTRODUCTION

Situated at 60° and 70° of northern latitude, Finland may well be considered the northernmost country in the world. The Finns account for about one third of the world's total population living to the north of the 60th latitude. Because of her northern location and cold climate, energy has always been important to Finland, and climate is an important factor in determining energy consumption. The power plants are normally used for decades, and climate is one of the design factors of the energy system. The purpose of this study is to find out, whether, and how, the possible climate change could affect energy economy in the coming decades.

The geographic location of Finland, its industrial structure and the long transport distances result in a great need for energy. Industry accounts for more than one-half of the total consumption of electricity, and space heating for more than 10%. The total electricity consumption fluctuates during the year, being the highest in winter. Today, hydropower accounts for about one-fifth of the electricity production /Ministry of Trade and Industry 1990a/.

The study focuses on factors directly dependent on the climate. Should the greenhouse effect accelerate rapidly, the counter measures necessary to slow it down, for instance restrictions on the use of fossil fuel sources, might greatly affect the energy economy. The changes in the structure of the world economy or any migratory movements could probably have the greatest impact. Factors of this kind are not included in this study. We can say that it is assumed that the climate change would take place "suddenly" somewhere around the year 2025.

In recent years some studies in countries with different climates have been made on the subject. In two areas in the United States, the electricity consumption and the capacity demands are found to increase, because of the increased air conditioning and the reduced water supply for hydropower /Linder et al. 1987/. In another study, the cooling load in the United States is found to increase more than the heating load decreases, except in the residential sector in the coldest regions /Loveland and Brown 1989/. The results of a study made for Quebec, Canada, show an increase in the potential for hydropower, and a decrease in winter heating energy requirements /Singh 1988/. Also in Norway, the hydropower production is expected to increase /Saelthun et al. 1990/. In a European study, Northern Europe is expected to have benefits in terms of energy savings /Warrick et al. 1990/.

2. CLIMATE CHANGE AND SCENARIOS

Many climate change studies indicate that when greenhouse gas concentrations increase, the climate changes most at high latitudes in winter /IPCC 1990/. The regional predictions of the different studies in Finland, or in other northern European areas, are not very reliable. As we do not know exactly how Finland's climate will change, when studying the possible impact on energy production and consumption, we have to make assumptions on the changes which could take place. Then the impact of these assumed changes has to be considered.

Based on a survey of the literature, three climate change scenarios for the year 2025, A, B and C, have been constructed. The scenarios are not strictly related to any particular future emission scenario or greenhouse gas concentration scenario, but are within the range of possible climate changes, based on different global circulation model studies and palaeoclimatological studies /e.g. Academy of Finland 1986, Bolin et al. 1986, Budyko 1989, Heino 1987, IPCC 1990/. Scenario A entails the least change and scenario C the most. The annual mean temperature and precipitation in all scenarios will increase. In all scenarios the change is largest in winter. The change in evaporation rate is correlated with the temperature and humidity conditions. The potential evaporation rate (Class-A evaporation) is expected to increase in Northern Finland by 11%...45% in the climate change scenarios A...C, when compared to the base case. The real evaporation rate is calculated with HBV run-off model, and it is found to increase by 10%...42% from the present value. The climate change scenarios are described in Table 1.

Table 1. Climate change scenarios for the year 2025 in Finland.

	Temperature change Winter	 Spring	 Summer	 Autumn	Annual temp. change	Annual precipitation change
Scenario A	+1.5°C	+1.2°C	+0.8°C	+1.2°C	+1.2°C	+10%
Scenario B	+4.0°C	+3.0°C	+2.0°C	+3.0°C	+3.0°C	+20%
Scenario C	+6.0°C	+4.5°C	+3.0°C	+5.0°C	+4.6°C	+35%

The scenarios are not meant to be predictions of the future. The regional results of any climate model or palaeoclimatological study are not very reliable. The warm North Atlantic sea current, the Gulf Stream, keeps Finland and the rest of northern Europe warmer than the areas of Siberia or North-America at the same latitude. Some of the studies with coupled ocean-atmospheric general circulation models indicate that, if the global mean temperature increases, the ocean circulation in the North Atlantic may become weaker. This would result in only little warming, or even cooling in the area. Most of the studies show, however, that the mean temperature would rise and the precipitation would increase also in northern Europe /IPCC 1990/.

If no climate change should happen, the structure of the energy economy of the year 2025 - the "base case" scenario - is estimated to accord with a present official assessment of the Ministry of Trade and Industry /Ministry of Trade and Industry 1990b/.

3. IMPACTS ON HYDROPOWER PRODUCTION

3.1 Methods

The study on the possible changes in hydropower production concentrates in the Kemijoki river basin, which is situated in northern Finland. The power plants of the Kemijoki river basin produce at present about 40% of the annual hydropower production in Finland. Typical for the area are low winter discharges, because in winter the precipitation accumulates in snow cover, whereas when the snow melts in the spring, there are heavy discharge peaks. During the spring floods a considerable part of the water has to be run past the power plants. In the river basin there are three regulating reservoirs to even out seasonal discharge variations.

In this study the river basin is mainly modelled by the HBV run-off models. Also, simple models of the river system, as well as models describing the lakes and regulating reservoirs, are added /Vehviläinen 1989/. Every power plant of the river is described by a simple power plant model which calculates the daily electricity production, and also the amount of water directed past the power plant, as daily averages throughout the year /Aittoniemi 1990/.

The models use daily weather data as an input. The hydropower production of the base case is first calculated, using the real weather data of the present climate. Then the weather data is changed according to the climate change scenarios, and the daily electricity production is calculated again, using these changed weather data. The model results are then compared to each other /Aittoniemi 1990/.

3.2 Results

The conditions for hydropower generation change considerably in the climate change scenarios. As the annual precipitation rate increases, the annual hydropower generation also increases. Fluctuations from one year to another grow in northern Finland. In some winters there are as much snow as today. In others, however, the accumulation of annual snow cover begins much later than today, the spring arrives earlier, and the volume of spring run-off is much smaller. The climate in northern Finland begins to resemble, in this respect, the climate in central or southern Finland today.

The increase in the total annual average hydropower production with already existing power plants in the Kemijoki river basin in the climate change scenarios can be seen in Table 2. The changes are larger than the changes in the annual mean discharge, because the discharge evens out somewhat and the share of the water past the power plant decreases.

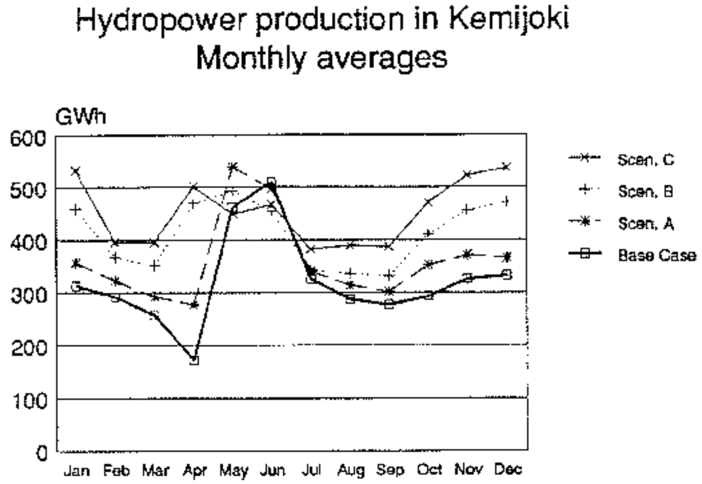
Table 2. Changes in annual mean hydropower production in the Kemijoki river basin with existing power plants and machinery.

	Scenario A	Scenario B	Scenario C
Change in annual hydropower production	+12%	+28%	+41%

Most of the production increase occurs in winter. The monthly variation in electricity production in the Kemijoki River basin at present and in the climatic change scenarios can be seen in Figure 1. Notice the low electricity production rate in winter at present (the base case) and the increase in electricity production in the climatic change scenarios, especially during the winter months.

If the climate changed according to these scenarios, more flexible water regulation would be needed. The timing of the "spring low" in the upper limit of Lake Kemijärvi regulation has to be changed in scenarios B and C, as the flow rate peak is brought forward by several weeks on the average.

The increase in evapotranspiration, resulting from the increases in temperature and precipitation, may be the most uncertain thing in the calculations. If the vegetation changes due to climate change, the evapotranspiration may change in a different way than expected.



	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Scen. C	533	396	396	501	449	467	382	390	387	471	522	537
Scen. B	460	367	352	469	493	454	343	336	332	410	455	471
Scen. A	357	323	292	277	539	497	341	314	302	353	371	366
Base Case	313	292	257	172	462	510	326	287	277	293	326	333

Figure 1. The monthly variations of the electricity production in the Kemijoki River basin at present (base case) and in the climate change scenarios.

4. IMPACTS ON ELECTRICITY CONSUMPTION

4.1 Methods

The calculation of the changes of the electricity consumption in the climate change scenarios has been based on the changes in Heating Degree Days (HDD). The amount of heating degree days within a certain time period (eg. a year, a month, or two weeks) is the sum of the differences between the indoor (or "reference") temperature and the daily average outdoor temperature. The reference temperature used is +17°C, and HDD is calculated only during the days with the average temperature below +10°C from January to June, and below +12°C from July to December. When the outdoor climate changes, the amount of HDD also changes.

At present in Finland, the changes in heating degree days are found to be statistically correlated to changes in different sectors of electricity consumption. The correlation is strongest between HDD and the space heating electricity, but residential electricity and some parts of the industrial electricity consumption also decrease with decreasing HDD, i.e. when climate gets warmer /STYV 1985/. These correlations have been used to calculate the changes in electricity consumption in the climate change scenarios. In the base case, the HDDs of a 30 year time series of daily temperatures of Tampere, Finland, is calculated. Then the daily temperatures are changed according to climate change scenarios, and the HDDs are calculated again using the changed time series. The changes in HDDs define the changes in energy consumption /Aittoniemi 1990/.

At present, there are practically no air-conditioning systems in private houses or apartments in Finland. In this study the possible changes in the power consumption of cooling and refridgerating equipment, or of the air conditioning systems of office buildings, are not taken into account.

4.2 Results

The annual average heating degree day sum (HDD) in the base case and in the climate change scenarios, as well as the resulting changes in the annual heating energy and in the total annual electricity consumption can be seen in Table 3. When considering the heating energy alone, the changes are quite remarkable. The changes in the annual total electricity consumption are not particularly large, and more than half of the changes are due to changes in the electric heating consumption alone.

The seasonal fluctuations of the total electricity consumption changes somewhat in the climate change scenarios. The shape of the seasonal fluctuations of the electricity consumption remains qualitatively the same in the climate change scenarios. The consumption decreases in absolute terms are of about the same magnitude in autumn, in winter and in spring. In summer there is almost no change. The relative change (per cent of the base case consumption) is largest in the early autumn and late spring.

Table 3. The annual heating degree days (HDD) sum, and changes in annual heating energy and total electricity consumptions in Finland.

	Base Case	Scen. A	Scen. B	Scen. C
Annual HDD sum	4600	4200	3600	3100
Change in annual heating energy consumption		-7%	-15%	-23%
Change in annual total electricity consumption		-1.2%	-2.9%	-4.4%

5. IMPACTS ON THE WHOLE OF ELECTRICITY PRODUCTION

The aggregate effects of the climate change scenarios on the whole of electricity production system of Finland have been estimated using a computer model "KAPAS", developed by Imatran Voima Oy. The model describes the whole electricity producing system of Finland, as well as the fluctuations of electricity consumption. The model uses available hydropower and the specified separate condensing power plant capacity in its optimum, so that the variable costs of the separate condensing power are minimized.

The structure of the electricity production system in the year 2025 has been estimated to accord with an official scenario of the Finnish Ministry of Trade and Industry, and it has been assumed to remain similar in the climate change scenarios. The absolute values of the energy scenario are not very important in this study, because the climate-induced changes, which we are interested in, would probably be quite similar, even if the energy scenario were different.

In the climate change scenarios, electricity consumption has been altered according to calculations described before. The estimates for the changes in hydropower production have been based on the changes in Kemijoki river basin, and on the results of Vehviläinen and Lohvansuu (1991).

When the results of KAPAS model in the base case and the climate change scenarios are compared, the variable costs of the separate condensing power production are found to decrease by 5% in scenario A, 9% in scenario B and 15% in scenario C. This is due to the increase in hydropower production and the reduction in electricity consumption. An opposite, but weaker effect is due to the reduction in the electricity production in the district heating power plants, because of the smaller need for district heating. It can be seen that there is too much electricity generating capacity in the climate change scenarios.

The main results of the impacts on the whole of electricity production system are summarized in Table 4. The assumed climate scenarios resemble each other, and thus also the results are of somewhat similar type in the different scenarios. In any of the climate change scenarios the electricity generation is easier to match with the demand, owing to the reduction in consumption and increase in hydropower, especially in the winter.

Table 4. Summary of the main results of the impacts of the climate change scenarios on the whole of electricity production system in Finland.

	Scen.A	Scen.B	Scen.C
Decrease in annual heating energy consumption	- 7%	- 15%	- 23%
Decrease in total annual electricity consumption	- 1.2%	- 2.9%	- 4.4%
Decrease in peak power consumption	- 1.3%	- 2.6%	- 4.6%
Increase in annual hydro power product. with existing plants	+ 11%	+ 22%	+ 38%
Decrease in annual district heat production	- 6%	- 14%	- 22%
Annual savings in variable costs of condensing power	- 5%	- 9%	- 15%

6. CONCLUSIONS AND DISCUSSION

The impact of the eventual climate change should be considered when planning any actions dependent on the climate. In energy systems, hydropower production may meet the strongest impacts. Today, when power plant operation or electricity generating systems are being designed, the climate is normally taken as a constant factor, and the uncertain variables are such as the price and the obtainable amount of fossil fuels, the electricity consumption level in the future, etc. The long-range mean temperatures and mean precipitation rates used today as the basis for design will not necessarily remain constant, not even during the lifetime of the power plants in use today. Thus one more uncertainty factor has been added, namely the possibility of a climate change.

So far the exact estimates on the climate change are partly speculation. The study shows, however, that the impact on the energy sector could be significant. We must therefore follow up on the development of the prognosis for climate change, and re-evaluate its consequences, as more information is gained.

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THE HBV MODEL AFTER TWENTY YEARS

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ABSTRACT

It is now 20 years since the first presentation of results from the HBV model at the Nordic Hydrological Conference in Sandefjord in 1972. Since then the use of hydrological models has grown dramatically, and today they are standard tools for an increasing number of applications. The HBV model has followed this trend, and there are examples of applications in some 30 countries. The span of applications has also widened and covers today hydrological forecasting, spillway design, studies of effects of climate change, synoptic water balance mapping, simulations of groundwater response among others. The paper describes the development of the HBV model during these 20 years and summarizes national and international experiences from its application.

1. INTRODUCTION

The first successful run with an early version of the HBV hydrological model was carried out in the spring of 1972 (Bergström, 1972; Bergström and Forsman, 1973). This was the result of a short period of model development towards an operational model of reasonable complexity, and with a requirement on input data that could be met in most Swedish drainage basins. The goal was a conceptual model primarily to be used for hydrological forecasting. The development process continued with an increasing number of test applications and introduction of a routine for snow accumulation and melt (Bergström, 1975). In the early summer of 1975 the first operational forecasts were carried out.

The work on the HBV model followed, to a high degree, the ideas lined out by Nash and Sutcliffe (1970) among others, who saw the risk that increasing computer capacities may result in too complex model formulations, unless the significance of model components is carefully checked. This philosophy is responsible for the relative simplicity of the HBV model. A lot of modifications of the model have been tested, but few have been showed to improve the results. The basic ideas behind the model are discussed in more detail by Bergström (1991).

After twenty years the HBV model has become a standard tool for runoff simulations in Scandinavia, and the number of applications in other countries is growing. Some of the applications abroad are carried out by, or in cooperation with, the Swedish Meteorological and Hydrological Institute using a standard computer code and the version six of the model (HBV-6). Such examples are the applications to five basins within the WMO project on intercomparison of models for snowmelt runoff (WMO, 1986) and a large number of applications to basins in Latin America (Häggström et al., 1990). Some other applications are carried out by modified codes or model versions which are totally rewritten. New standard codes with modified snow routines are, for example, in use in Norway, Finland and Switzerland. Many of the applications abroad can be considered as scientific tests, but the number of operational applications is growing along with the development of user-friendly desk top computer systems.

2. MAIN FIELDS OF APPLICATION OF THE HBV MODEL

Hydrological forecasting was the aim of the first operational applications of the HBV model. Today the field of application is much wider, and there is a number of by-products in use.

Real-time forecasting

The hydrological forecasts are either short term, with a few days lead time, or long term, covering the whole snowmelt season (several months). For short term forecasting meteorological forecasts are often used as input to the models (see, for example, Björkenes, 1990). The long term forecasting is based on the present hydrological conditions, as described by the model, and a number of simulations with climatic data from the same season earlier years. The output from the model is then subject to a statistical analysis which can be used to judge the risk of flooding or the probability of refilling of a reservoir.

Quality control, extension of runoff records and filling in of gaps

The HBV model is sometimes used as a tool for control of the quality of the runoff data. It has proved to be particularly useful for the correction of effects of ice-jamming on the records. The extension of runoff records and filling in of gaps are straightforward applications of hydrological models. The methods are very useful in areas where the climatological records are more complete than the hydrological ones.

Design floods

In 1990 new guidelines for the computation of spillway design floods were adopted in Sweden (Flödeskommittén, 1990). The Swedish Committee on Design Flood Determination concluded that hydrological modelling in combination with reservoir simulation was the most feasible method for a multi-reservoir system with a mix of snowmelt and rain floods.

The guidelines are based on prescribed regional design sequences of precipitation, corrected for basin size, elevation and time of the year, and a hydrological model. Reservoir operation strategies are also considered. The most critical timing of all flood generating factors is found by an iterative simulation where the design precipitation is systematically inserted, at all possible locations, into a climatological record of ten years, and the response of the levels of the reservoirs is analysed.

In order to meet the requirements of the new guidelines a computer system has been worked out by the Swedish Meteorological and Hydrological Institute, where the HBV model provides the hydrological input to the reservoirs. In Norway a simplified version of the HBV model is in use for a similar purpose (Andersen et al., 1983).

Synoptic water balance mapping

One of the most important spin-off products of the HBV model is an operational synoptic water balance map, which is produced daily by the Swedish Meteorological and Hydrological Institute (Bergström and Sundqvist, 1982). This map illustrates the hydrological situation in the country by symbols describing snowpack, soil moisture deficit and runoff generation.

Water balance studies

In connection with the work on spillway design guidelines the HBV model was used in a nationwide study of the interaction and timing of flood generating processes. This study revealed the importance of critical timing and had great impact on the final guidelines (Brandt, et. al., 1987). The modelling technique has also been used for the computation of soil moisture statistics in connection with studies on forest damage (Grahn et al., 1985) and for analyses of the effects of forest management an runoff (Brandt et. al., 1988). Jutman (1992) used the HBV model concept for the production of a new runoff map of Sweden.

Studies of the effects of a changing climate

The growing concern about the risk for a changing climate and its effects on our water resources has started a discussion on the possible use of hydrological models as an analysis tool. The HBV model has been used in this respect in Norway (Saelthun et al., 1990) and in Finland (Vehviläinen and Lohvansuu, 1991). In this type of application the problem of local interpretation of climate scenarios and model stationarity have to be considered carefully.

Groundwater simulations

Another spin-off of the HBV model is a model for simulation of groundwater response to climatological input (Bergström and Sandberg, 1983). These simulations required a modification of the saturated zone of the model. Thanks to the success in the attempts to model groundwater response, the synoptic water balance map has been complemented by a synoptic map of the groundwater reservoirs.

Water quality and simulations in ungauged basins, the PULSE model

The modification of the HBV model used for groundwater simulations was the starting point for the development of a new model generation, the PULSE model. The PULSE model has most of its subroutines in common with the HBV model but has a better representation of the shallow groundwater and is thus more feasible for hydrochemical simulations. It is used for studies of short term variability in stream flow acidity (Bergström et al., 1985), modelling of transport of non-point source pollution (Brandt, 1990) and has also become widely used for the simulation of runoff in ungauged catchments after generalization of the model parameters (Johansson, 1986).

3. APPLICATIONS OF THE HBV MODEL IN THE WORLD

Below follows a summary of those applications of the HBV model that are known to the author today (1992) and some key references (Table 1, Figure 1).

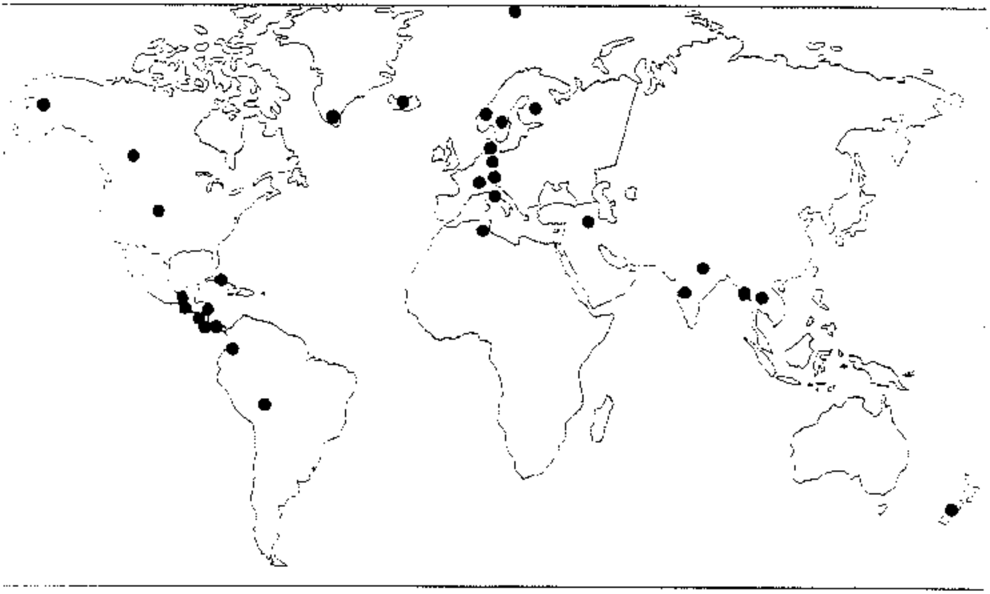

Figure 1. Countries or regions where the HBV model is known to have been applied until 1992.

The presentation is based on work that has been carried out by, or in cooperation with, the Swedish Meteorological and Hydrological Institute and reports that have reached us. We know that the model is available in more than these 28 countries and therefore more applications are likely to exist. In the table an attempt is also made to classify the main objectives of the applications although this is not always very straightforward since there may exist overlapping objectives.

Table 1. Known applications of the HBV model in the world.

EUROPE

Sweden:	Some 100 basins for hydrological forecasting and computation of design floods (Bergström, 1976; Häggström, 1989; Bergström, 1990). Some 50 applications of the PULSE model for environmental studies and production of runoff records (Brandt, 1990).
Norway:	Some 50 basins for hydrological forecasting and studies of the effects of a changing climate. Norwegian version of the model (Killingtveit and Aam, 1978; Saelthun and Taksdal, 1988; Saelthun, 1990; Saelthun et al., 1990; Killingtveit et al., 1990). Scientific test of Norwegian version in Svalbard (Bruland, 1991).
Finland:	Some 20 basins for hydrological forecasting and studies of the effects of a changing climate, Finnish version (Vehviläinen, 1986 and 1991; Vehviläinen and Lohvansuu, 1991).
Denmark:	Scientific test of an early version (Houmøller, 1976).
Iceland:	Scientific test of SMHI version (Bergström et al., 1982).
France:	WMO intercomparison of models of snowmelt runoff (WMO, 1986). WMO real-time intercomparison of hydrological models (WMO, 1987).
Italy:	Scientific test of SMHI version (Capovilla, 1990).
Poland:	WMO intercomparison of models of snowmelt runoff (WMO, 1986).
Switzerland:	WMO intercomparison of models of snowmelt runoff (WMO, 1986, SMHI version). Scientific test of the model in four basins (Renner and Braun, 1990; Braun and Aellen, 1990, Swiss version). Hydrological forecasting in the Rhine (Jensen and Braun, 1990).

NORTH AMERICA

Canada:	WMO intercomparison of models of snowmelt runoff (WMO, 1986). WMO real-time intercomparison of hydrological models (WMO, 1987).
USA:	WMO intercomparison of models of snowmelt runoff (WMO, 1986). WMO real-time intercomparison of hydrological models (WMO, 1987). Scientific test of SMHI version (Hinzman and Kane, 1991).
Greenland:	Scientific test of Norwegian version (Bruland, 1991).

LATIN AMERICA

Bolivia:	Hydrological forecasting, SMHI version (Johansson et al., 1987).
Colombia:	Hydrological forecasting, SMHI version (Häggström et al., 1988).
Costa Rica:	Hydrological forecasting, SMHI version (Johansson et al., 1985).
Cuba:	Hydrological forecasting, SMHI version (Rodrigues et al., 1991).
El Salvador:	Hydrological forecasting, SMHI version (Häggström et al., 1990).
Guatemala:	Hydrological forecasting, SMHI version (Häggström et al., 1990).
Honduras:	Hydrological forecasting, SMHI version (Häggström et al., 1990; Espinosa, 1991).

Nicaragua:	Hydrological forecasting, SMHI version (Häggström et al., 1990).
Panama:	Hydrological forecasting, SMHI version (Häggström et al., 1990).

ASIA

Burma:	Scientific test of SMHI version (Gyaw and Persson, 1985).
India:	Scientific test of SMHI version (Bhatia et al., 1984).
Iraq:	Hydrological forecasting, SMHI version (unofficial report).
Nepal:	Scientific test of the Swiss version (Braun and Demierre, 1991).
Thailand:	Hydrological forecasting, SMHI version (Harlin, 1990).

AFRICA

Tunisia:	Scientific test, local version (Berndtsson et al., 1985).

OCEANIA

New Zealand:	Scientific test of local model version (Moore and Owens, 1984).

The applications cover a large number of basins in different climatological and geographical regions, and the basins are ranging in size from less than one km^2 up to 40 000 km^2. Thanks to the subbasin option there is no theoretical upper limit in size.

4. COMPUTER SYSTEM

Thanks to the relative simplicity of the structure of the HBV model the demand for computer power is low and can be met by most modern desk top computers. The SMHI version of the model is normally operated in a PC-environment, but there are also main frame versions available. The code contains subprograms for input data control, model calibration, hydrological forecasting and computation of design floods in systems of reservoirs. The computer time for a simulation of a single basin model over a ten year period is in the order of minutes on a 386 processor, while design flood simulations for larger systems or automatic calibrations can be completed after ten hours. More powerful computers and more effective programming will decrease the demand for computer time considerably.

5. TRAINING

Although the HBV model has an uncomplicated structure and user-friendly computer systems are available, it is not recommended to apply it without a thorough insight into its structure. All models of this kind contain complex interactions and feed-back mechanisms, which requires a dynamic way of thinking to be fully understood. It is also important to have a sound philosophy when choosing subbasins and climate stations and when correcting input data for undercatch, elevation and other systematic errors.

The Swedish Meteorological and Hydrological Institute has carried out a number of training courses in connection with applications abroad and decentralization of the national forecasting system. Courses aimed at the hydro-electric power industry have also been carried out by the Norwegian Hydrodynamic Laboratories. Experience has shown that, after proper training, the user of the model is self-sufficient and can go on with new applications without further assistance.

6. CONCLUDING REMARKS

The large number of applications of the HBV model in the world have proved that this relatively simple conceptual model is surprisingly general. The key processes seem to be described in a reasonable way. The model has the advantage of limited demand on data coverage and computer facilities. The low complexity of the model has made it easy to teach others how to use it and to install it in a number of countries. There are also several examples where scientists have been able to reproduce the model code just from a description in the literature.

The existence of different versions of the HBV model and different groups who apply it makes generalization of parameter values difficult. The parameter values are depending on the type of input data used, computational details in the model and, to some degree, on the calibration skill of the user.

Although the computer technology has developed dramatically during the last 20 years, the operational runoff models, represented by the HBV model, have not experienced the same development. The model structures have remained surprisingly stable, but the number of applications has increased thanks to the availability of handy computers.

It is, of course, very difficult to foresee the development of models for the 20 years to come. It is quite certain that the use of models will continue to expand. There is also a need for a new model generation, able to incorporate more field information than the existing ones. This requires further research in areal climatological and hydrological processes. It is important that the modellers maintain an interest in the physics of these processes and don't get blinded by the beauty of modern computer systems.

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GENERATION OF SURFACE RUNOFF IN A SPATIALLY VARIABLE FIELD

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ABSTRACT

Natural formations are heterogeneous. A basic problem is to quantify the influence of field variability on hydrological response in spatially heterogeneous terrain. Based on observations in a lateritic hillslope in Kerala, India, a model has been developed, where the process of surface runoff generation is defined in relation to soil heterogeneity. Hortonian generation of surface runoff is the important mechanism in the experimental field. Thus, the mean area over which ponding occurs and the expected amount of ponded water can, in principle, be determined from the statistical structure of the soil physical variability. This principle is utilized in the model. The model simulations demonstrate the importance of soil physical variability for distributed field behaviour. A spatially variable field exhibits a bias in infiltration properties as compared to a homogeneous field with corresponding mean soil physical properties. Spatially averaged time to ponding is shorter, the averaged infiltration rate is lower and, correspondingly, the mean surface runoff is higher in a heterogeneous field. Moreover, contrary to the homogeneous case, surface runoff may generate also when the rainfall intensity is less than average saturated hydraulic conductivity in a heterogeneous field. The model does not consider surface interactions, which is expected to modify the tendencies described, and to reduce the bias shown.

INTRODUCTION

Natural formations are heterogeneous. Soil physical properties, as measured in soil samples in the laboratory, exhibit spatial variability. This variability may be considered as random. The impact of the variability of most soil physical properties has been shown to be rather limited with the exception of saturated hydraulic conductivity, K_s, which tends to vary within much broader limits than the other properties. By considering soil physical coefficients in the flow equations as stochastic variables, dependent variables, e.g. infiltration capacity, satisfying these equations and the boundary conditions are also stochastic functions of space. A basic problem is to quantify the effect of variable soil physics on the dependent flow variables, i.e. to depict their statistical characteristics, for practical purposes in terms of their expectation and covariance.

A field study was undertaken in the state of Kerala, southwest India, in order to collect information on the water balance on a lateritic hillslope. Laterite is a residual deposit covering vast areas of the tropics. It is characterized by textural diversity and highly varying soil physical characteristics. An approximate analytical stochastic model has been developed to simulate the water balance in this hillslope. The stochastic framework which is the basis for the model is utilized to define the process of surface runoff generation in relation to soil heterogeneity. In this paper, we shall present this simplified model of runoff generation and use it to demonstrate some effects of field variability on hydrological response in spatially heterogeneous terrain.

SURFACE RUNOFF GENERATION

The hydrological response to a storm on a hillslope is a complex product of the soil physical characteristics coupled with the time-dependent rainfall intensity. Soil saturation and ponding occur on spatially distributed partial areas that expand and contract according to rainfall intensity and soil moisture conditions, which in turn is related to the groundwater level. Surface runoff may be generated by the Horton mechanism when the rainfall intensity exceeds K_s and the rainfall duration is longer than the required ponding time for the given initial moisture profile. A second mechanism is found under shallow groundwater table conditions, where saturation excess surface runoff may occur due to a rising groundwater table, making no further soil moisture storage available. Both mechanisms lead to variable contributing areas; in the one case where the surface hydraulic conductivity is lowest, and in the other case when the groundwater table is shallowest.

Which mechanism of runoff generation that is the dominant is a matter of environmental control. The classical mechanism presented by Horton in 1933 was based on studies in agricultural fields and dry areas in southern USA. In such areas the surface may be subjected to hardening during dry periods, giving a low infiltration capacity. Moreover, rainfall intensity may be high. Similarly, the Horton mechanism may be assumed to be generally valid in climates with a pronounced dry season and where the vegetation cover is discontinuous. In most humid and temperate regions, however, infiltration capacities are high because vegetation protects the soil from rain packing and dispersal, and because the supply of humus and the activity of microfauna create an open soil structure. Under such conditions the generally moderate rainfall intensities do not exceed infiltration capacity.

Hortonian generation of surface runoff is the important mechanism in the experimental hillslope, where very high rainfall intensities are observed in the showers and uncovered soil in between patches vegetation constitutes a surface of moderate permeability. The relatively deep groundwater table generally excludes saturation excess surface runoff. In this situation, the mean area over which ponding occurs and the expected amount of ponded water can, in principle, be determined from the statistical structure of the soil physical variability at the site. Applications of this principle can be traced back to the 1960's, when Karchenko and Roo (1963) used probability curves for the parameters of infiltration to determine the percentage of runoff producing area in relation to rainfall characteristics. Better known is the similar technique used in the Stanford Watershed Model (Crawford and Linsley, 1966). More recently, a few authors go deeper into the relation between the statistical properties of the soil physical parameters and surface runoff characteristics. Smith and Hebbert (1979) analyzed the effect on surface runoff of random variations superimposed on a deterministic trend of infiltration properties along the surface flow path. For a set of rainfall intensities they demonstrated that runoff occurs earlier and increases more gradually for large coefficients of variation in the parameters of the infiltration equations. They also concluded that systematic variation of infiltration along surface flow paths can drastically affect runoff, particularly when rainfall intensity is only a small multiple of the average K_s, which is common for soils that generate Hortonian surface runoff. Freeze (1980) demonstrated the separate influence of the mean, variance and covariance of K_s on the statistical properties of runoff events arising from the hillslope. He concluded that the statistical properties of runoff events from a homogeneous hillslope with mean soil physical properties, may be greatly in error compared to the heterogeneous case. Binley et al. (1989) explored the effects of dependence in soil physical parameters on runoff events, and showed that the range of responses from different realizations was much greater in the case of highly correlated fields than for fields with less correlation, resulting from the greater probability of having larger areas of either relatively high or relatively low conductivity within the random field. Dunne et al. (1991) studied the combined effect of temporally variable rainfall intensities and spatially variable vegetation and soil physics on surface runoff. One of their conclusions was that mean field infiltration rate may increase with hillslope length. This is due to down-slope increase in surface flow depth, progressively inundating more permeable, vegetated mounds so that the hydraulic conductivity of a greater portion of the surface is raised to infiltration capacity.

STOCHASTIC APPROACH

We shall consider horizontal soil physical heterogeneity. A one-dimensional approximation to such a domain, is to regard the medium as a set of vertical, decoupled soil columns with different soil properties. Each column is treated as a homogeneous flow domain, where simplified flow equations based on the concept of a moving front are applied. Special functional forms of saturated hydraulic conductivity and soil moisture content in relation to matric suction are assumed. The equations are solved analytically and replaced by their integrated expressions between the soil surface and the penetrating front or the groundwater table. Averaging the flow variables over the columns yields expected moisture characteristics as functions of time, ergodicity assumed. In line with reported observations, we shall make the simplification to associate soil physical variability with K_s, only. K_s on the hillslope will be looked upon as a realization of a stochastic field characterized by the probability density function (pdf), f_{K_s} . The pdf of K_s has been shown to be approximately log-normal (Langsholt, 1992). Conditioned on the discretized, log-normal pdf of K_s, spatially distributed calculations of infiltration rate, moisture content and matric suction can be developed, providing a basis for the estimates of their first statistical moments (mean and variance).

At a given rainfall intensity, I_p, only on those portions of the field (or columns, figuratively) with infiltration capacity, I_c, less than I_p runoff is generated. Other areas of the soil surface absorb rainfall at an infiltration rate equal to I_p and less than the local I_c. By increasing I_p, I_c is exceeded on an increasing part of the surface, which is brought to saturation and generates runoff. The field's mean infiltration rate increases with rainfall intensity until the total area is saturated. For a given I_p the mean surface runoff for a field is

$$E(q_s) = \int_0^{I_p} (I_p - \iota)\, f_{I_c}(\iota)\, d\iota \tag{1}$$

where f_{I_c} is the pdf of the infiltration capacity, conditioned on f_{K_s} . The mean infiltration rate may be calculated by subtracting the instantaneous mean surface runoff rate from the rainfall intensity,

$$\begin{aligned} E(I) &= I_p - E(q_s) \\ &= I_p - I_p \int_0^{I_p} f_{I_c}(\iota)\, d\iota + \int_0^{I_p} \iota\, f_{I_c}(\iota)\, d\iota \\ &= I_p - I_p F_{I_c}(I_p) + \int_0^{I_p} \iota\, f_{I_c}(\iota)\, d\iota \end{aligned} \tag{2}$$

where F_{I_c} is the cumulative distribution function (cdf) of I_c and yields the proportion of the field which has attained surface saturation at I_p. The two first components on the right hand side represent the contribution of all the areas not producing runoff, whereas the last term represents the contribution from those areas producing runoff.

Fig. 1 shows cdfs of infiltration under ponding as observed by double-ring infiltrometers in the field. A sharp decrease in variability from the initial transient situation towards a more moderate variability as the infiltration rate approaches steady state at t=3 h, at which point the infiltration capacity is approximately equal to K_s, can be seen. Thus, the infiltration variability is much larger than the variability in K_s. The cdf of the K_s-data observed in the laboratory, i.e. by a measuring device of a smaller scale than the infiltrometer, is indicated as well. This curve can be compared with the infiltrometer curve at t=3 h. These two curves demonstrate the effect of instrument scale on statistical properties of the measured variable. K_s as measured by an infiltrometer is a space average over a circular area of 40 cm diameter, whereas the laboratory-data represent 7 cm diameter soil probes. Such a statistical average, itself being a statistic, is subjected to random variations, and thus characterized by a mean value and a variance. It can be shown that the mean of this average is independent of the size of the averaging sphere, i.e. the dimension of the measuring device, whereas the variance tends to zero when the averaging sphere is large compared to the correlation scale. Or, intuitively, some extent of probe-scale heterogeneity is present in the infiltrometer's measuring sphere, extremes even out and the sample variability reduces correspondingly.

BASIC EQUATIONS

Infiltration in a homogeneous domain is modeled according to the notion of a distinct front separating an already wetted front zone from the as yet unwetted parts of the

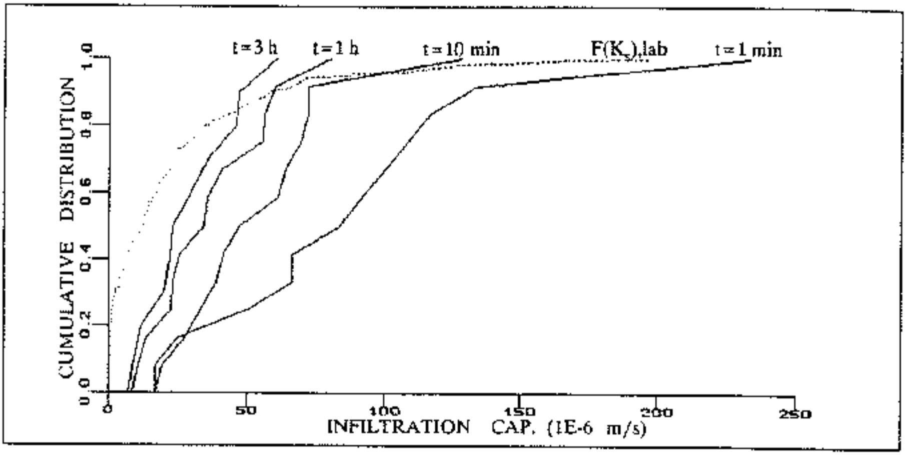

Figure 1. Cumulative distribution of infiltration capacity under ponding. Curves at 4 points in time: after 1 minutes ponding, after 10 minutes, after 1 hour and after 3 hour ponding. The curves are based on 13 infiltrometer tests. The dotted curve is the cumulative distribution of the K_s-data obtained from soil samples.

profile. Initially, hydrostatic equilibrium between the unsaturated and saturated zone prevails, i. e. the moisture content in the unsaturated zone is determined by a matric suction distribution given by

$$\psi = h - z \tag{3}$$

That means, at a height $h-z$ above the groundwater table at depth h, the z-axis is positive downwards from zero at the surface, the pressure is less than that at the water table by a head $h-z$. Then and there is no water transport through the profile. In the front zone, from the ground surface down to the front at depth L, a positive soil moisture flux operates. The relationship

$$\theta = n\left(\frac{\psi_a}{h-z}\right)^{\lambda+\delta} + \theta_r \tag{4}$$

describes the general moisture profile. θ is volumetric moisture content, n is the porosity, ψ_a is the air entry suction, h is the depth to the groundwater table in a coordinate system where the z-axis is positive downwards from zero at the surface, θ_r is the residual water content and δ is a parameter attaining negative values from zero at equilibrium to $-\lambda$, an empirical coefficient, at saturation. The front zone, where δ is less than zero, has a discontinuous connection with the initial moisture profile, where δ equals zero.

Integration of Darcy's law from the surface to the front gives the average flux, $\overline{q}$, in the front zone,

$$\int_0^L q\,dz = \overline{q}L = \int_0^L K(\psi)\,\frac{\partial\psi}{\partial z}dz + \int_0^L K(\psi)\,dz \tag{5}$$

The relations between hydraulic conductivity and soil moisture content on the one hand and matric suction on the other, $K(\psi)$ and $\theta(\psi)$,respectively, are parameterized according to Brooks and Corey (1964) (hysteresis is not taken into consideration):

$$K(\psi) = K_s\left(\frac{\psi_a}{\psi}\right)^{\beta} \tag{6}$$

$$\theta(\psi) = n\left(\frac{\psi_a}{\psi}\right)^{\lambda} + \theta_r \tag{7}$$

where β is an empirical coefficient. By inserting equation (6) and the relationship

$$\psi = \psi_a^{-\delta/\lambda}(h-z)^{1+\delta/\lambda} \tag{8}$$

obtained from equation (4) in combination with the relation (7), the integral (5) can be solved, and an analytical expression can be substituted for the differential equation in the front zone. The wetness and the depth of the front zone are determined by the relations

$$\overline{q} = I \tag{9}$$

and

$$Vol = Idt \tag{10}$$

where Vol is the moisture content in the front zone in excess of equilibrium moisture content,

$$Vol = \int_0^L n\left(\frac{\psi_a}{h-z}\right)^{\lambda+\delta} dz - \int_0^L n\left(\frac{\psi_a}{h-z}\right)^{\lambda} dz \tag{11}$$

and dt is the length of the period under consideration. Equation (9) and (10) are solved iteratively for δ and L. Using the derived equations, the infiltration capacity may be represented by the mean flux in a penetrating front of moisture content equal to saturation,

$$I_c = \frac{1}{L}\int_0^L q_{\delta \div -\lambda}\, dz \tag{12}$$

where L depends on cumulative infiltration.

MODEL SIMULATIONS

The presented model was run for a heterogeneous flow domain, represented by a discretized log-normal pdf for K_s scaled according to data from the field, and for a homogeneous domain with K_s equal to the estimated mean of the heterogeneous field. Figures 2a and b show spatially mean infiltration rate for the heterogeneous and the homogeneous situation and its time-changing pattern, two different constant rainfall rates applied. I_p in Fig. 2a equals 6 mm rain per minute, which approximates the maximum observed in the field for short time periods, and which is more than four times the mean K_s. A clear bias is seen for the infiltration pattern of the heterogeneous field as compared to that of the homogeneous formation. Mean ponding time is shorter (here it is shorter than the time-step used) and the mean infiltration rate for the field is lower until steady state infiltration is reached. Correspondingly, a higher amount of runoff is generated, and it starts generating before mean time to ponding is reached. A similar bias can be seen in Fig. 2b. Here, rainfall is applied at a rate less than the mean K_s. Consequently, I_c is never reached in the homogeneous field, and surface runoff is not generated at all. For heterogeneous soil, however, surface runoff is generated in those parts of the field where K_s is low and I_c is less than I_p after an initial time to ponding. The spatially mean infiltration rate approaches a level lower than I_p.

The spatially averaged surface runoff presented must be regarded as a point generated potential value, i.e. the amount of surface runoff when no loss mechanisms are active. Under field conditions, however, surface runoff generated at any part of the hillslope contributes to the infiltrable water along the flow the path below in addition to rainfall. Thereby, surface runoff should be expected to be reduced in a field situation compared to what have been calculated, as an effect of flow from low-permeable segments of origin onto segments with higher I_c. Remaining runoff collects in a drainage network, and routing controls the time distribution downstream. Evaporation is an additional loss factor.

The algorithm is, moreover, very sensitive to applied time step. This is a problem well known in conceptual modeling and stems from the transition from the field's continuous processes to the model's discrete ones. Thus, model adaption to a field is to some extent time-step dependent.

The model has been tested for the two major rain events in 1989. Surface runoff in the field was collected and observed at the downstream end of the hillslope and is compared with the simulation results. Figures 3 and 4 show hourly rainfall and simulated point-generated surface runoff and observed runoff in corresponding periods for the two events. In line with the previous discussion, the simulated values are overestimations compared to downstream lumped surface runoff. On the other hand, our discretizing of the time-domain gives an opposite tendency. Rainfall intensity is a determining factor in the surface runoff calculation. When discretizing the time, this intensity evens out relative to

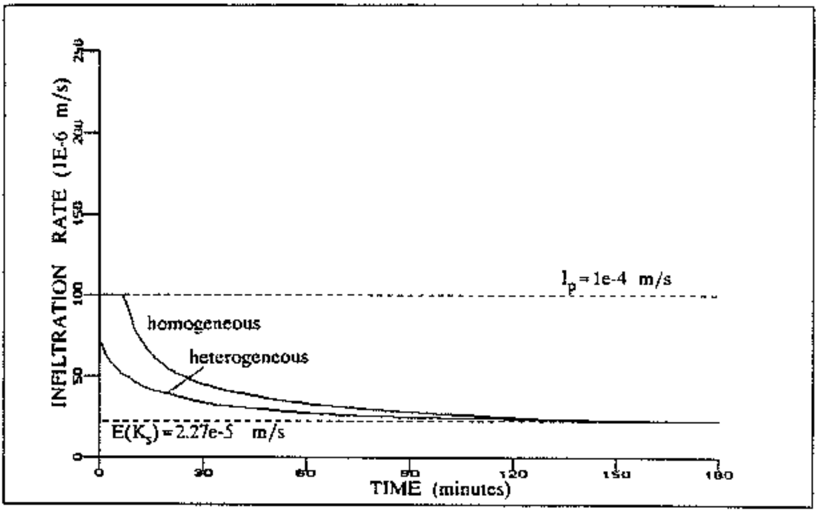

Figure 2a. Mean infiltration rate for a heterogeneous soil and infiltration rate for a homogeneous soil with K_s equal to the average K_s in the heterogeneous field during a rainfall of constant rate equal to 1e^{-4} m/s. Generated surface runoff is hatched. Average K_s is indicated.

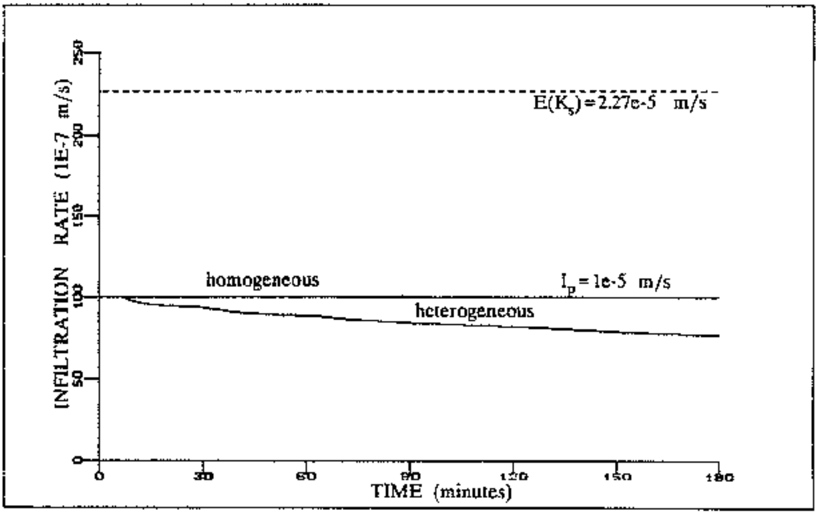

Figure 2a. Mean infiltration rate for a heterogeneous soil and infiltration rate for a homogeneous soil with K_s equal to the average K_s in the heterogeneous field during a rainfall of constant rate equal to 1e^{-5} m/s. Generated surface runoff is hatched. Average K_s is indicated.

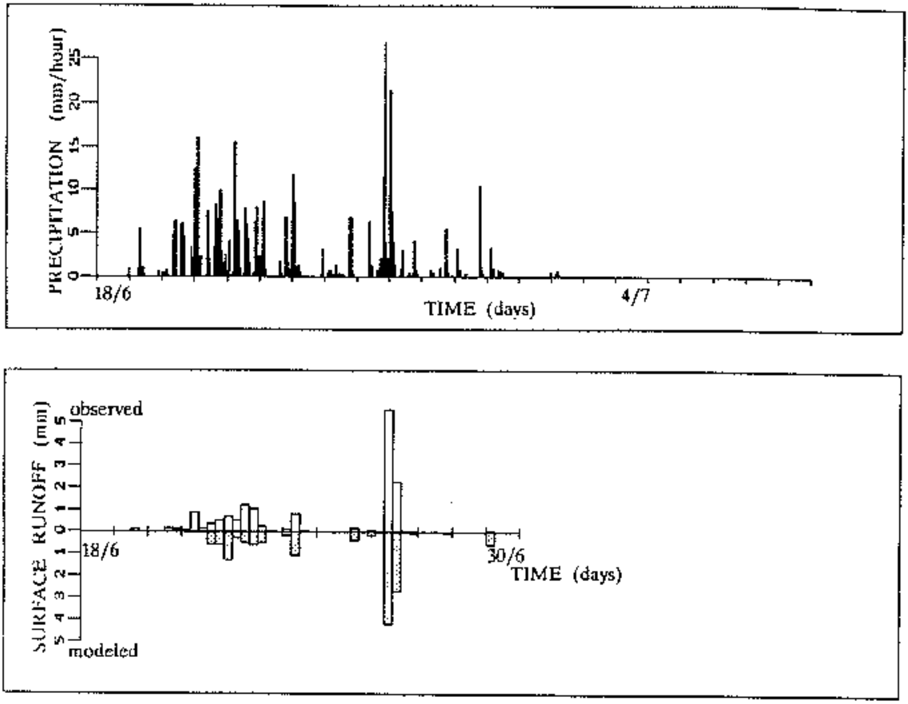

Figure 3. Hourly rainfall and predicted point-generated surface runoff compared to observed lumped surface runoff during an active monsoon period by the end of June 1989.

the continuous pattern with a marked underestimating effect on the surface runoff. However, our primary aim is to demonstrate the outlined conceptualization of surface runoff generation in a heterogeneous field and not to present an operative model, and the simulations must be regarded as preliminary estimates. As such, the model proves promising for further development.

CONCLUSIONS

We have studied some effects of spatially variability in K_s on infiltration and generation of surface runoff in a field where runoff is mainly generated by the Hortonian mechanism, i.e. as infiltration excess. The study is based on a number of infiltrometer tests and observations of surface runoff in an experimental field site and simulations by an

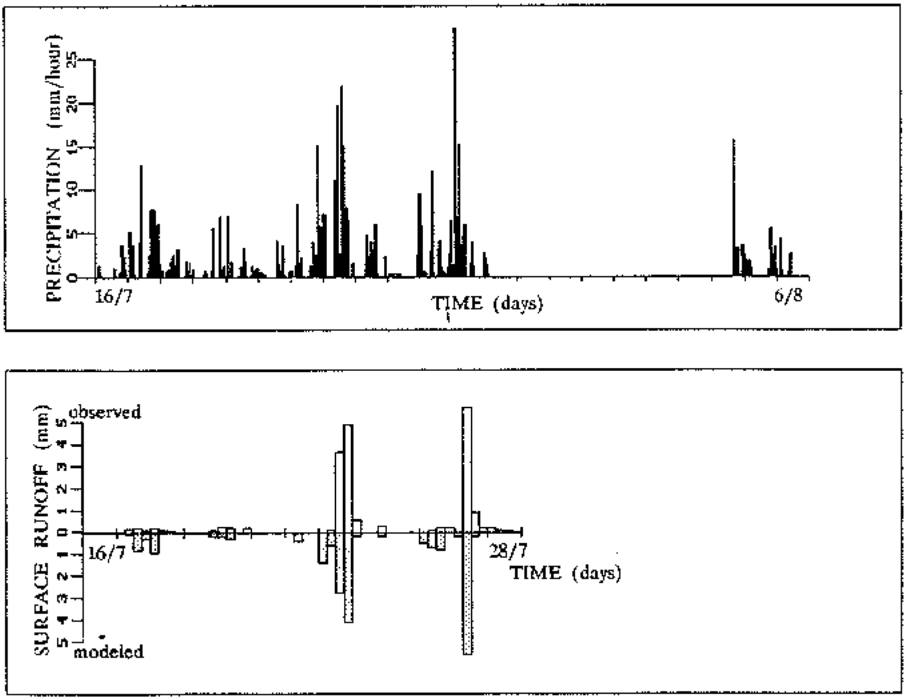

Figure 4. Hourly rainfall and predicted point-generated surface runoff compared to observed lumped surface runoff during an active monsoon period by the end of July 1989. Surface runoff simulations does not extend beyond 28th July.

approximate, stochastic model in the same site. The importance of soil physical variability for distributed field behaviour is demonstrated.

The infiltrometer tests show that variability in infiltration rates in the initial phase of infiltration is much higher than the variability in K_s.

A spatially variable field exhibits a bias in infiltration properties as compared to a homogeneous field with corresponding mean soil physical properties. Spatially averaged time to ponding is shorter, the averaged infiltration rate is lower and, correspondingly, the mean surface runoff is higher in a heterogeneous field. Moreover, contrary to the homogeneous situation, surface runoff may generate also when I_p is less than $E(K_s)$ in a heterogeneous field.

The model provides estimates of potential surface runoff. In a field situation, surface interaction will modify the tendencies described, and the bias shown should be expected to be reduced. Due to the lack of transport algorithm in the model, which follows the generated runoff from the spot of origin and down the drainage network, the simulated surface runoff presented in Figures 3 and 4 must be regarded as preliminary estimates. These results show good agreement with observed lumped runoff from the field, and thus prove that further development of the model is an interesting future problem.

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HYDROLOGISK MODELLERING AV EXTREMA FLÖDEN I SVERIGE

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SAMMANFATTNING

Hydrologiska modeller används idag för simulering av extrema flöden för dimensionering av dammar och utskov. Vid sådana beräkningar sker en extrapolation med modellen till flöden som är avsevärt större än de som använts vid kalibreringen. Denna artikel belyser denna problematik i samband extremflödessimulering med HBV modellen. Modellrutinen som beskriver flödesdynamiken (responsfunktionen) studeras. Metodiken är att kalibrera olika formuleringar av responsfunktionen över små till måttligt stora flöden och verifiera modellansatserna på stora observerade flöden. Vidare har modellerna använts för beräkning av ett dimensionerande höstflöde för att illustrera effekten av modellstruktur på beräkning av dimensionerande flöde. Det visas att HBV modellens responsfunktion kan bytas ut mot ett flertal alternativa formuleringar, med färre parametrar, utan att försämra simuleringen av extrema flöden. Däremot, är det svårt att från resultaten särskilja någon alternativ modellformulering som bättre än den ursprungliga HBV modellen.

ABSTRACT

Hydrological models are today used for simulating extreme floods in the purpose of designing dams and spillways. In doing so, an extrapolation beyond the floods of the calibration period is made. This paper addresses this problem in connection to the HBV hydrological model. The model component describing flood dynamics, the runoff-response function, is studied. The methodology has been to calibrate different runoff-response functions over small to moderately large floods and to verify the performance over independent periods containing large experienced floods. Furthermore, the different model versions were run with extreme rainfall in order to generate design floods. It was found that the five parameter response function of the original HBV model could be replaced by nonlinear functions including fewer parameters. However, it was difficult to select any response function formulation as superior when extreme floods larger than those of the calibration period were simulated.

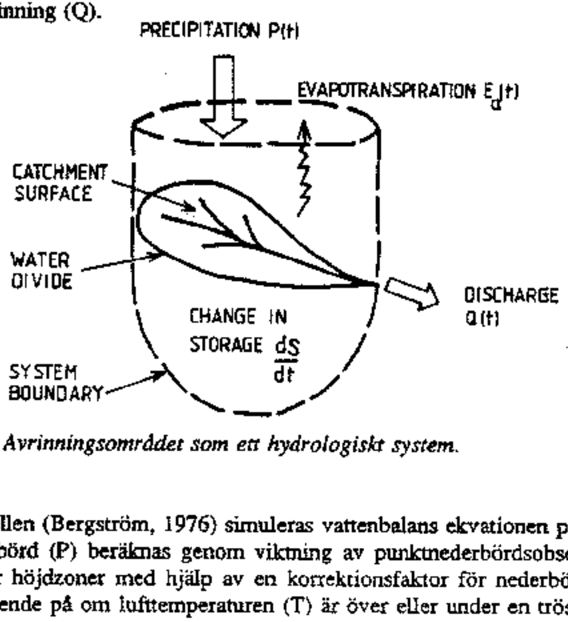
INTRODUKTION

Det hydrologiska kretsloppet är komplicerat och svårt att i detalj beskriva. Men genom att betrakta kretsloppet som ett slutet system kan det modelleras. Den grundläggande vattenbalansekvationen för en hydrologisk modell är :

$$Q(t) = P(t) - E_a(t) - \frac{dS}{dt} \qquad (1)$$

där Q = vattenföring,
P = nederbörd,
E_a = evapotranspiration,
S = magasinering i avrinningsområdet, och
t = tid.

Denna ekvation stämmer exakt under villkoret att allt grundvatten passerar ut ur systemet som avrinning (Q).



Figur 1. Avrinningsområdet som ett hydrologiskt system.

I HBV modellen (Bergström, 1976) simuleras vattenbalans ekvationen på följande vis. Areell nederbörd (P) beräknas genom viktning av punktnederbördsobservationer och fördelas över höjdzoner med hjälp av en korrektionsfaktor för nederbördens höjdberoende. Beroende på om lufttemperaturen (T) är över eller under en tröskeltemperatur (TT) faller nederbörden som regn eller snö.

Snötäcket (S_{sp}) är den första komponenten av den generella magasineringstermen (S). När temperaturen stiger över TT börjar snötäcket att smälta. Smältvatten (Q_m) lämnar dock snötäcket först efter att snöns vattenhållande förmåga mättats. Den vattenhållande förmågan sätts normalt till 10 % av snöns vattenekvivalent. Snösmältning och ackumulation beräknas med en graddagekvation.

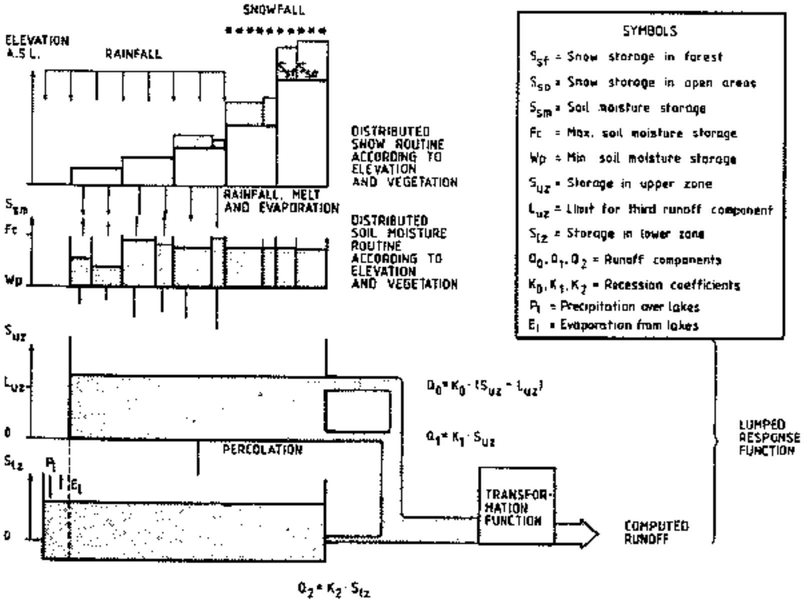
Den generella magasineringstermen (S) konstitueras även av markfuktigheten (S_{sm}).

Perkolation av överskottsvatten från marken (Q_s) beräknas genom ett samband mellan nederbörd och markfuktighet. Regn eller snösmältning genererar små bidrag av överskottsvatten från marken när denna är torr och stora bidrag när marken är blöt.

Evapotranspiration (E_a) beräknas som en funktion av markfuktigheten och den potentiella evapotranspirationen (E_p). När markfuktigheten överskrider ett tröskelvärde (Lp), kommer evapotranspirationen uppnå det potentiella värdet.

Snö och markfuktighets beräkning sker separat för varje höjdzon och vegetationstyp. däremot beräknas avrinningsbildningen gemensamt för alla höjd- och vegetationszoner med en gemensam responsfunktion. Denna beskrivs av två kar, Figur 2. Det undre karet är en linjär reservoar, med magasinet S_{lz}, och fylls från det övre karet med PERC (mm/dygn). Det undre karet simulerar även nederbörd (P_l) och avdunstning (E_l) från öppna vattenytor i området. Det övre karet, med magasinet S_{uz}, simulerar flöden och har två recessionskomponenter separerade av ett tröskel värde. Magasinering av vatten i reponsfunktionen är den tredje delkomponenten av den generella magasineringstermen (S), Ekvation 1. Den totala magasineringen blir således: $S = S_{sp} + S_{sm} + S_{uz} + S_{lz}$.

Genom att simulera det hydrologiska kretsloppet som ett system på det beskrivna sättet är man tvungen att kalibrera modellparametrarna genom att jämföra modellens utdata (simulerad vattenföring) mot observerad vattenföring. Bergström (1991) föreslår att datamängden delas i två delar, en del för kalibrering och en del för verifiering av modelprestanda. Om denna metodik upprepas för ett antal områden erhålls ett bra mått på modellens förmåga att simulera avrinningsprocessen.



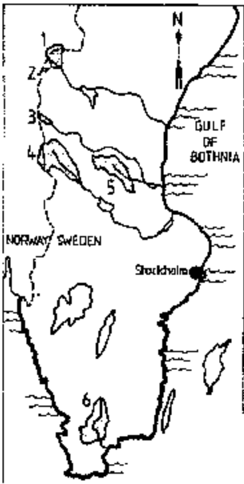
Figur 2. Schematisk figur av HBV modellens grundstruktur.

Hydrologiska modeller används numera inte enbart för att simulera avrinning utan även för att förlänga avrinningsserier, fylla i luckor av saknade värden, för studier av tänkta förändringar i klimatet och för att simulera extrema flöden i syfte att dimensionera dammar och utskov. Sådana tillämpningar går ej att verifiera mot observerad vattenföring. I Sverige pågår i dagsläget ett omfattade arbete med att beräkna dimensionerande flöden för dammar och utskov med HBV modellen. De simulerade flödena är betydligt större än de högsta observerade flödena som använts vid kalibreringen (Bergström et al., 1989). Följaktligen görs en extrapolation med HBV modellen och modellstrukturen och kalibreringen påverkar resultaten.

Syftet med denna artikel är att belysa recessionen av extrema flöden och studera HBV modellens responsfunktion. För att studera effekten av att extrapolera med modellen till större flöden än de som använts under kalibreringen har olika modellansatser kalibrerats på små till måttligt stora flöden och verifierats på stora observerade flöden. Vidare har modellerna använts för beräkning av ett dimensionerande höstflöde för att illustrera effekten av modellstruktur vid en dimensionerings beräkning.

STUDERADE OMRÅDEN

Sex avrinningsområden har studerats, se Figur 3.



CATCHMENT	(km²) AREA	RIVER
TORRÖN 1)	1370	INDALSALVEN
ÄCKLINGEN 2)	157	RUTSÄLVEN
LJUSNEDAL 3)	340	LJUSNAN
TRÄNGSLET 4)	4483	ÖSTERDALÄLVEN
ALFTA 5)	3140	VOXNAN
TORSEBRO 6)	3676	HELGEÅN

Figur 3. *Studerade avrinningsområden.*

Dessa områden representerar olika delar av Sverige och deras avrinningsserier innehåller några exceptionellt stora flöden. Äcklingen och Ljusnedal är relativt små och snabba områden. I dessa gjordes recessionsanalyser och utprovning av åtta olika modellansatser. Två alternativa responsfunktioner valdes för vidare studium i de vattenkraftutbyggda områdena Torrön, Trängslet and Torsebro samt vid Alfta. För avrinningsområdet till Alfta används HBV modellen för flödesvarning.

RECESSIONSANALYS

Recessionen av ett flöde är en funktion av magasineringen och magasineringsförändringen i avrinningsområdet efter det att snösmältningen eller regnet upphör. Recessions förloppet beskrivs av:

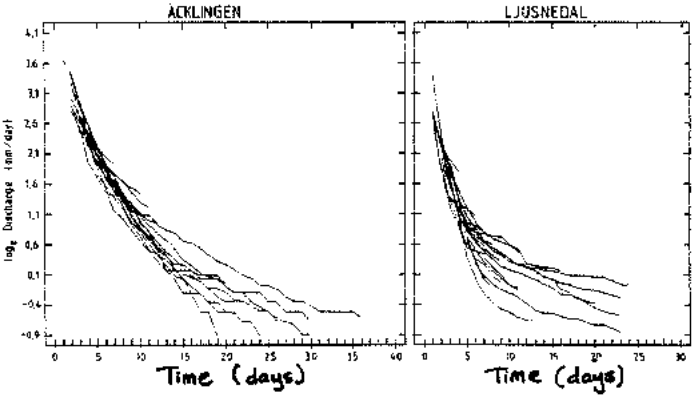
$$Q_t = Q_0 \, e^{-K \cdot t} \tag{2}$$

där Q_t = vattenföringen vid tiden t,
Q_0 = vattenföringen då t = 0, och
K = recession koefficienten.

Om Ekvation 2 logaritmeras fås:

$$\ln Q_t = \ln Q_0 - Kt \tag{3}$$

som kan plottas som en rät linje med gradienten -K i semilogaritmisk skala. Ekvation 2 kan härledas från ett linjärt förhållande mellan magasinering och utströmning, dvs. en linjär reservoar. HBV modellens nedre kar beskrivs av en linjär reservoar. En linjär reservoar formulering används däremot inte för att simulera flödesförlopp eftersom K sällan är konstant under en flödesrecession. Figur 4 visar recessioner av regnflöden vid Äcklingen och Ljusnedal, plottade i semilogaritmisk skala. Det framgår tydligt från denna figur att recessionshastigheten ökar med flödet. I HBV modellen simuleras denna ökning i recession genom det övre karet med två recessionskomponenter.



Figur 4. Recessioner för regnflöden vid Äcklingen och Ljusnedal.

VAL AV ALTERNATIVA RESPONSFUNKTIONER

Av de åtta utprovade responsfunktionerna vid Äcklingen och Ljusnedal valdes två stycken för jämförelse med den ursprungliga HBV modellen. Dessa kallas i det följande för "E-boxen" och "Ln-boxen". E-boxen innehåller två kar, där utströmningen ur det övre karet beskrivs av:

$$Q_u(t) = e^{K_1 \cdot S_{uz}(t)} - 1 \qquad (4)$$

där: Q_u = avrinning från det övre karet,
K_1 = recession koefficient,
S_{uz} = magasinering i det övre karet, och
t = tid.

Från det övre karet perkolerar vatten enligt PERC till ett undre kar, som är identiskt med det undre karet i HBV modellen. Dess ekvation är:

$$Q_l(t) = K_2 \cdot S_{lz}(t) \qquad (5)$$

där: Q_l = avrinning från det undre karet,
K_2 = recession koefficient, och
S_{lz} = magasinering i det undre karet.

E-boxen har således tre parametrar: K_1, K_2 och PERC.

Den andra responsfunktionen som valdes (Ln-boxen) beskrivs av ett kar, en icke-linjär reservoar. Denna funktion är en variant på den responsfunktion som presenterades av Lindström et al. (1990) och har endast två parametrar, enligt:

$$Q(t) = K_1 \cdot S(t)^{(1 + K_2 \cdot \ln S(t))} \qquad (6)$$

där: Q = avrinning,
K_1, K_2 = recession koefficienter, och
S = magasinering i karet.

Tabell 2, visar modellprestanda för HBV, E-boxen och Ln-boxen som R^2 värden (Nash and Sutcliffe, 1970). Alla tre modellformuleringar kördes med HBV modellens snö- och markrutiner och kalibrerades automatiskt med POC metoden (Harlin, 1991).

Tabell 2. *Modellprestanda, uttryckt som R^2 värden (%), för HBV modellen och de två alternativa modellansatserna.*

	Äcklingen		Ljúsnedal	
	Kal.	Ver.	Kal.	Ver.
HBV	87.3	86.7	80.7	86.4
E-box	87.0	86.2	79.4	83.6
Ln-box	86.6	86.0	78.5	79.9

Kal. = Kalibrerings period (1971-08-01 -- 1981-07-31)
Ver. = Verifierings period (1981-08-01 -- 1989-07-31)

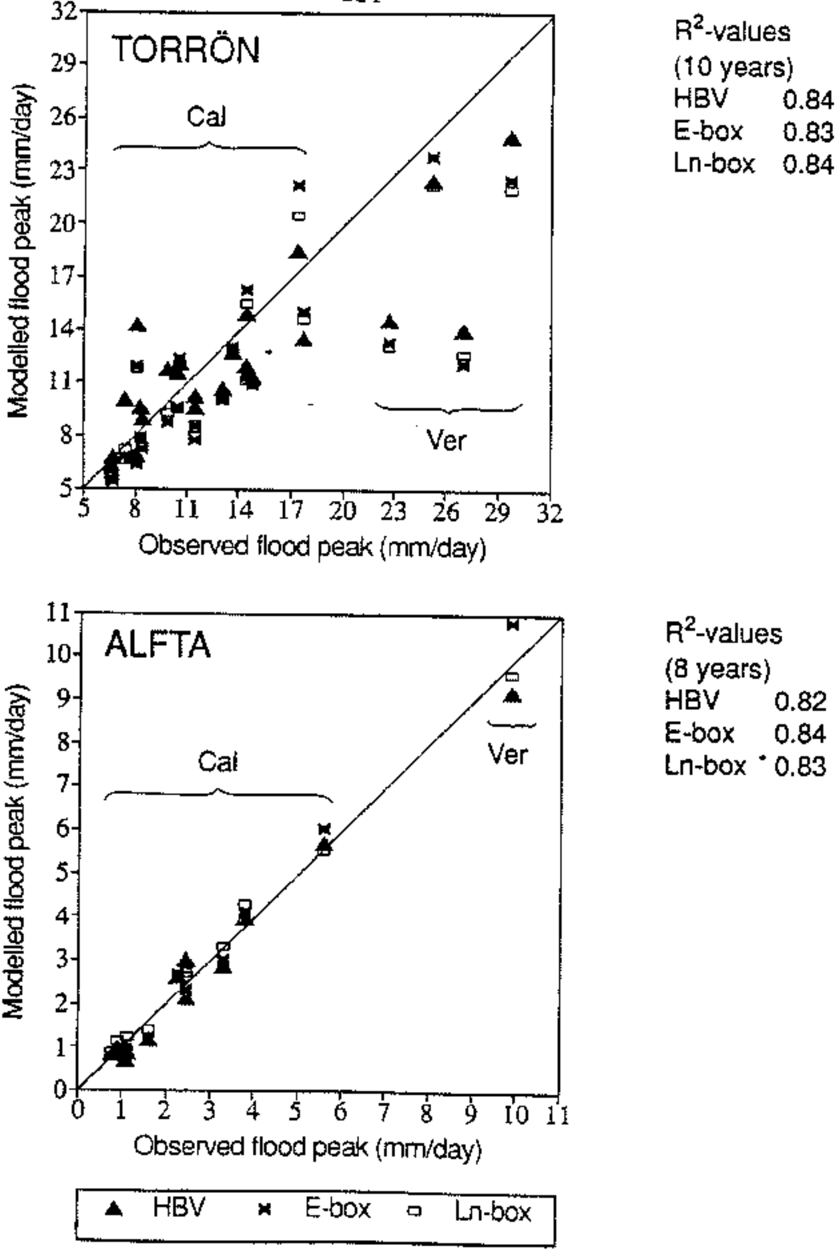
SIMULERING AV EXTREMA FLÖDEN

För att studera hur väl de olika modellansatserna kunde simulera större flöden än de som använts vid kalibreringen, kalibrerades de över små till måttligt stora regn flöden och verifierades över stora observerade regn flöden. Resultaten visas i Figurerna 5 och 6. Anledningen till att endast studera regnflöden var att undvika effekten av fel i snösimuleringen och därigenom få en bättre bild av hur responsfunktionen betedde sig. Noteras kan att verifieringsflödet för Alfta (Figur 5) är den kända höstflödessituationen i Dalarna och Hälsingland 1985. Det var under denna flödesperiod som damraset i Noppikoski inträffade.

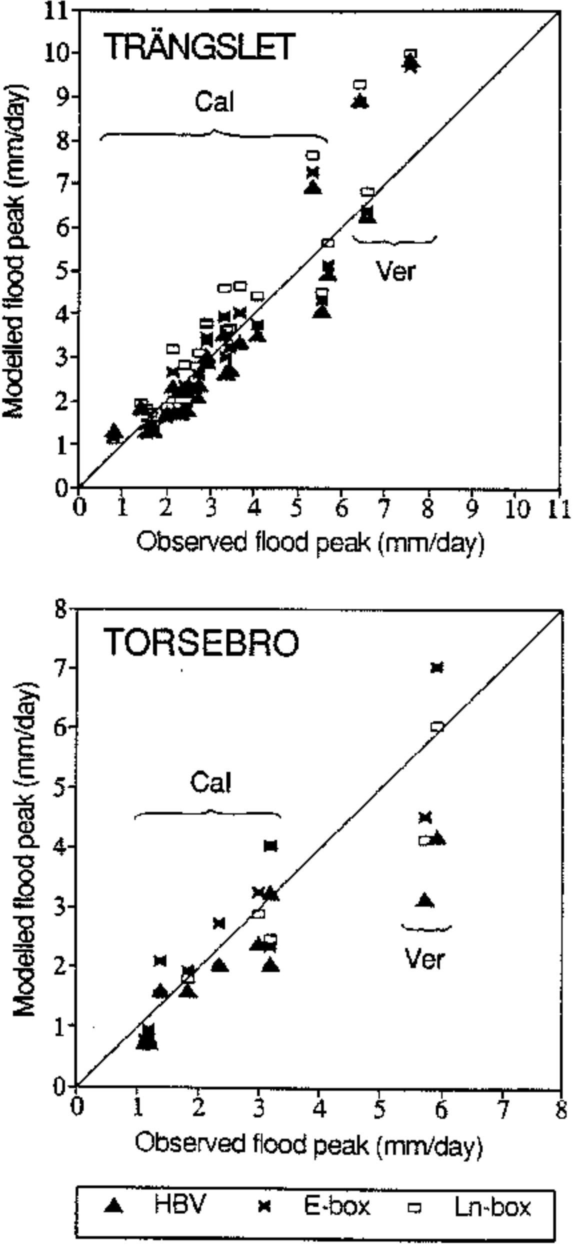
För att illustrera effekten av modellstruktur på simulering av dimensionerande flöden kalibrerades modellerna över de största regnflödena och sedan simulerades det mest kritiska höstflödet enligt de Svenska riktlinjerna för dimensionerande flödesberäkning (Flödeskommittén, 1990). De resulterande maxflödena redovisas i Tabell 3.

Tabell 3. *Simulering av de mest kritiska höstflödena i en dimensioneringsberäkning med HBV modell och de två alternativa modellansatserna. Tabellen redovisar resulterande maxflöden i (mm/dygn). Intervallet har beräknats med avseende på medelvärdet av det högsta och lägsta värdet.*

	Torrön (1983-10-16)	Alfta (1985-09-24)	Trängslet (1985-08-18)	Torsebro (1988-08-16)
HBV	63.3	14.2	19.6	10.1
E-box	113.1	18.5	31.8	14.3
Ln-box	91.5	16.6	25.1	13.0
Intervall	± 28 %	± 13 %	± 24 %	+- 17 %



Figur 5. *Modellprestanda för de olika modellansatserna vid simulering av extrema regnflöden i Torrön och Alfta. R^2 värden gäller endast kalibreringsperioden.*



R^2-values
(16 years)
HBV 0.91
E-box 0.90
Ln-box 0.86

R^2-values
(10 years)
HBV 0.91
E-box 0.87
Ln-box 0.90

Figur 6. *Modellprestanda för de olika modellansatserna vid simulering av extrema regnflöden i Trängslet och Torsebro. R^2 värden gäller endast kalibreringsperioden.*

DISKUSSION OCH SLUTSATSER

Det visade sig att responsfunktionen i HBV modellen kunde bytas ut mot ett stort antal alternativa formuleringar utan att radikalt förändra modellen prestanda. Vid formulering av alternativa responsfunktioner var avsikten att reducera antalet kalibreringsparametrar och erhålla responsfunktioner med kontinuerligt ökande recession med flöde. Men, HBV modellens responsfunktion var genomgående bättre vid simulering av basflödesperioder jämfört med de alternativa formuleringarna och var i regel enklare att kalibrera. Detta beror på att parametrarna i HBV modellens responsfunktion är relativt oberoende inbördes och effekten av att ändra en enskild parameter är lätt att se.

Resultaten av simuleringar av större flöden än de som använts vid kalibreringen gav ingen tydlig skillnad mellan de prövade modellansatserna. Det framgick att kvalitén på simuleringen över verifieringsperioden speglades av kvalitén under kalibreringsperioden. Oftast gav de olika modellformuleringarna inbördes lika resultat. Antingen underskattade samtliga ett verifieringsflöde eller så överskattade samtliga flödet. Därför härstammar felen i simuleringen inte enbart från denna modellkomponent utan även från fel i indata och i markfuktighetsrutinen. Ytterligare en källa till fel är att de extrema flödena som används vid verifieringen ofta är mycket större än de som använts vid beräkning av avbördningskurvan som ligger till grund för flödesmätningen.

Vid simulering av dimensionerande flöden gav E-boxen högsta flödesmaximum följt av Ln-boxen och HBV modellen. Detta beror på att vid simulering av så extrema flöden som de dimensionerande flödena domineras avrinningen av utströmning via den översta recessionsparametern i HBV modellen (K_0). För E-boxen och Ln-boxen ökar däremot recessionen kontinuerligt med flödet utan att begränsas av något tröskelvärde. Spridningen mellan modellerna vid en dimensioneringsberäkning var i storleksordningen plus/-minus 20 %. Resultaten av simuleringar av observerade extremflöden visade däremot inte att HBV modellen systematiskt underskattar extrema flöden. Därför bör HBV modellen vara lämplig för extremflödesberäkningar under förutsättning att modellparametrar kalibreras noggrant över de största observerade flödena.

Det är svårt att från denna studie dra någon slutsats om vilken modellformulering som ger den bästa simuleringen av flöden i storleksordning som de Svenska dimensionerande flödena. Det finns helt enkelt inga observationer att jämföra med. Man kan föra olika teoretiska resonemang för att välja modellansats. Som exempel kan nämnas att det vid extrema flöden avrinner närmare markytan än vid normala flöden. Den hydrauliska konduktiviteten ökar kraftigt närmare markytan och därför bör även recessionsförloppet vara snabbare för extrema flöden än för normala flöden. Fortsatt forskning med modellutveckling för simulering av extrema flöden borde därför vara befogad.

SLUTORD

Detta projekt genomfördes i samarbete med Göran Lindström. Vattenregleringsföretagens Samarbetsorgan (VASO) har bidragit till projektets finansiering.

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REPRESENTATION OF HILLSLOPE HYDROLOGICAL PROCESSES USING DIGITAL ELEVATION DATA - A REVIEW

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ABSTRACT

In humid temperate climate net precipitation generally infiltrates undisturbed soils, migrate down-slope, and maintain saturation or near saturation in the discharge area in lower slope positions. The discharge area rapidly contribute subsurface and saturated overland flow to storm-flow as the zone of saturated soil expands. Hydrological and hydrochemical processes are affected by the spatial variability of soils, topography, land use and cover, climate and human-induces changes. To model flow paths, detention times and hydrochemical transformations, a distributed hydrological model is hence the logical base. As flow paths is largely determined by topography, elevation data is a way to generate accurate flow paths. For representation of hillslope contours there are three main computer based approaches: digitized contour data, triangulate irregular networks (TIN) and rectangular grids of points (raster). Contours are advantageous since maps present elevation data as contours. TINs are better suited for abrupt changing terrain. However, raster data is the most commonly used data for digital elevation models, largely because procedures are simple and unambiguous.

INTRODUCTION

Water is one of the most essential requisites for life. Water is also the most important link in most biogeochemical cycles, acting as a solvent for both natural and anthropogenic substances (Stumm, 1986). The greatest change brought about in the hydrological cycle and other biogeochemical cycles due to mans activity can be traced back to changes in the watershed (Ripl, 1991). A common feature of those changes is the opening up of cyclic processes. The outflow of substances from the watershed to the sea has increased several-fold due to mans activity (*op.cit.*). The resulting increase of entropy (disorder) on land is the cause of several serious environmental problems; acidification of land and water (SNV, 1991), eutrophication of lakes, rivers and even the sea (SNV, 1988; Ryding and Rast, 1989), global climate change (Houghton *et al.*, 1990; Gumbricht, 1992a). Hence the solution of those problems are to be found in the watershed, once again creating cyclic processes, minimizing losses to the sea. A starting point is to adequately understand and represent the watershed hydrological and hydrochemical function.

AIM AND SCOPE OF THE STUDY

The study has been conducted for the scope of chosing a proper approach for understanding and modelling watershed hydrological processes and connected environmental problems in temperate, humid climate. Emphasis is put on eutrophication and acidification. The following requisites were set up for the approach to be chosen:

* physically sound representation of flow paths and detention times
* possible to model in GIS environment
* able to rely on available data
* possible to integrate with remotely sensed data for calibration and verification (water-quality and soil moisture)

RUNOFF GENERATION HYPOTHESIS

The traditional view is that the hydrograph consists of a base flow (i.e. groundwater outflow) and a storm flow part, generated by some overland flow. The original hypothesis behind this view is that the infiltration capacity regularly is exceeded during rainfall (Horton, 1933; 1945). An alternative, more dynamic view, was suggested already in 1934 by Lowdermilk, who suggested that only minor parts of the drainage basin contributed to overland flow. This was further emphasized by Hoover and Hursh (1943) suggesting subsurface storm-flow as a major contributor to storm runoff.

Starting with the hortonian concept Betson (1964), developed a concept known as the *partial or contributing area concept*. Betson's original concept assumed that the horton mechanism was the cause of saturation. Later development (Ragan, 1968; Freeze, 1972a;b; 1974; Dunne and Black, 1970a;b; 1971; Dunne, 1983) made it clear that the partial areas more often are wetlands whose location is controlled by the topographic and hydrogeological configurations in the basin. Dunne and Black (1970a;b; 1971) also hypothesized that the contributing area could contract or expand due to groundwater and soil-moisture conditions, a hypothesis known as the *variable source area - overland flow concept.*

Dunne and Black (1970a;b) showed that the contributing areas mainly consisted of concave slopes, whereas convex slopes were dominated by subsurface-flow, and also could dominate the recession limb of the storm hydrograph. They also found that macropores could play a substantial part. This view was confirmed by Freeze (1972a;b) who also dressed the hillslope runoff processes in an elaborate mathematical dress. However, Engman (1981) and Bernier (1982) could show that subsurface flow was a much more important factor in runoff generation in the studies conducted by Dunne and Black (1970a;b) than the original study had revealed. Thus they raised the question about the dominance of saturated overland flow in hydrographs from undisturbed lands. However, already in the 1960s Hewlett and coworkers (Hewlett and Hibbert, 1963) discussed what is known as the *variable source area - subsurface storm flow concept.* The variable source area is assumed to be connected to the stream, and apart from generating surface flow, also mediating subsurface storm flow from the upper part of the hillslope (translatory flow). This view is similar to the general picture of runoff generation that has emerged in Sweden since the 1960s (Gustafsson, 1968; Rodhe, 1987). The central percept of this theory is that input generally infiltrates undisturbed forest soils, migrates down-slope, and maintains saturation or near saturation at lower slope positions. These lower slope positions rapidly contribute subsurface flow to storm-flow as the zone of saturated soil expands. The degree to which saturation and subsequent lateral expansion would occur, for a given slope, varies as a function of antecedent soil-moisture conditions, precipitation volume, and duration of input (Troendle, 1985; Rodhe, 1987). Flow in this concept is concentrated to the surface soil with higher conductivity (Lundin, 1982; Grip and Rodhe, 1985; Johansson, 1987; Rodhe, 1987; Espeby, 1989).

The catchment response to input in this hypothesis is perhaps best dissected and analysed from the three building blocks - the convex, the concave, and the uniform slope segment (Grip and Rodhe, 1985; Troendle, 1985). The concave slope giving rise to much faster response than the convex, with the uniform in between. Those blocks also largely determines the extension of recharge and discharge areas along the hillslope, and hence also partly defines the catchments different hydrochemical functional units (Eriksson, 1985); the biomass, the soil surface, the rootzone, the unsaturated (vadose) zone, the saturated zone.

Much of the research indicating groundwater as a significant factor in the generation of storm and snowmelt runoff divide the discharge into event and pre-event derived water using environmental isotopes as tracers (Dincer *et al.*, 1970; Martinec, 1975; Fritz *et al.*, 1976; Sklash and Farvolden, 1979; Rodhe, 1987). The research leading to this concept was thus conducted in the stream in contrast with hillslope research that led to the hortonian theory. Elaborate reviews of studies of hillslope hydrology can be found in Dunne (1978) and Troendle (1985).

HILLSLOPE HYDROLOGICAL MODELLING

The agreement between a hydrological model and real flowpattern depends on a physically correct specification of flowpaths and detention times through the different compartments of the catchment. The physical soundness becomes extremely important if hydrochemical processes shall be linked to the hydrological model (Bergström and Lindström, 1989; Vieux, 1991). It is also important to choose a concept that is adequate for the problem under study. For watershed studies, hillslope hydrology probably is the most adequate scale (Kirkby, 1988).

Continuous simulation conceptual models, based on a soil-moisture accounting routine as central percept, represent the present state of development of lumped parameter models. Examples of such models are thé Sacramento model (Burnash *et al.*, 1973), used by the U.S. National Weather Service, the Swedish HBV-model (Brandt, 1990), used by the Swedish Meterological and Hydrological Institute and the Soil Moisture Accounting and Routing model (SMAR) (O'Connel et al., 1970; Gallagher, 1986; Kachroo, 1988). The latter model was developed as an alternative to the more elaborate conceptual models, and has also been further developed at the Institute of Hydrology (Wallingford, U.K.) (Blackie and Eeles, 1985). These models demands calibration and optimization of their parameter sets, which means a loss of their physical interpretation. Further, the available data can hardly carry more than 3 to 4 parameters (Betson and Ardis, 1978; Mein and Brown, 1978). Even in the SMAR model, only using 4 to 5 parameters, 2 or 3 can be fixed and only 2 or 3 optimized, without loss of prediction power (Gallagher, 1986; Kachroo, 1988). In a recent published study, Gan and Burges (1990a;b) showed that the Sacramento model even was not able to describe runoff in an idealised hillslope in a physically correct manner. They concluded that models having similar structure were unsuitable for the needs of exploring catchment scale phenomena.

During the last decade models regarding spatial distribution of governing parameters have evolved (Beven, 1985, Abbot *et al.*, 1986a;b). This kind of model has also recently been used together with hydrochemical models (Storm *et al.*, 1991). However, those models contain the same problems as the lumped models, but at a subgrid scale (Beven, 1989). To partly come around this problem a distributed model must not only consider spatial variability correctly, but also be validated against distributed measurements (Beven, 1989; Vieux, 1991). A possible way to go is to use remotely sensed data with spatial resolution and coverage in agreement with the chosen grid-scale (Ottle *et al.*, 1989; Schultz, 1989)

An alternative approach is to describe the hillslope as a two-dimensional flow profile with regard to saturated and unsaturated flow (Bernier, 1982; Troendle, 1985). A concept stemming from the variable source area concept. The basin is divided into segments that allow the elimination of one of the horizontal components. Each segment is then divided into increments. A number of increments *(I)* and soil layers *(J)* within each increment combined with the three-dimensional description of the segment generate the individual volumes of *(I,J)* soil elements. Flow is simulated using the Darcy equation, modified by Richards (1931) and represented as:

$$q = -K(\Psi)\Delta H$$

where q is moisture flux or flow unit per unit cross-sectional area, $K(\Psi)$ is the hydraulic conductivity of soil as a function of the matric or suction potential and ΔH is the hydraulic gradient or driving force caused by the sum of matric (Ψ) and gravity (z) heads. Combining the Richards equation with the continuity equation, the general equation of flow through an element becomes:

$$\frac{d\theta}{dt} = \Delta(K(\psi)\Delta H)$$

where θ is moisture content as a fraction by volume per unit volume of soil and t is time. Expanded to account for flow in three dimensions the flow equation is generally shown as:

$$\frac{\partial \theta}{\partial t} = -\frac{\partial}{\partial x}\left(K\frac{\partial \psi}{\partial x}\right) - \frac{\partial}{\partial y}\left(K\frac{\partial \psi}{\partial y}\right) - \frac{\partial}{\partial z}\left(K\frac{\partial \psi}{\partial z}\right) + \frac{\partial K}{\partial z}$$

The model simulates flow between the segments and water content in the segments solving this equation for the x and z components, y being eliminated through the segmentation, using time steps in the order of minutes (Bernier, 1982; Troendle, 1985).

In a simplified version of the original model, TOPMODEL (Beven and Kirkby, 1979; Quinn *et al.*, 1991), empirically derived topography and soil characteristics governs water content and extension of the saturated zone. The model is based on the simple assumptions that flow can be adequately represented by a succession of steady-state water table positions, and that there is an exponential relationship between water table level and down-slope flow rate (Quinn *et al.*, 1991).

Flow pathways are generated using digital elevation data applying the index $\ln(a/\tan\beta)$, where a is the quota of upslope area A divided by the contour length (L) orthogonal to the flow direction, and $\tan\beta$ is a reflection of the tendency for gravitational forces to move water down-slope. If spatial data is available $\tan\beta$ can be non-uniformely modelled.

Also one-dimensional models, solemnly based on the Richards equation, are frequently being used for simulation of vertical flow (Jansson and Halldin, 1980; Espeby, 1989). Simulation of flux of dissolved substances is usually done by coupling of a convection-dispersion model (van Genuchten, 1991; Hansen *et al.*, 1991). However, the assumption of homogeneity in both the soil and the fluid is crucial and far reaching. And in a complex catchment environment this approach is probably less encouraging.

BIOGEOCHEMICAL LOSSES FROM THE WATERSHED

Processes governing losses of different substances from a watershed differ depending on the substance under consideration. Phosphorus is not very mobile in soil, it is readily immobilized by adsorption and precipitation reactions with aluminium, iron, manganese, calcium and clay minerals (Lindsey, 1979; Pionke and Urban, 1985; Gumbricht, 1991). Thus many studies show that phosphorus losses correlate with erosion rates and surface runoff (Maas *et al.*, 1985; Andersson, 1986; Pionke *et al.*, 1988).

Nitrogen, in the form of nitrate, acts more as a conservative tracer, following the flowpath of water through the hillslope (Wellings and Bell, 1980; Pionke and Urban, 1985). Nitrogen, however, participate in many reactions when travelling through the landscape (Gumbricht, 1991), and is removed from the soil-water sphere by biological and biochemical processes, i.e. ammonification, assimilation and denitrification. In fine textured, organic soils nitrate is almost completely denitrified (Andersson, 1986), whereas in coarse soils it travels more or less unaffected. Another important source for denitrification seems to be the discharge area, especially when organic material is present at the soil surface (Cooke and Cooper, 1989; Slater and Capone, 1987). Again this points at the crucial importance of correct understanding and modelling of flowpaths and detention times.

Also the processes of acidification in soil and its connection to water is well known (Sverdrup and Warfinge, 1991; Sverdrup and Sandén, 1991). Again it is mainly detention time and flow paths that determines the sequence of acidification, given a certain environment (i.e. soil composition and texture, slope, vegetation etc).

USING GIS TO OUTLINE HILLSLOPE HYDROLOGY

Geographical Information Systems (GIS) are computer based tools for capturing, storing, manipulating, analyzing and displaying geographical data (Burrough, 1986). As discussed above, for catchments dominated with near surface or surface flow, topography might serve as a useful basis for modelling the spatial variability in both flow pathways and detention times. This has also been done for both distributed kinematic overland flow models (Smith and Woolhiser, 1971; Ross *et al.*, 1979) as well as for kinematic subsurface flow models (Beven and Kirkby, 1979; Beven, 1982; Quinn *et al.*, 1990).

For representation of hillslope contours there are three main computer based approaches: rectangular grids of points (raster), triangulated irregular networks (TIN), and digitized contour data (Mark, 1979; Moore *et al.*, 1991). The best approach depends on the specific use of the terrain model, the available data, and the hardware and software platform (Carter, 1988; Moore *et al.*, 1991).

Contours are characteristic vector data, and is in the form in which slopes are commonly represented on traditional maps. TIN data is the way land surveyors traditionally measure and calculate terrain data, it is also advantageous when slope change irregular as in urban areas (Djokic and Maidment, 1991). Raster data, however, seems to be the most favoured form of representing elevation in hydrological modelling (Hutchinson and Dowling, 1991; Moore *et al.*, 1991; Jenson, 1991; van Deursen and Kwadijk 1990; Quinn *et al.*, 1991): The reason for this primarily being that procedures are simple and unambiguous.

For raster data structures procedures for depression filling, flow direction determination, flow accumulation, watershed and subwatershed delineation and drainage network definition have been presented by several authors (Mark, 1982; O'Callaghan and Mark, 1984; Band, 1986; Jenson and Trautwein, 1987; Jenson and Domingue, 1988; Morris and Heerdegren, 1988; Hutchinson, 1989; Tarboton *et al.*, 1991; Quinn *et al.*, 1991). Bork and Rohdeburg (1986) and Heerdegren and Beran (1982) present a variety of parameters that can be derived from raster data and relate them to hydrological applications. Speight (1974; 1980) describes about 20 both primary and secondary topographic attributes that can be used to characterize the landscape, of which several are relevant for hydrological and hydrochemical modelling in GIS (Moore *et al.*, 1991)

Flow pathways can also be derived directly from contour data (O'Loughlin, 1986; Moore *et al.*, 1988) or from TIN data (Palacois-Velex and Renaud, 1986; Gandoy-Bernasconi and Palacois-Velex, 1990; Vieux, 1991).

DISCUSSION AND CONCLUSION

For representation of hillslope hydrology for the purpose of coupling related environmental problems, obviously traditional lumped conceptual models are not accurate enough. Physically distributed models also seems difficult to use. This leaves the variable source area - groundwater flow concept models, that represent the watershed as hillslopes as the most advantageous approach. In the original concept this concept is physically based (Troendle, 1985), whereas the simplified version (TOPMODEL) uses empirically derived relations for generating flow paths (Quinn *et al.*, 1991). The consequences of relaxing the criteria of physical soundness in this way must be further investigated.

Spatial data in GISs can be represented either as raster (grid) or vector structures. Both structures have advantages and disadvantages (Burrough, 1986). The vector system is better fitted to the true shape of the data, but simulation is tedious since each unit has a unique shape. Analysing natural resources over extended areas, using raster structures facilitates overlay techniques and simulations. If remotely sensed data is used, this data is represented in raster form. And a possible way to overcome the problem of calibration and validation for a distributed model is to use remotely sensed data. Several hydrologically adopted algorithms already exist for raster data, and raster based GISs have been applied for hydrological modelling in catchments of different scales (van Deursen and Kwadijk, 1990; Hutchinsson and Dowling, 1991; Quinn *et al.*, 1991). Hence it is concluded that a raster based GIS is more convenient to use for watershed hydrological modelling. Also, most available input data is in the form of raster, and converting vector to raster data is much easier than the vice versa.

Without using a hydrological model as a starting point, GIS is used as a tool for evaluating soil acidification and targeting critical areas of nonpoint sources of nitrogen and phosphorus, as part of the education at the Department of Land and Water Resources, Royal Inst. of Technology (Gumbricht, 1992b;c). Critical load of soil acidification is modelled using soil mineralogical composition and texture, landuse, slope and precipitation as input (see Nordic Council of Ministers, 1988). Actual load is computed using models for both local and regional sources of emissions, partly based on the GIS. Critical areas for phosphorus and nitrogen leakage are targeted using modified versions of USLE (Wischmeier and Smith, 1978), and is similar to the approach used by Reinelt (1989). The GIS that has been used is GRASS (the Geographic Resource Analysis Support System), developed by the U.S. Corps of Engineers, a raster based system.

The results have been encouraging. The next step thus will consist of implementation of a hydrological model and then a marriage between hydrological and hydrochemical models as outlined in this article (also see Vieux, 1991).

In a first effort to use elevation data for analyzing drainage networks, watershed delineation, flow paths etc using available routines in GRASS (Band, 1986; Shapiro and Westerfelt, 1991) it became clear that the available elevation data carried errors. New data from the Swedish national elevation database is presently being captured. This data is raster based with 50-meter grid scale. Quinn *et al* (1991) discusses grid-resolution of 50 vs 12.5 meters and concludes that the former might be to coarse, even in larger catchments. Merlin and Andersson (1992) found that 25 meter grids gave more accurate determination of flow paths than larger grids.

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MÅLT OG SIMULERT AVRENNING FRA LANGTIDSNEDBØR OG SNØSMELTING. STUDIEOMRÅDE: RISVOLLAN I TRONDHEIM.

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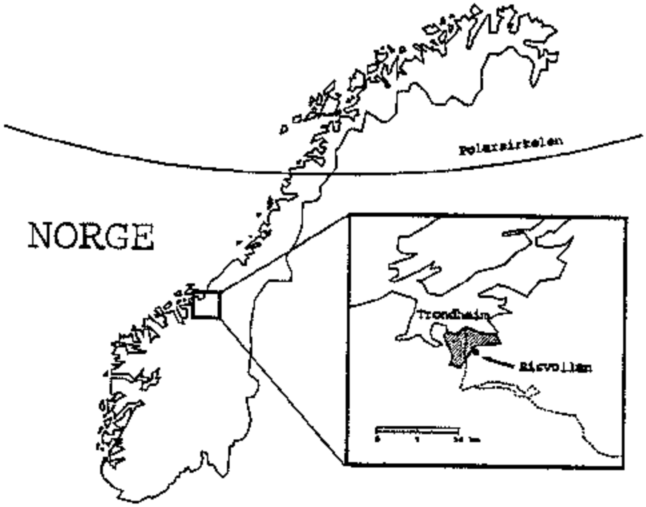
ABSTRACT

In Norway there is a significant increase in problems caused by floods in urbanized areas during the period, September - May. The paper deals with analysis of the stormwater runoff in the experimental urban hydrological catchment Risvollan (20.1 ha) in Trondheim during the winter season. Max. peak and volume flows from autumn and winter frontal rains (longterm rains), are often concurrent with snowmelt on saturated or frozen ground. Snow is a climatic parameter of particular concern in Norway. Due to generally unstable weather conditions, especially in the coastal areas, the snowcover does not stay very long. Therefore, snowmelt may occur several times during the winter period. The main problem in analyzing and modelling the winter runoff situations has been the lack of reliable and relevant hydrological data and observations from smal urbaniced areas. There is still a need for long time series of hydrological data with good reliability, high time resolution and a good time synchronisation (Thorolfsson 1990).

INNLEDNING

Dagens dimensjoneringskriterier for urbane områder bygger fortsatt på forutsetningen om at kraftige sommerregn er dimensjonerende for overvannsnettet. Imidlertid har vi i store deler av Norge klimatiske forhold som tilsier at langvarig regn eller kombinasjonen av regn og snøsmelting kan gi maksimal avrenning (Thorolfsson og Killingtveit 1991). Uten lange serier med pålitelige urbanhydrologiske observasjoner over hele året vil det være vanskelig, for ikke å si umulig, å finne størrelsene på disse avrenningene. Med et ønske om å styrke det urbanhydrologiske kunnskapsnivået og å få bygd opp en pålitelig urbanhydrologisk databank i Trondheims-regionen, ble det i 1985 besluttet å etablere et nytt urbanhydrologisk felt på

Risvollan i Trondheim, se figur 1. Kontinuerlige registreringer var i gang i juni 1986.



Figur 1. Lokalisering av Risvollan (Høgeli 1991).

Risvollan målestasjon har en god basisintrumentering, se tabell 1. Det foretas registreringer med stor tidsoppløsning (hvert 2. minutt) over hele året (Thorolfsson og Høgeli 1992).

Tabell 1. Parametre som bli observert hvert 2. minutt.

Parameter	Enhet	Merknad
Korttidsnedbør	l/sha	Hele året
Overvannsavrenning	l/s	Hele året
Spillvannsavrenning	l/s	Hele året
Lufttemperatur	°C	2000 mm over bakken
Snøsmelting	mm	Om vinteren
Bakketemperatur	°C	200 mm under bakken
Relativ luftfuktighet	%	Hele året
Total innstråling	mW/cm²	Hele året
Vindhastighet	m/s	Hele året

Med de urbanhydrologiske dataene som blir registrert på Risvollan har vi nå et grunnlag for å teste og videreutvikle avrenningsmodeller bl.a. for avrenningen fra langtidsnedbør og regn kombinert med snøsmelting. I forbindelse med prosjektet: Flom ved langvarig regn og snøsmelting i små urbane felt i kystsonen, er de to urbane avrenningsmodellene, NIVANETT og MOUSE, testet. I løpet av prosjektperioden ble NIVANETT utvidet slik at den nå kan simulere opp til 12000 minutters regn (200 timer). Dette var nødvendig da den gamle versjonen hadde en begrensning, maksimalt 1000 minutter regn (16,7 timer). Resultatene viste at ingen av modellene gir en akseptabel simulering av etteravrenningen (sekundæravrenningen) sammenlignet med observerte data.

Hverken NIVANETT eller MOUSE er laget for å simulere avrenningen fra snøsmeltingen. Av den grunn er det av spesiell interesse å studere snøsmeltingen i et forsøk på å finne en hensiktsmessig simuleringsmetode som kan kobles til en urban avrenningsmodell.
I prosjektet ble fire versjoner av temperatur-indeks modellen testet. Disse ga et relativt bra samsvar mellom de simulerte og observerte data. Forsøkene viser dessuten at simulert snøsmelting blir bedre jo mer kompleks simuleringsmodellen blir.

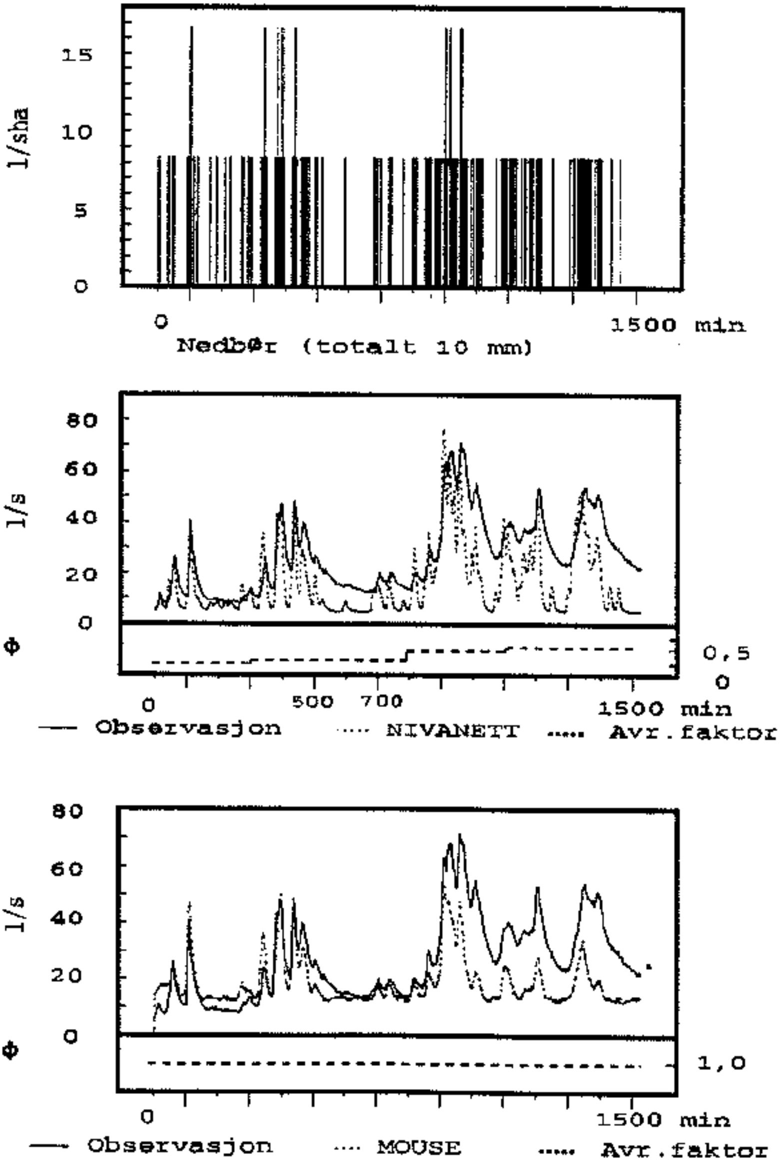
NAVF, Norges Hydrologiske Komite (NHK) og Trondheim kommune har gitt økonomisk støtte til prosjektet.

SIMULERING MED NIVANETT OG MOUSE

Høgeli (1991) kalibrerte NIVANETT og MOUSE for elleve regntilfeller i perioden mai-oktober, 1989. Et kalibrert regntilfelle fra 12. oktober 1989 er vist i figur 2. Resultatene viser at den simulerte avrenningen vha. NIVANETT modellen faller ned mot null når det blir opphold i nedbøren. Dette viser at etteravrenningen ikke blir simulert, se f.eks 500-700 minutter.

Avrenningstoppene blir simulert noenlunde riktig, slik at når en bare trenger å ta hensyn til maksimal avrenning, f.eks ved dimensjonering av rør, får en et akseptabelt resultat. Men dersom en skal dimensjonere etter totalt avrent vannvolum, f.eks. ved beregning av driftstid av overløp eller dimensjonering av et fordrøyningsbasseng, vil det medføre en stor usikkerhet å benytte de simulerte resultatene. Kalibreringene viser også at avrenningsfaktoren (ϕ) stiger når intensiteten av nedbøren øker.

Ved å benytte den enkle avrenningsmodellen i MOUSE kombinert med kinematisk bølgeteori



Figur 2. Simulering av avrenning fra langtidsnedbør den 12/10-89 (Høgeli 1991).

får en ikke kalibrert hele regntilfellet tilfredstillende. Årsaken til dette er at det ikke er mulig å benytte tidsavhengig avrenningsfaktor i MOUSE. Når en kalibrerer etter de "første" avrenningstoppene vil nødvendigvis de avrenningstoppene som oppstår senere i regntilfellet bli simulert for lavt.

MODELLERING AV SNØSMELTING

Som nevnt foran har vi forsøkt å simulere avrenningen fra nedbør kombinert med snøsmeltingen ved bruk av fire versjoner av temperatur-indeks modellen. Her gies en kort beskrivelse av disse modellene.

En temperatur-indeks modell er i sin enkleste form en lineær modell som sier at snøsmelting er kun påvirket av lufttemperatur. Den gir ofte gode resultater, pga. at det er god korrelasjon mellom lufttemperatur og netto energitilførsel.
Ved korte tidsintervall, f.eks en time eller mindre, kan det bli dårlig korrelasjon mellom simulert og observert snøsmelting ved bruk av temperatur-indeks modellen. Ved å sette inn et ekstra ledd i formelen, som tar hensyn til kortbølget stråling, vil en ofte få en bedre simulering. Den modellen kalles temperatur-stråle-indeks modellen.

For snøsmelting med høy tidsoppløsning, en time eller mindre, kan frysning av smeltevann om natten spille en betydelig rolle. Effekten av at smeltevann fryser når en får minusgrader kan taes vare på vha. refrysnings-modellen. Denne modellen sier at for kortere perioder enn en dag og for moderat lave temperaturer blir dybden av refrysningen omtrent proporsjonal med roten til antall negative time-grader i løpet av perioden (Thorolfsson and Sand 1991).
Smeltevann og regn beveger seg nedover i snølaget under påvirkning av tyngdekraften. Denne prosessen er svært kompleks og vanskelig å beskrive rent matematisk pga. de meget varierende fysiske forhold som finnes gjennom snødekket.

Sand (1990) har lansert en måte å modellere transporten av vann igjennom snødekke. Denne er basert på bruk av en lineær kar-modell, og modellerer transporten av smeltevann og nedbør falt på snøoverflaten vha. to lineære kar i serie med en dynamisk responsfunksjon.

I tabell 2 vises de fire modellene vi har forsøkt å kalibrere. Refrysningsmodellen inngår i alle modellene.

Ved kalibrering av modellene har vi optimalisert effektiviteten av dem ved å benytte kriteriene for modelltilpasning som Sand (1990) har brukt. Verdiene av effektivitetsfaktoren (R^2) vil være i intervallet - ∞ til +1, hvor +1 representerer lik verdi for observert og simulert avrenning.

Tabell 2. De fire snøsmeltemodellene.

Modell	**Effektivitetskonstant (R^2)**	**Akk.diff**
Temperatur-indeks	0,24	-38,8
Temperatur-stråle-indeks	0,28	-30,8
Temperatur-indeks + transport	0,26	-18,0
Temperatur-stråle-indeks + transport	0,29	-21,1

SIMULERING AV SNØSMELTINGEN

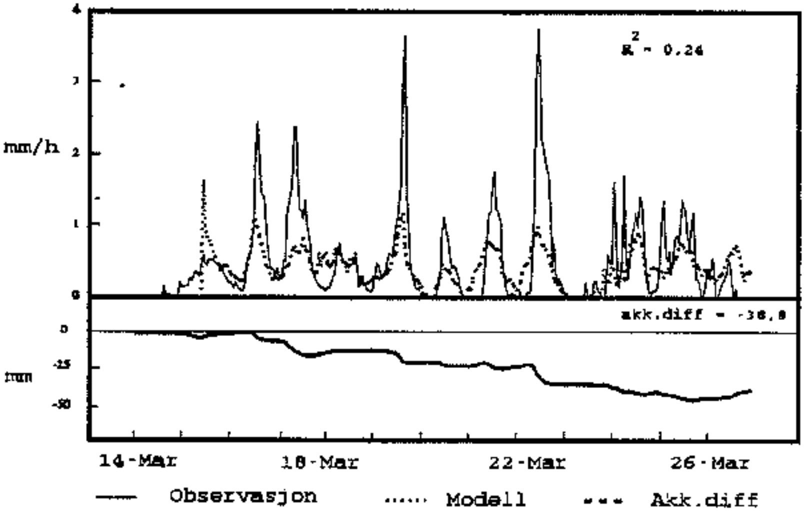
Som eksempel på snøsmeltingen og snøsmeltemodellens effektivitet er følgende episode valgt (Høgeli 1991):

Dato	:	150390 - 270390	
Registrert nedbør i form av snø forut perioden	:	60	mm
Registrert avrenning på snøsmeltebrettet i perioden	:	153	mm
Nedbør i form av regn og sludd i perioden	:	11	mm

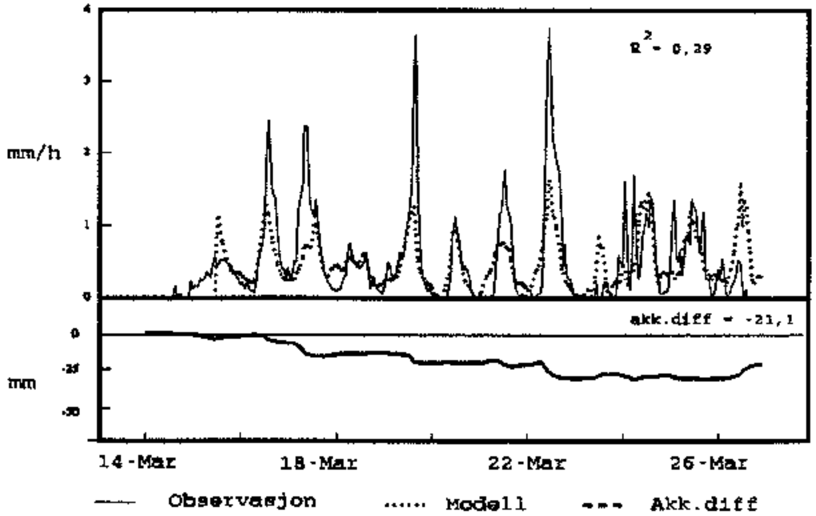
I figur 3 har vi presentert resultatene fra to av modellene grafisk. Resultatene fra alle fire modellene fremgår av tabell 2.
Modellen simulerer forløpet til den observerte avrenningen relativt godt, men modellene klarer ikke å ta vare på avrenningstoppene. Det medfører at akkumulert differanse (akk.diff) øker for nesten hver eneste topp. Mulige årsaker til at toppene blir underestimert diskuteres senere. Først vil vi kommentere det faktum at effektivitetskonstanten blir bedre dess mer kompleks modellen blir.

For å ta utgangspunkt i temperatur-indeks modellen ser vi at effektivitetskonstanten er 0,24. Når en benytter temperatur-stråle modellen øker effektivitetskonstanten til 0,28. Dvs. at en får en bedre simulering når en tar med strålingsleddet. I mars måned er kortbølgestrålingen blitt såpass intens at strålingen er en medvirkende årsak til snøsmeltingen
Når en sammenligner temperatur-indeks modellen med og uten transport-modellen ser en at effektivitetskonstanten er noe høyere når en tar hensyn til transportmekanismen igjennom

Tempratur indeks modell



Tempratur stråle indeks + transport modell



Figur 3. Simulert avrenning fra snøsmelting den 15/3 -27/3 1990 (Høgeli 1991).

snødekke, dvs. jo bedre beskrivelse av prosessen dess bedre resultat.
Dette ser vi også ved å sammenligne temperatur-stråle modellen med og uten transportmodellen.

Underestimeringene av avrenningstoppene kan skyldes at det har vært høy vindhastighet i løpet av perioden. Det vil medføre at snøsmeltingen, ikke bare øker med stigende temperatur, men også øker proporsjonalt med vindhastigheten. Dette pga. turbulente varmeflukser. Disse kan forklare avvikene mellom observert og simulert avrenning for avrenningstoppene.
Forsøk viser at smeltevannets penetrasjonshastighet i snødekket øker når smeltevannsmengden øker. Dette skyldes forholdet mellom tyngdekrefter og kapillærkrefter.
I begynnelsen av en smeltesyklus dvs. tidlig på dagen, går transporten av smeltevann igjennom snølaget langsomt. Dette fordi smelteintensiteten er lav. Etterhvert som snøsmeltingen tiltar øker mengden smeltevann som skal transporteres igjennom snølaget. Denne "store" smeltevannsmengden siger raskere ned igjennom snølaget enn smeltevannet som begynte å penetrere snølaget tidlig på dagen. Den siste smeltevannsfronten kan dermed ta igjen den første smeltevannsfronten før den forlater snølaget .

På denne måten kan smeltevannsfrontene superponeres og vi får en kraftig avrenningstopp som kan være en annen mulig forklaring på at de observerte avrenningstoppene er høyere enn de simulerte.

OPPSUMMERING

Arbeidet med prosjektet kan foreløpig oppsummeres slik:

1. Fra simuleringen med NIVANETT og MOUSE kan vi slutte at ingen av disse to avrenningsmodellene egner seg til simulering av avrenning forårsaket av langtidsnedbør, da de ikke kan simulere etteravrenningen tilfredsstillende.

2. Når man har funnet frem til en hensiktsmessig snøsmeltemodell kan den implementeres i en eksisterende urban avrenningsmodell for å simulere den totale avrenningen fra et helt feltet.

3. Prosjektet har vist at det er et stort behov for å få utviklet urbane avrenningsmodeller som kan simulere alle de hydrologiske situasjoner som kan oppstå i Norge. Dette fordi eksisterende modeller ikke dekker alle mulige hydrologiske situasjoner.

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SPATIAL DISTRIBUTION OF METEOROLOGICAL AND HYDROLOGICAL VARIABLES

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ABSTRACT

The spatial and temporal variability in the main water balance elements, precipitation, evapotranspiration and discharge are investigated within a small catchment (5.8 km^2) in eastern Norway. Five subcatchments are identified within the area, and have been selected based on differences in vegetation, soil properties, exposition and gradient. Areal representative meteorological input variables are calculated using different interpolation routines. The evapotranspiration is for each subcatchment calculated using the evapotranspiration model AMOR, which is based on the Penman-Monteith equation for calculating areal evapotranspiration. In the first part of the study the AMOR model simulations are evaluated against observed data from the subcatchments. The observations show that the internal variation in the main catchment is low for precipitation, whereas significant variation is found for runoff and evapotranspiration. This result emphasizes the role of evapotranspiration in the water balance. It is therefore of great importance to model soil-plant-atmosphere interaction correctly in order to improve water balance calculations. Investigation of the necessary or optimum spatial scale required for representation of the most important processes acting upon the water balance, is the challenge of further research.

INTRODUCTION

Many conceptual models have been developed for the purpose of predicting floods correctly. When the use of the models is extended to for example, predict the effect of climate or land use changes, it is important that the model operates correctly at both low and high discharges. In many cases this has been done by developing distributed 3D models, as for example in the SHE model (Abbot et al., 1986). Another approach is to represent the significant processes in such a manner that the model can perform equally correctly at the whole range of discharges.

The main goal of this project is to map the time and spatial variation in precipitation, evapotranspiration and runoff over a small catchment. The field measurements are also necessary for the evaluation of the evapotranspiration calculations. The calculations are done using the AMOR model, and the result evaluated against discharge and soil- and groundwater measurements during flood as well as during low water conditions.

Another important part of the study is to identify the most important processes governing the water balance, and to identify the spatial scale to integrate over, and the time resolution necessary. These questions are not easily dealt with, but important to focus on in order to improve water balance calculations.

In this article the interpolation routines for the input variables, field measurements and calculation routines for evapotranspiration will be presented. Water balance calculations are used to evaluate the preliminary results from one field season.

RELATED WORKS

Throughout the history there has been done a tremendous number of related work. This short review will focus on work presented by Nordic authors.

Precipitation

Sælthun (1973) investigated the distribution of precipitation in a mountainous area in Norway. He found that precipitation in the summer season could be related to altitude, x- and y-coordinates, the slope of the terrain and to the altitude difference in the terrain surrounding the station. The altitude parameters explained 50% of the variance, whereas the complete parameter set explained 85%. It is emphasized that the regression relationship is not valid for convective showers. Singh & Birsoy (1975) compared different methods for calculating areal precipitation. They found that the different methods gave similar results, and concluded that it was acceptable to use a simple mean of the measured precipitation provided that the station was representative for the whole catchment. Førland (1979) investigated annual precipitation in different parts of Norway and found that station altitude and distance to the coast were the most important factors. Dahlstrøm (1986) present different methods for calculating areal precipitation, along with an evaluation of their usefulness for different catchment types.

Water balance studies

Many water balance studies were performed in the Nordic countries during the IHD-period and encompassed a varity of catchments with respect to geology, soil, vegetation, altitude and latitude (see for example Forsman, 1975; Gjørsvik, 1972; Furmyr, 1975; Ruud, 1975). These studies show that evapotranspiration is of great importance in all the different catchment types included, even in mountainous areas. Killingtveit (1978) made a comprehensive study of the water balance in the Sagelva research basin near Trondheim, Norway. The work focuses on different methods for measuring all the components of the water balance, inclusive the different storages. He found that 430 mm of a total precipitation of 1366 mm, was lost by evaporation during a five year period (31%). This loss was close to the potential evaporation over the period.

Spatial variation in runoff

Spatial distribution in runoff has been investigated in many parts of the Nordic countries, usually as part of a water balance study (refer the studies presented above). Large differences are found even over small distances. The results have shown that the internal variation in the water balance elements in a catchment is significant. As a result of this Amerman (1965) published the concept of the "Unit source area", which was based on the idea that it is possible to separate a catchment into parts that are homogeneous in relation to biological, geological and climatic variables. The most optimistic researchers in this period meant that this could be the solution of translating point measurements to areal values. It was later shown, however, that there also was an internal variation in the "Unit source areas". A fact that resulted in increased activity in hillslope hydrology. Many studies has dealt with this field of hydrology in the last decades (for a review, see for example Anderson & Burt, 1990).

Spatial variation in evapotranspiration

Evapotranspiration has been investigated in details in single points or on small plots (Hansen & Jensen, 1986). Few studies has been done concerning the spatial variation of evapotranspiration. Some early attempts were done in Norway by Høiland et al. (1952) and Søgnen (1967). Maps of the regional distribution of evapotranspiration in the Nordic countries have been presented by Forsman (1976) and on a more local scale by Lundquist (1980). Recent development has provided the opportunity to measure areal evapotranspiration, and instrumentation and measuring techniques have among other studies been tested in the HAPEX-MOBILHY program (André et al., 1990). In this experiment remote sensed data were evaluated against field measurements, and the results were promising. A similar project, NOPEX, has been initiated in the Nordic countries (Halldin, 1992; this volume).

TEST SITES

The five subcatchments used in this study are all part of the

Sæternbekken experimental area (Erichsen & Nordseth, 1985), is situated about 10 km west of Oslo, Figure 1. The subcatchments differ in exposition, gradient, vegetation cover and soil properties. Subcatchment characteristics are given in table 1.

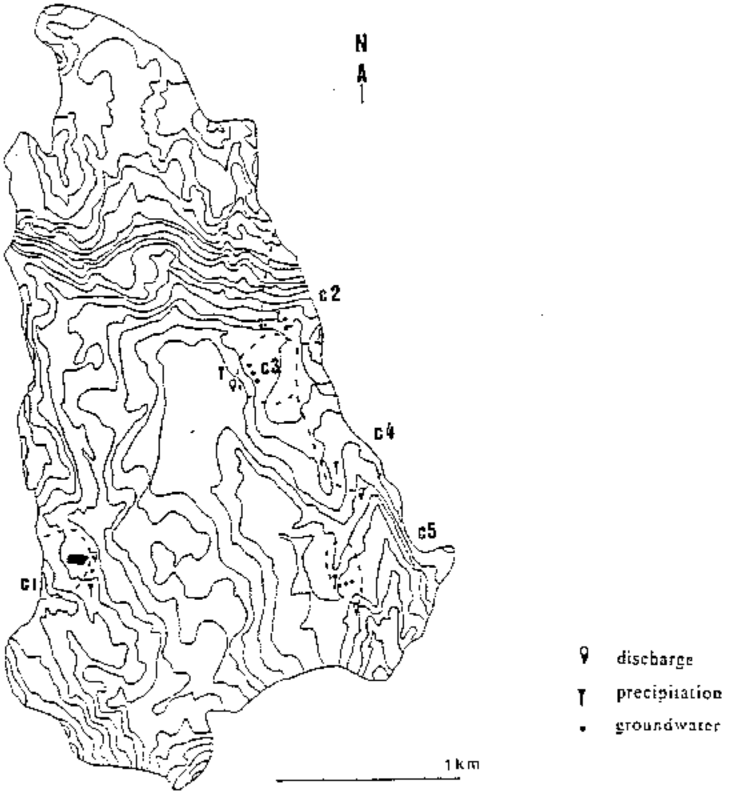

Figure 1. Location of subcatchments and measurement sites.

Soil class is given for each cover type in accordance with MORECS, which classifies soils of high (1), medium (2) and low (3) water capacities. The available water capacity is defined for each surface cover and corresponds to the value for soils of medium capacity. Values 25 % larger and smaller are used to arbitrary define soils of high and low capacity. Available water capacity are for grass, riparian and conifer vegetation, 125, 200 and 175 mm, respectively. Any other value of soil water capacity may be chosen.

Table 1. Catchment characteristics. Soil class is for each cover type given in brackets.

Catchment	C 1	C 2	C 3	C 4	C 5
Area [km^2]	0.080	0.200	0.045	0.148	0.053
Altitude range [m]	255-290	210-375	215-230	185-260	135-185
Relief	0.09	0.24	0.07	0.09	0.13
Lakes [%]	5	0	0	0	0
Forest [%]	95(3)	92(3)	49(1)	93(2)	75(2)
Cleared area [%]	0	0	51(3)	7(3)	0
Riparian [%]	0	8(2)	0	0	0
Cultivated [%]	0	0	0	0	25(2)

METHODS

In each subcatchment precipitation, discharge and groundwater levels are measured, on average between two and three times a week. Location of measurement sites are shown in Figure 1. Daily values of precipitation have been obtained by regression with observations from nearby recording stations, whereas daily discharge values are obtained using interpolation routines in combination with precipitation data.

Areal representative values of each input variable, which are important for the calculation of evapotranspiration, are calculated from various interpolation routines. Temperature and relative humidity are calculated as a function of elevation, whereas wind, cloudiness and global radiation are given a constant value over the catchment by using data from the most representative recording station. Table 2 shows the different variables included in this work.

Table 2. Measured (M), interpolated(I) and calculated (C) variables.

Precip.	M, I
Runoff	M
Groundwater level	M
Eac.	C
Epot.	C
Humidity	I
Temperature	I
Cloudiness	I
Wind speed	I

Areal values of precipitation in Sæternbekken catchment were calculated in two ways; as a mean of the five measured values in the subcatchments and as the interpolated values from five regular recording precipitation stations situated outside the main catchment area. The different methods used for interpolation are:

* The mean of the five surrounding stations (MEAN)
* Inverse distance interpolation (INV DIST)
* Regression with the altitude of the station as the independent variable. Interpolation was done for two altitudes, 125 & 250 m. (ALT125 & ALT250).
* Trend surface (TREND SURF)

Further details about the interpolation methods are given in Erichsen & Tallaksen (1992). General statistics of the interpolated and measured values, calculated over the period 20.07 to 01.10.91, are given in table 3.

Table 3. Statistics of interpolated and measured values for precipitation.

	Pmean	Std	Min	Max
INV DIST	1.97	4.32	.0	24.9
MEAN	2.08	4.54	.0	25.0
ALT125	2.05	4.47	.0	24.0
ALT250	2.10	4.63	.0	26.1
TREND SURF	2.07	4.57	.0	22.5
MEASURED	1.71	4.10	.0	23.0

The measured mean values are in every case significant lower than the interpolation estimates. This may be related to the lack of windshields in the local measurements of precipitation, or a result of the surrounding stations not being representative for the catchment in the summer season, when much of the precipitation is formed by convection. The difference in calculated areal precipitation will be further investigated in 1992 by including data from a shielded precipitation gauge.

The evapotranspiration calculation is done using the AMOR model, which is based on the Penman-Monteith combination equation (Monteith, 1965). Calculations are made for various surface types, and an areal average obtained from the relative proportion of each surface. Intercepted precipitation is determined from the leaf area index and rainfall amount. The time surface is wet depends on the evaporative demand and amount of intercepted water. Aerodynamic resistance is given as a function of wind speed and effective height of the vegetation, whereas surface resistance depends on the leaf area index and soil moisture deficit. An additional vapor pressure deficit and temperature dependence is introduced for conifers.

Surface types represented in this study are conifers, riparian, grass and water. Basic information for each vegetation type is maximum leaf area index, albedo, effective crop height, daytime values of surface resistance for dense crop freely supplied with water and available water capacity. Representative values are provided by the model.

MORECS/AMOR uses the simplifying assumption that the available water is held in two reservoirs X and Y which contains reserves of x and y mm (Figure 2). All water in X is freely available, while that in Y becomes increasingly difficult to extract as y decreases. The maximum available water is distributed 40 % in X and 60 % in Y. Water is drawn from X until it is completely exhausted, when extraction from Y begins. Recharge replenishes Y only when X is filled.

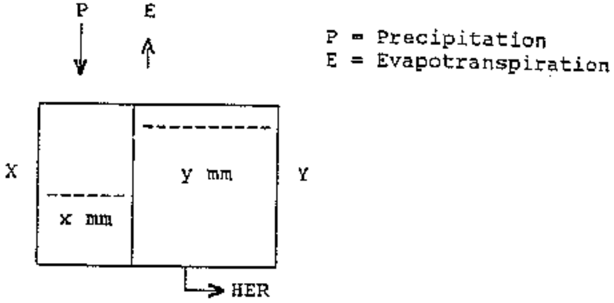

Figure 2. MORECS/AMOR soil moisture extraction model.

The aim of the second part of the project is to link the evapotranspirations routines of AMOR with the soil moisture routines of the HBV model. The linked HBV-AMOR model will be evaluated against the original HBV in a comparative study.

RESULTS

So far, only data from the summer season of 1991 are available, and the results presented here are of preliminary character. Some of the results regarding the areal and spatial distribution of the main water balance elements are given in the following.

Runoff

Pronounced differences between specific discharges and runoff regime are found for the five subcatchments. Summed over 74 days, discharge ranges from 6.7 to 28.5 mm, in catchment 2 and 5, respectively (Tallaksen & Erichsen, 1992). Widely different regimes are also found between the subcatchments and illustrated in Figure 3, where subcatchment 3 and 4 are plotted separately. The flat, bog area of catchment 3 acts like a swamp, producing high runoff values when the soil reservoirs are filled, whereas the river quickly runs dry despite a high soil moisture. The continuing loss of soil moisture can be seen from the plot of water level in the groundwater tubes. Catchment 4 on the other hand, with its regular river slope and its medium soil capacity, produces low flood peaks and ensures river flow even through the extensive dry period.

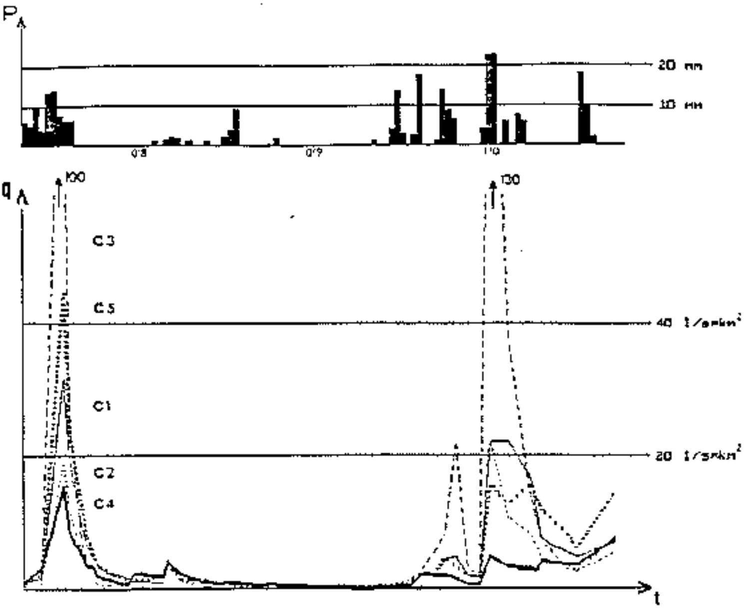

Figure 3. Specific discharge and precipitation of the five subcatchments.

Precipitation

Measured precipitation in the five subcatchments shows only minor variation over the main catchment as illustrated in figure 4, where daily values for the five stations are plotted together. The precipitation measurements will continue in 1992. In a previous study in Sæternbekken, a similar result was found by Stavestrand (1979) for the accumulated summer precipitation.

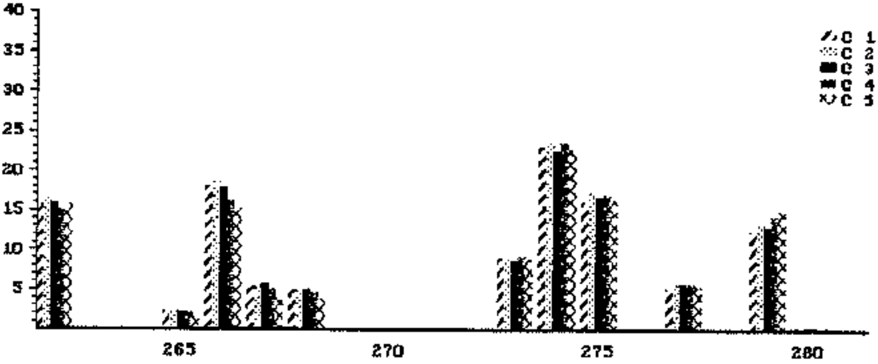

Figure 4. Precipitation measurements in the five subcatchments.

Evapotranspiration

Evapotranspiration was calculated for the five subcatchments using the AMOR model. General statistics for the calculated evapotranspiration are given in table 4.

Table 4. Statistics for the calculated evapotranspiration in the five subcatchments. WB refers to the range of values encountered over the season using the water balance equation (precipitation minus runoff).

	Mean	Min	Max
C 1	1.1	0.0	2.7
C 2	1.3	0.0	3.1
C 3	1.2	0.0	3.5
C 4	1.3	0.0	3.1
C 5	1.4	0.0	3.2
WB	1.5-1.9	-	-

The AMOR estimates are generally lower than the observed P-Q values summarized over the whole season (table 4). This might be a result of input variables not being representative, i.e., low wind values, or choice of model parameters and structure. In this case, the main explanation is thought to be related to the soil moisture extraction model. Increased evapotranspiration losses can be gained by increased soil water capacity and changes in the proportion of the X and Y magazines. By including the soil moisture zone as part of a dynamic rainfall-runoff model, it is possible to incorporate an interaction between the soil- and groundwater reservoirs. This could also allow for increased evapotranspiration losses, and would give a better representation of the physical processes involved. Further modeling work and simulations will focus on these issues. Lowest evapotranspiration rates during the extensive dry period is found for C 3 and C 5. This is due to the higher grass percentage of these catchments, and a result of the lower soil moisture capacity of grass compared to forest. As there are only minor differences in the meteorological input variables, it will be vegetation type and soil moisture capacity that determine the evapotranspiration. The inclusion of a site dependent global radiation is thought to produce larger differences between the catchments.

CONCLUDING REMARKS & FURTHER RESEARCH

Precipitation measurements in the subcatchments have shown that the internal variation in the Sæternbekken catchment is low. During the summer of 1991 a maximum difference of 7.6 % was found between the highest and lowest accumulated value. A higher variation is found for runoff. The largest difference between accumulated runoff values summed over the summer period, is 325%. The single day variation is also great. During one flood the specific discharge of catchment 3 equalled 20 times the specific discharge in catchment 4 (ref. figure 3).

Looking at the water balance elements of the five subcatchments during the summer of 1991, it is clear that evapotranspiration plays a significant role in determining the water balance in this area. The recorded values calculated as the difference between precipitation and runoff is greater than the values obtained from AMOR. The main explanation is thought to be related to the soil moisture extraction model. Increased evapotranspiration losses can be gained by increased soil water capacity and changes in the proportion of the X and Y magazines. These are model features which will be investigated in more details in 1992.

Calculation of global radiation will be extended to depend on gradient and exposition, and will be done by including standard formulas for radiation against an inclined surface. Allowance for shadow effects will also be investigated. Wind measurements in the Sæternbekken catchment will be carried out this year in order to evaluate the representativity of the station used, whereas cloudiness will remain a constant value.

The results so far show the significance of evapotranspiration in the water balance. It is of great importance to model soil-plant-atmosphere interaction correctly to improve the calculation of the water balance elements. This requires a more sofisticated modeling of this interaction than are represented in existing conceptual models. One approach to this problem is described in Tallaksen et al. (1992). The identification of important processes to include and the necessary time and spatial scale will be a major task in 1992. These questions are not easily dealt with, but important to focus on in order to improve water balance calculations.

ACKNOWLEDGEMENT

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VARIASJON I TID OG ROM AV GRUNNVANN OG RESPONS AREAL

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ABSTRACT

Results from a field study in a small forest catchment in South-Eastern Norway are presented.

The main object of the study has bee to describe the pathways and the processes generating rainfall to runoff. The findings in this study are in agreement with previous work, i.e. that the response area model gives a good description of the behaviour of the processes in natural fields in Norway. Maps of the distribution of areas with different soil moisture at different stream discharge are made from more than 100 observational sites. The maps are based on measurements of the groundwater level and field mapping.

The variations of the measured groundwater level as obtained automatically each hour, and at various stream discharges, are thoroughly investigated. Correlation analysis and comparison of the increasing and decreasing part on the discharge - groundwater level plot, shows distinct "hysteresis" effects. The plot also shows distinct levels for each groundwater tube. These levels indicate the limit for quick runoff from distinct parts of the catchment. The soil moisture/response area before each precipitation event is important for the behavior of the discharge - groundwater relation.

INNLEDNING

Resultatene presentert i denne artikkelen er en del av en Dr. Scient oppgave, hvor hovedmålet var å undersøke og gi en dypere innsikt i avløpsprosessene for norske forhold. Spesiell vekt ble lagt på tids- og romskalaer for prosessene, og beskrivelse av tilstander i små felt. Det var derfor spesielt viktig å få samtidige registreringer av jordfuktigheten, grunnvannsnivået, avløpet og det mettede arealet.
Forsøksfeltet hvor disse studiene ble utført ligger ved Muren i Bærumsmarka, 10 km vest for Oslo. Feltarealet er ca. 0,001 km^2 og er en del av et større forskningsfelt typisk for øst-norsk morene og skogs terreng. For nærmere beskrivelse av feltet, instrumenteringen og andre undersøkelser utført der, se Myrabø 1988 og Udnæs 1991.

MÅLE- OG BEREGNINGSMETODER

I den første delen av artikkelen ser en på mettet areal/feltfuktigheten ved forskjellige vannføringer. Her baserer en seg bl.a. på "samtidige" manuelle grunnvannsmålinger i 105 nivilerte PVC-rør, som var spredt rundt i feltet. Ved interpolasjon av disse verdiene får en ut kart over fuktigheten/grunnvannstanden i feltet ved bestemte vannføringer.
I siste delen legges hovedvekten på variasjonen i vannføringen i forhold til automatisk registrerte grunnvannstander for hver time. En har fire slike grunnvannsrør på ulike steder i feltet. På disse dataene har en kjørt forskjellige analyseprogram, slik at en bl.a. ser på korrelasjon og kurver mellom vannføring og grunnvannstand for både stigende og synkende vannføring.

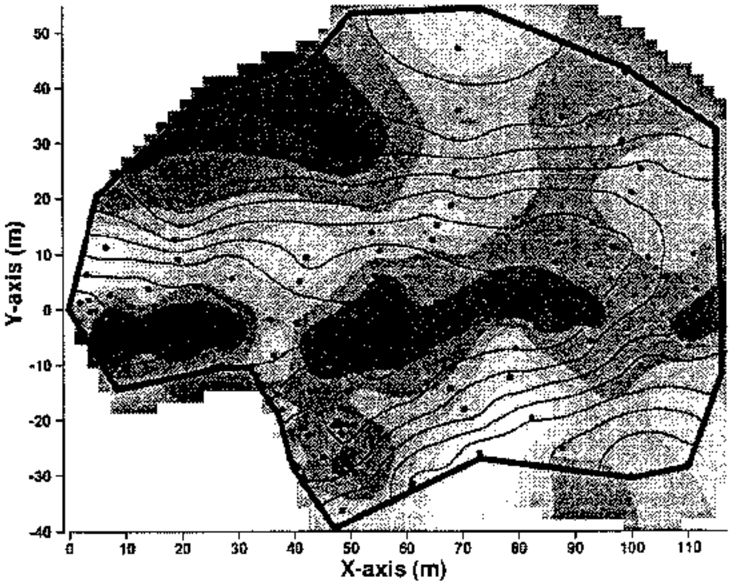

Fig. 1. Topografisk kart over forsøksfeltet. Gråtonen viser de forskjellige grunnvannsnivåene (cm) når Q er 0,2 l/s. Grunnvannsrørene er markert med svarte punkt.

PRESENTASJON OG DISKUSJON AV MÅLERESULTATER

Resultatene av feltstudiene er i overensstemmelse med tidligere arbeid, som viser at respons-areal modellen gir en god beskrivelse av prosessene i naturlige felt i Norge (Myrabø 1985 og Myrabø 1986).
Gjentatte observasjoner og registreringer viste også her at feltfuktigheten var tilnærmet lik ved samme vannføring. Variasjonen av feltfuktigheten ved forskjellige vannføringer sees i figurene 1-4. Kartene viser at de fuktigste arealene som gir hurtig respons og styrer de prosessene som gir rask avrenning varierer ganske mye innen feltet, både i tid og rom. Dette medfører at den relative betydningen av de forskjellige avløps

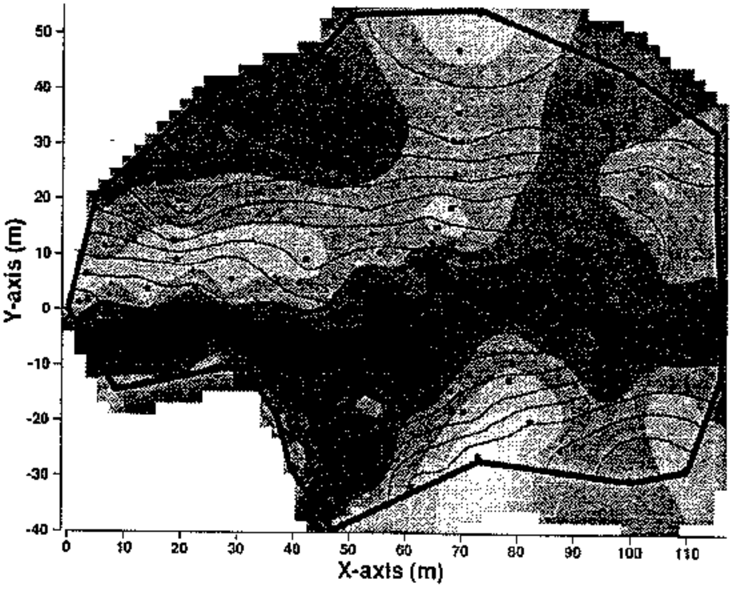

Fig. 2. Viser det samme som figur 1 , men når Q er 1,3 l/s.

prosessene kan ha store inbyrdes variasjoner ved hvert nedbørtilfelle.
Når en først har funnet/kartlagt sammenhengen mellom feltfuktigheten og vannføringen, kan en benytte vannføringen som en indikator på initialfuktigheten og respons-arealet. Kartlegging av mettet areal i feltet og/eller direkte målinger av en mengde grunnvannsvariasjoner er derimot veldig arbeidskrevende og vanskelig å overføre til andre områder. Siden topografien er med på å indikere fuktighetsfordelingen i et felt, ville en se nærmere på digitale terrengmodeller (DTM) med ulike topografiske variable som har innvirkning på de hydrologiske prosessene. Derfor ble det utarbeidet en metode for å benytte digitale terrengmodeller til å utlede respons-arealene i et felt og

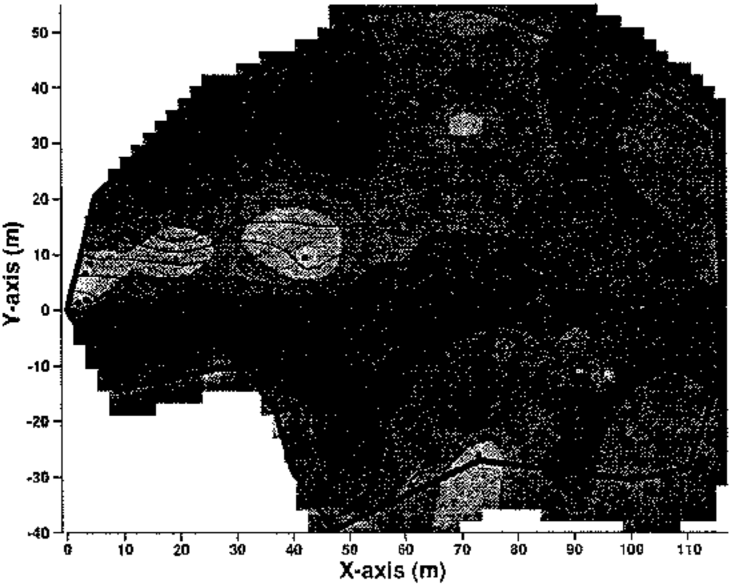

Fig. 3. Viser det samme som figur 1 , men når Q er 10,2 l/s.

deres potensielle variasjonsområde (Erichsen and Myrabø 1990). De topografiske variable som ble benyttet var drenert areal, gradient og kurvatur.

Kart konstruert ved hjelp av denne DTM-modellen og de fra grunnvannsmålingene viser i grove trekk det samme mønster for respons-arealet. De største forskjellene skyldes at interpolasjonen av grunnvannsdataene ikke tar hensyn til terrenget og at en i DTM-modellen ikke tok hensyn til jorddybde og permeabilitet.

Benyttelse av modellen i nivilerte felt vil gi et godt grunnlag for beregning av respons-arealet ved å foreta grunnvannsobservasjoner i et fåtall punkter (h.h.v. i de forskjellige "fuktighetsklassene") og ved kun få observasjoner. Dette vil gi et mye

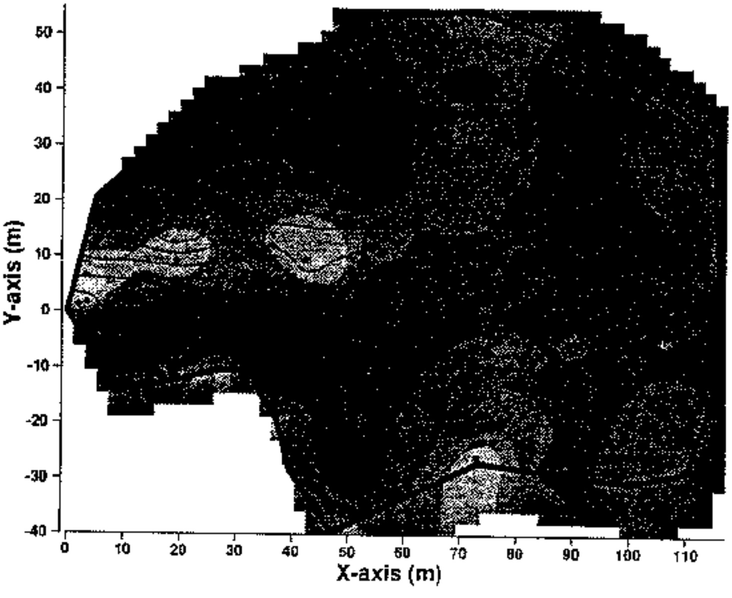

Fig. 4. Viser det samme som figur 1 , men når Q er 14,2 l/s.

bedre grunnlag for bruk av respons-areal modellen i et felt. Ved enten kontinuerlige målinger av grunnvannstanden eller vannføringen kan en således til enhver tid vite utbredelsen av respons-arealet/fuktigheten i feltet. Dette gjør at man både arbeidsmessig og økonomisk kan benytte mer fysisk riktige, fordelte hydrologiske modeller operativt.

Presentasjonen og diskusjonen av dataene fra de automatisk registrerende grunnvannsmålingene i forhold til vannføringen blir presentert på posteren!

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DIMENSJONERENDE HENDELSER I URBANE OG DELVIS URBANE OMRÅDER I KYST-NORGE. GRUNNLAG FOR MODELLTILPASNING

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ABSTRACT

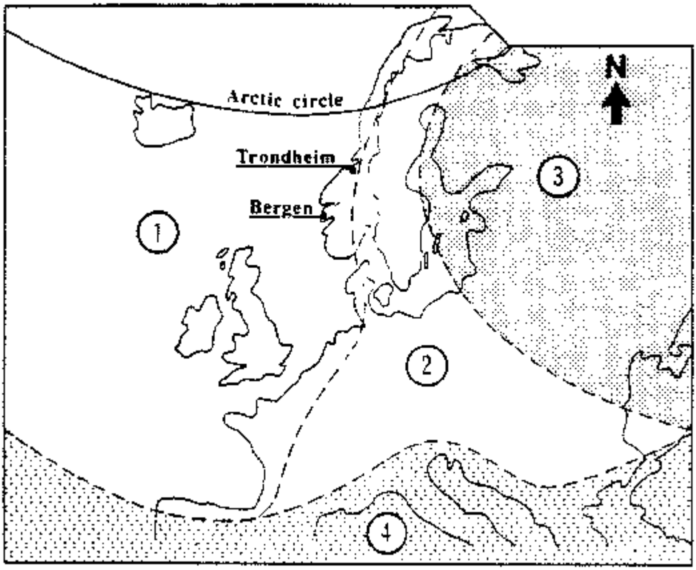
The objective of the current study is to identify "design events" for runoff from urbanized areas in the coastal part of Norway and form the basis of model-building/modification. There is a growing awareness of having maximum peak and volume runoff from urban and suburban areas during the autumn or the winter season and not the summer season as traditionally designed for.

INNLEDNING

Norge ligger nordligst i jordens tempererte sone. Pga. Golfstrømmen strekker denne seg lenger mot nord enn i noe annet land. Det finnes ikke noe annet land på jorden som med rette kan sies å ha samme klima som Norge. Det er store forskjeller mellom kystklima og innlandsklima. Nedbørforholdene er preget av store nedbørmengder vest for vannskillet og meget mindre østenfor.

Figur 1 viser grov inndeling av klimaet i Europa. Vi ser at grensen mellom maritimt og kontinentalt klima ligger langsetter Norge.

I Norge er det årlige antall dager med regn- og snøvær ca. 100 i innlandet, ca. 150 innenfor kysten og over 200 langs vestkysten. Et fellestrekk er at våren er den tørreste tiden og at andre halvdel av året har de fleste nedbørdager, Østlandet mest i august, kysten mest i september til november. Nedbørmengden er størst litt innenfor vestkysten, eller mellom 2000 og 3000 mm.



- Lokalisering av forskningsfeltene/målefeltene.

1. Nordvest Europa/maritimt klima:
   Milde vintre og kjølige somre, størst nedbør om høsten.
2. Sentral Europa/kontinentalt klima:
   Kalde vintre og varme somre, størst nedbør om sommeren.
3. Øst Europa:
   Meget kalde vintre og meget varme somre.
4. Sør Europa:
   Milde vintre, varme og tørre somre, størst nedbør om vinteren.

Figur 1. Grov inndeling av Europa i klimasoner.

Avrenningen fra urbane områder i kontinentalt klima om sommeren er etterhvert vel dokumentert. Modeller for å simulee slik avrenning, f.eks. NIVANETT, MOUSE, SWMM, WALLRUS, BEMUS, o.fl. er lett tilgjengjelige. Derimot er det fortsatt mangel på hensiktsmessige urbane avrenningsmodeller for simulering av avrenningen i vinterhalvåret. Datamaterialet for kalibrering og verifisering av slike modeller er fortsatt noe mangelfullt.

Prosjektet er et samarbeidsfortagende mellom Institutt for vassbygging, Norges tekniske høgskole, Trondheim kommune og Bergen kommune. Prosjektet støttes økonomisk av NAVF-Norsk Hydrologisk Komitè og de deltakende kommunene.

NEDBØR OG AVRENNINGSFORHOLD

I urbane og delvis urbane områder kan den hydrologiske tilstanden over et år inndeles i følgende avrenningsgivende situasjoner:

1. Sommersituasjon

Kraftige, kortvarige regnbyger (korttidsnedbør) på tørr mark. Avrenningen stammer stort sett fra tette flater. Ubetydelig avrenning fra semipermeable og permeable flater.

2. Høstsituasjon

Langvarig regn på mettet mark. Betydelig avrenning fra semipermeable og permeable flater i tillegg til avrenningen fra de tette flatene. Høy grunnvannstand.

3. Vintersituasjon

Langvarig regn og snøsmelting på mettet og evt. frossen mark. Stor andel permeable flater deltar i avrenningen i tillegg til de tette flatene. Liten infiltrasjon.

4. Vårsituasjon

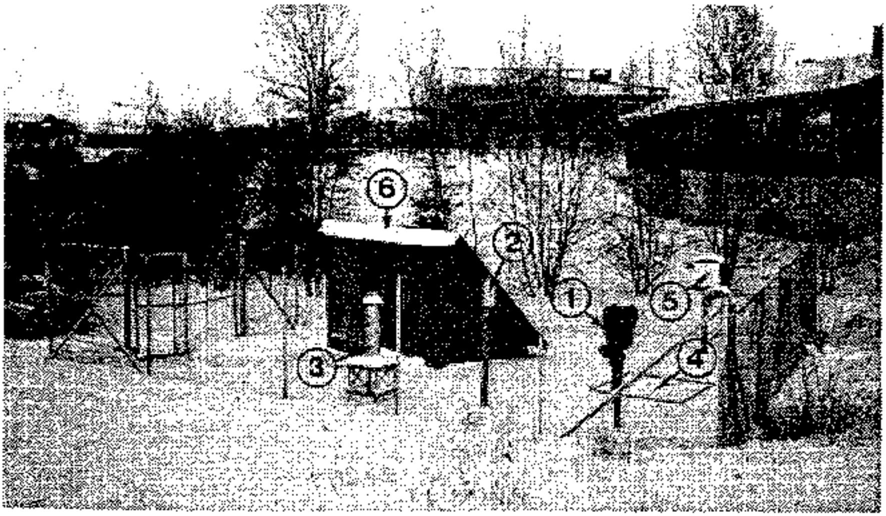
Snøsmelting. Liten magasineringsevne på overflaten. Betydelig avrenning fra permeable flater.

Tradisjonelt har man benyttet sommersituasjonen ved dimensjonering og etteranalyse av overvannsanlegg. Imidlertid har man erfart at kapasitetsproblemer og overløpsavlastninger ofte oppstår i situasjoner som er beskrevet under 2 og 3. Spesielt gjelder dette i kystområdene, men det kan også forekomme i innlandet. Erfaringsmessig gir situasjon 4 ikke kapasitetsproblemer, men gir store overløpsavlastninger. Den samme trenden finnes i materialet fra det nasjonale urbanhydrologiske stasjonsnettet i Norge (Skretteberg 1990). For å kunne bestemme overvannsavrenningen over tid f.eks. ett år, må alle situasjoner kunne behandles. Korttidsnedbørstatistikk er ofte en mangelvare i store deler av landet. Det nasjonale stasjonsnettet har kun ca. 45 korttidsnedbørstasjoner. Av tekniske årsaker tas disse ut av drift i vinterhalvåret. Det betyr at korttidsnedbørdata eller langtidsnedbørdata med tilstrekkelig tidsoppløsning ikke forefinnes for denne perioden. Følgelig er det ikke mulig å behandle situasjon 4, og ofte heller ikke situasjon 2. Det blir også vanskelig å definere situasjon 4.

FORSKNING OG UNDERSØKELSER

To urbanhydrologiske forskningsfelt, Sandsli i Bergen (10.1 ha) og Risvollan i Trondheim (20.1 ha) er etablerte med sikte på å klarlegge avrenningsforholdene under vekslende nedbør- og klimaforhold. Her samles det inn data for en rekke hydroklimatologiske parametre som influerer på avrenningen. Figur 2 viser Risvollan urbanhydrologiske målestasjon.

Figuren viser "PLUMATIC" korttidsnedbørmåler (1) i vintertilstand, dvs. ute av drift. Lambrecht (2) er oppvarmet og måler hele året. Målestasjonen i Sandsli er i prinsippet lik.



1. Korttidsnedbørmåler (vippepluviograf) type PLUMATIC
2. " " type Lambrecht
3. " (hevertpluviograf) type Fuess
4. Snøsmeltebrett (1.5x1.5m²)
5. Instrumentbur med:
    - Sensor for lufttemperatur
    - " " relativ luftfuktighet
    - " " total innstråling
6. Målestasjon med:
    - Måleinnretninger for overvann, spillvann og smeltevann (V-overløp, P-B-renne og oppsamlingskar for smeltevann)
    - Registreringsutstyr (for inntil 11 parametre) tilkoblet PC og telefonmodem

Figur 2. Risvollan målestasjon, Trondheim. Bilde tatt 2.12.1987.

På begge stasjonene registreres alle parametre i sanntid med høy tidsoppløsning, (2 minutter). Det produseres fort store datamengder. For å lagre, bearbeide og presentere dataene er det derfor utviklet eget PC-basert databaseprogram.

Tabell 2. Sensorer som var i drift pr. 01.01.1992.

Parameter	Enhet	Risvollan	Sandsli	Merknad
Korttidsnedbør	l/sha	X	X	
Overvannsavr.	l/s	X	X	
Spillvannsavr	l/s	X		
Lufttemperatur	°C	X	X	2000 mm over bakken
Snøsmelting	mm	X	X	Om vinteren
Bakketemperatur	°C	X	X	200 mm under overfl.
Relativ luftfukt.	%	X	X	
Total innstråling	mW/cm^2	X	X	
Vindretning	400°		X	
Vindhastighet	m/s	X	X	

I tillegg til Sandsli og Risvollan-feltene er det foretatt avløpsmålinger i Ladebekken-feltet i Trondheim (685 ha, tette flater 120 ha eller 17.5 %) og Lønningen 1 og 2 i Bergen (28.8 og 43.9 ha, liten andel tette flater).

RESULTATER

I perioder med langtidsnedbør viser avrenningen to faser:

1. Primæravrenning

Avrenning med rask reaksjonstid som stammer fra direkte tilknyttede tette flater.

2. Etteravrenning (Sekundæravrenning)

Avrenning med forsinket avrenningsforløp. Den stammer fra de semipermeable og permeable flatene, samt de ikke direkte tilknyttede tette flatene.

Etteravrenningen (sekundæravrenningen) kan bli betydelig større enn primæravrenningen, både mht. maksimal- og volumavrenning.

En regnbyge 19.09.89 (sommersituasjon) ga største målte avrenning på Risvollan. Denne bygen ga i Ladebekken en avrenning på ca. 2200 l/s. Derimot ga en nedbørepisode den 31.03.90 maks. 5017 l/s kl 17.20. Det var en typisk vintersituasjon med frossen mark og nysnø på bakken før det begynte å regne. Lignende forhold er registrete flere ganger i Sandsli og Lønningen 1 og 2 i Bergen.

Den maksimale avrenningen forsårsaket av regnnedbør er lett å simulere med de tradisjonelle urbane avrenningsmodellene. Derimot kan disse ikke simulere tilfeller med snøsmelting på en tilfredsstillende måte og de gir for liten etteravrenning i forhold til den målte.

Et forsøk på å bruke HBV-modellen ved å simulere etteravrenningen fra disse feltene ga en overraskende god tilpassning (Thorolfsson og Killingtveit 1991).

Ved å legge inn et ekstra kar "urbant kar" i bunnen av HBV-modellen har man klart å simulere både maksimale avrenningstopper og etteravrenningen på en tilfredsstillende måte (Røstum 1991).

MÅL FOR SIMULERING AV OVERVANNSANLEGG

Resultatene fra prosjektet styrker teorien om at det bør utarbeides nye og reviderte kriterier for dimensjonering og etteranalyse av overvannsanlegg. Dette gjelder spesielt i kystområdene. Inntil videre bør man ved dimensjonering og etterprøving av overvannsanlegg i urbane og spesielt i delvis urbane felt undersøke avrenningen ved følgende forhold:

1. **Sommersituasjon:** Korttidsnedbør på tette flater. Andel avrenningsgivende flater settes lik tette flater multiplisert med en reduksjonsfaktor "a" ($0.5<a<1.0$).

2. **Høstsituasjon:** Langvarig regn med lokalt større intensiteter mot slutten av regnet. Andel avrenningsgivende flater settes større enn andel tette flater, avhengig av grunnforholdene.

3. **Vintersituasjon:** Langvarig regn og snøsmelting, mettet mark.

Situasjon (1) kan simuleres med en urban avrenningsmodell som f.eks. NIVANETT. Situasjon (2) og (3) krever en modell som kan simulere kontinuerlige tidsserier for flere inngangsparametre. Den må også kunne ivareta snøsmeltingen samt den varierende felttilstanden.

VIDERE ARBEID

De siste 20-30 årene er det gjort en stor FOU-innsats innen fagområdet urban overvannsavrenning i Norge og internasjonalt. Imidlertid gjenstår fortsatt å løse en del av de særnorske problemene. 90-tallets FOU-aktiviteter bør konsentreres om å løse disse. Dette betyr fortsatt studier av forholdet mellom nedbør og avrenning med spesiell vekt på forholdene i kystsonen gjennom hele året, og i innlandet for vintersesongen (okt.-apr.). I tillegg trengs videreutvikling av og/eller tilpassninger av egnede metoder og beregningsteknikker.

Disse aktivitetene kan oppsummeres som følger:

1. Utvikling/tilpassning av kontinuerlig urban avrenningsmodell for simulering av tidsserier for nedbør, avrenning, temperatur og snøsmelting for lange perioder.
2. Utvikling/tilpassing av snøsmelterutine i en urban avrenningsmodell, f.eks. NIVANETT.
3. Utvikling av modeller for simulering av avrenningen i delvis utbygde avløpsfelt (delvis urbane modeller).
4. Bedre kunnskap om de forhold/prosesser som styrer avrenningen i et urbant/delvis urbant avløpsfelt ved alle avrenningssituasjoner. Her nevnes:
   - Effekten av langvarig regn (høstsituasjon).
   - Regn på frossen mark.
   - Regn på snødekket og evt. frossen mark.
   - Avrenning fra snøsmelting.
5. Etablering av flere helårlige målestasjoner for registrering av nedbør, avrenning, temperatur og snøsmelting i urbane og delvis urbane områder.

I dette prosjektet vil arbeidet med de overfornevnte punkter fortsette og forsøkes intensivert gjennom dr.ing.-studier, samt nærmere samarbeid internasjonalt. Her vil kontakten med det UNESCO-støttede IRTCUD-senteret (Maksimovic et al., 1990) spille en viktig rolle.

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NOPEX - ETT NORDISKT HYDROMETEOROLOGISKT PILOTEXPERIMENT

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ABSTRACT

NOPEX - A NOrdic hydrometeorological Pilot EXperiment. *S. Halldin, Department of Hydrology, Uppsala University, Västra Ågatan 24, 752 20 UPPSALA, Sweden.* One of the most uncertain aspects in GCM models used to predict a possible global change is the land-surface-atmosphere interaction. A correct parameterization of the exchange processes (evaporation, radiation budget, fluxes of sensible heat and trace gases such as CO_2) and their interaction with the vegetation at a regional scale is needed in order to model both areal evaporation and the surface energy balance for use in hydrological and meteorological models from the meso- to the global scale. The soil-vegetation-atmosphere interaction must also be understood in order to predict the influence of changes in land use on the availability of water resources. The NOPEX project aims at solving these problem by bringing together hydrologists and meteorologists from the nordic, as well as other european countries during a series of concentrated field efforts in 1994-96. Standard hydrological and meteorological data will be collected continuously during these three years from a 50×100 km^2 area, mainly forest-covered, north-west of Uppsala. One or a few sites will be instrumented for more complex measurements. Measurements during a series of concentrated field effforts will encompass several types of surface based, local measurements (of, e.g., soil moisture, evaporation, radiation components), airborne flux and radiometric measurements and satellite imagery. The data collected during NOPEX will be used in the development of an already rich flora of models spanning several orders both in temporal and spatial resolution.

REFERAT

Växelverkan mellan jordens landytor och atmosfären är en av de mest osäkra faktorerna i de globala klimatmodeller som används för att förutspå tänkbara förändringar i klimatet. Det behövs en riktig parametrisering av utbytesprocesser (avdunstning, strålningsbudget, flöden av förnimbar värme och spårgaser som CO_2) och deras växelverkan med växttäcket i regional skala för att kunna modellera såväl den areella avdunstningen som jordytans energibalans för användning i hydrologiska och meteorologiska modeller från mesoskala till global skala. Växelverkan mellan mark-växt-atmosfär måste också förstås för att kunna förutsäga effekter på vattenresurserna av förändringar i markanvändningen. NOPEX-projektet (NHP-projekt nr. 3) syftar till att lösa dessa problem genom att sammanföra hydrologer och meteorologer från såväl de nordiska länderna som internationellt under en serie koncentrerade fältsatsningar 1994-96. Hydrologiska och meteorologiska standardmätningar kommer att ske fortlöpande under dessa tre år från ett ca. 50×100 km^2 stort område, huvudsakligen skogsklätt, nordväst om Uppsala. En eller två mätplatser kommer att utrustas för mera fullständiga mätningar. Verksamheten under de koncentrerade fältsatsningarna kommer att innefatta olika typer av markbaserade mätningar (t ex markvatten, avdunstning, strålningskomponenter) samt flygburna mätningar av flöden och strålningsfält. Mätningarna kommer att samordnas i tiden med passage av satellitburen fjärranalysutrustning. Data som insamlas under NOPEX kommer att användas för att utveckla en redan rik flora av modeller med stor spännvidd såväl i tid som rum.

INLEDNING

En av de största svagheterna i dagens globalklimatmodeller är den otillfredsställande representationen av jordytans hydrologi. Det finns behov av att förbättra behandlingen av avdunstning, framför allt från beväxta landområden och växelverkan i regional eller större skala mellan mark, vegetation och atmosfär är inte klarlagd. Det finns ett stort behov av att öka förståelsen för hur beskogning, avskogning, utbredning av öken och tätorter samt industrialisering påverkar vattenresurser och klimat.

Dessa problem har lett till att man internationellt har initierat ett flertal program, däribland ICSUs IGBP (populärt benämnt "Global Change") samt WMOs GEWEX, med syfte att samordna forskningsinsatser från olika grupper av forskare i flera länder. Inom ramen för Nordiskt Hydrologisk Program startade Sirkka Tattari 1989 NHP-projekt nr 21 med syfte att förbättra areella avdunstningsberäkningar m h a satellitdata och befintliga mätningar. På grund av otillräckligheten hos sådana data, ändrades inriktningen på detta projekt och det lanserades 1991 som NHP-projekt nr 3 under förkortningen NOPEX, med syfte att få fram relevanta mätdata och modeller i regional skala. Ursprungsmålen för den nordiska projektgruppen var att (i) identifiera intresset bland nordiska meteorologer och hydrologer samt tänkbara resurser som skulle kunna ställas till projektets förfogande, samt att (ii) fastställa kriterierna för och välja ut området där studierna skulle bedrivas.

Från början var NOPEX ett rent nordiskt, hydrologiskt projekt, men under planeringens gång har intresset växt såväl ämnesmässigt som geografiskt. I skrivande stund har mer än åttio forskare från tretton olika länder och från ett flertal olika ämnesområden anmält intresse av att vara med i NOPEX.

SAMORDNING I TID OCH RUM

En av de bärande idéerna i NOPEX är att man måste samordna olika forskargruppers satsningar i tid och rum, även om de olika grupperna normalt arbetar med olika upplösning såväl rumsligt som temporalt. Uppsplittringen av forskningen i olika tids- och rumsskalor är ett stort bekymmer när forskare från olika ämnen söker varandras stöd, trots att de alla är intresserade av avdunstning eller andra utbytesprocesser mellan jordytan och atmosfären. Ett sätt att komma förbi detta hinder är att få de olika forskarna att samverka med gemensamma mätningar och analyser under en och samma tidsperiod och i ett och samma område. Denna samverkan ger de olika ämnesgrupperna stöd från varandra trots de olika skalorna. Den stimulerat också till nya teoretiska ansatser vad gäller relationen mellan de olika rums- och tidsskalorna och är till hjälp för att identifiera vilka processer som måste parametriseras och vilka som kan försummas i en viss skala.

MÅL FÖR NOPEX

Övergripande mål

NOPEX kan ses som en paraply under vilken enskilda forskningsprojekt med väl definierade mål kan delta. Målen som definierar denna paraply är följande:

- Landskapet i Norden liksom i övriga Europa kännetecknas av en mosaikform, med de enskilda elementen i längdskalan mellan ungefär 100 m och 1000 m. Enskilda fält kan bestå av jordbruksgrödor, skog av olika typ och ålder, våtmarker, sjöar och tätorter. Syftet med NOPEX är att studera just detta sammansatta landskap för att förstå hur flöden och tillstånd i varje element tillsammans bildar det totala flödet och tillståndet för en hel region.
- Projektet syftar till att ge fysikaliskt sunda data för att tillåta en parametrisering av flödena från landytan i hydrologiska och meteorologiska modeller från mesoskala till global skala.
- Det finns ett behov av att studera regionala utbytesprocesser i ett landskap som domineras av skog. Sådana landskap är dominanta i Sverige och Finland och spelar en allt större roll i övriga Norden och Europa. Skogens roll i mark-växt-atmosfärssystemet är därför central i NOPEX.

Specifika mål

Samtidigt som de övergripande målen anger färdriktningen för projektet, är det viktigt att klarlägga mera specifika mål som projektet skall uppfylla. Dessa mål är delvis avhängiga av vilka deltagare som i slutändan kommer att bära upp

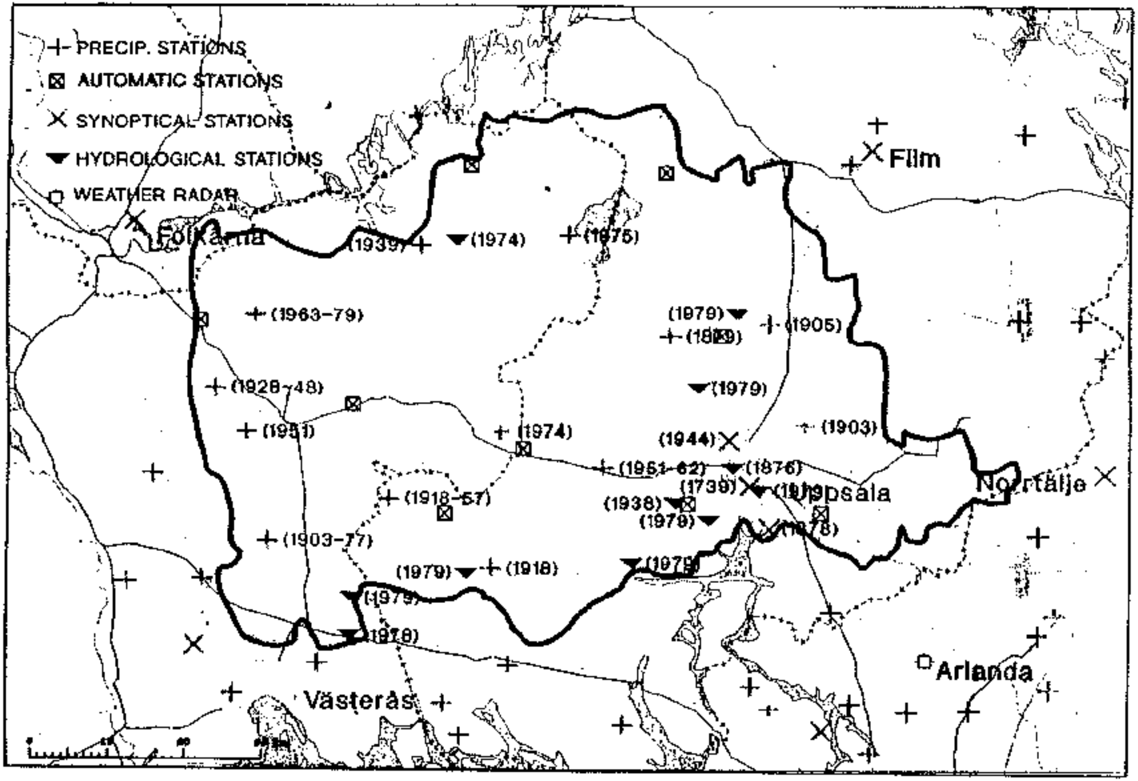
NOPEX. Det kan därför tänkas att följande lista på operativa mål kan komma att utvidgas:

- Kvantifiera storleken av termerna i jordytans energi-, vatten- och kolbalanser från olika typer av mark, såväl under dygnet som under året.
- Kvantifiera betydelsen av advektion och andra randeffekter för balanserna för enskilda fält och bestånd (det antas allmänt idag att utbytena av vatten, värme och kol är större än summan från de enskilda fälten).
- Studera hur avdunstningen och växttäckets vattenanvändningseffektivet beror på markvattenstress, interception och växttäckets utveckling under året.
- Studera hur fjärranalysdata från satelliter och flygburen utrustning kan användas för att utvärdera flöden och tillstånd vid jordytan genom att skaffa fram hårda data på marksanningen.
- Kritiskt utvärdera vilken mätnoggrannhet som krävs för att mäta inte bara ytegenskapernas absolutvärden utan även hur dessa varierar regionalt.

NOPEX-OMRÅDETS PLACERING

Då målet var att koncentrera studierna på växelverkan mellan atmosfären och den beväxta jordytan, var det viktigt att hitta ett område där effekterna av topografi och land-havväxelverkan var så små som möjligt. Området fick därför inte ligga närmare än 50 km till hav eller bergstrakter. Totala ytan skulle vara i storleksordningen 100 km gånger 100 km. Vidare måste det finnas några mikrometeorologiskt ideala mätplatser över skog inom området. En region i Norden som visade sig uppfylla dessa krav var ett cirka 100 × 50 km^2 stort område i Uppland och Västmanland (Figur 1). Inom denna region kunde åtminstone tre mätplatser över skog identifieras, som var acceptabla. Alla dessa tre ligger längs en rak linje i väst-östlig riktning och är därför idealiska att göra flygmätningar över.

Landskapet i NOPEX-området är topografiskt och morfologiskt kännetecknat av det mycket platta subkambriska peneplanet. Berget i området domineras av urgranit, leptit, sedimentär gnejs och yngre granit. Man kan också finna grönsten, kristallin kalksten och dolomit. Sprickzonerna i området är huvudsakligen orienterade i öst-västlig riktning. Lerjordar och morän dominerar i området. De finkorniga lerjordarna tillsammans med områden av sandig och moig mark

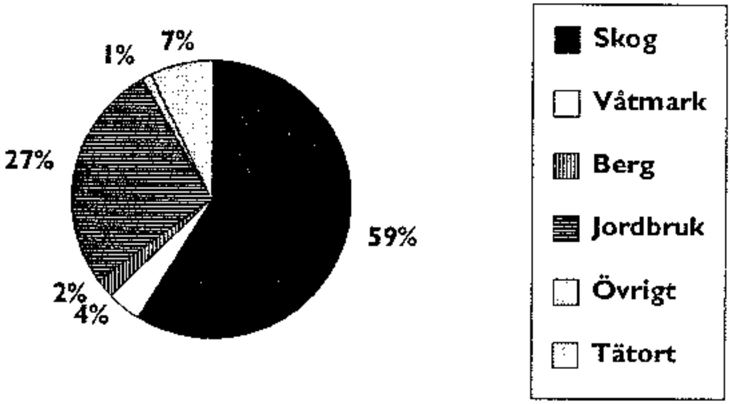


Figur 1. NOPEX-området med SMHIs stationer för nederbörd, synoptiskt väderobservationer och avrinning samt väderradarn på Arlanda. Vägverkets automatstationer är också markerade. Startår och eventuellt stoppår är markerade för flertalet stationer.

återfinns i söder. Områden med morän och myrmark blir alltmer dominanta i områdets norra del. Moränen är ofta storblockig i ytan. Området genomkorsas av fem nord-sydliga åsar. Höjdskillnaderna är små med huvuddelen av området mellan 30 och 70 m ö h och extremvärdena 1 och 131 m ö h.

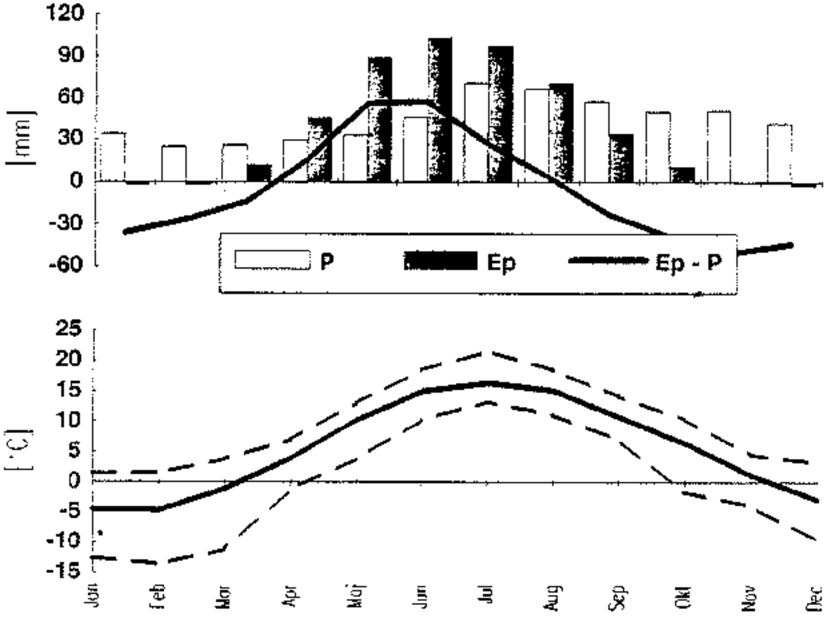
Skogen dominerar i området som helhet (Figur 2) med jordbruket koncentrerat i söder och en fortlöpande större andel av marken är täckt av skog ju längre norrut man kommer. Detta möjliggör en utvärdering av den relativa betydelsen av jordbruksgrödor och skog längs en serie nord-sydliga flygmätlinjer. Skogen domineras kraftigt av tall och gran, med ett litet inslag (15 %) av lövträd, främst i söder. Jordbruksmarken används främst till vall och för grödor som vete, korn och havre. Jordbruk har bedrivits i området i mer än tusen år och skogen har skötts planmässigt i åtminstonde tvåhundra år. Huvudmätplatsen för skogliga mätningar ligger i den mer än tusenåriga Norunda allmänning.

Det finns en halvstor sjö och flera små sjöar inom området, vilket möjliggör studier av den lokala advektionens betydelse och hur sjöavdunstningen skiljer sig från områdets medelavdunstning. NOPEX-området har blivit utvalt så att det omfattar tre större avrinningsområden som rinner av till Mälaren, medan två mindre avrinningsområden dränerar ut i Dalälven. Då området är ytterst



Figur 2. Markanvändningen inom NOPEX-området

platt, finns det inte så många naturliga platser där man kunnat sätta upp permanenta avrinningsstationer. Trots detta mäts avrinningen på flera platser inom området och en av stationerna är mer än hundra år gammal. Klimatdata (Figur 3) finns i god mängd från området och vissa av klimatserierna tillhör de allra äldsta i världen. Flera olika klimatologiska och hydrologiska experiment har tidigare utförts inom NOPEX-området. Tärnsjö, ett av fältforskningsområdena inom NHP-ramen ligger i norra delen av området. På grund av närheten till Uppsala Universitet, Sveriges Lantbruksuniversitet och Sveriges Geologiska Undersökning har området studerats ur många olika aspekter och man kan säga att få områden i världen kan uppvisa ett så stort material av olika bakgrundsdata.



Figur 3. Medelklimat (1960 - 89) för Uppsala. Överst nederbörd (P) och potentiell avdunstning (Ep) samt skillnaden mellan dem. Nederst lufttemperaturen, tillsammans med historiska maximal- och minimitemperaturerna

Huvudmätplatserna för skog och jordbruksmark befinner sig mindre än 70 km från Arlanda i närheten av E4-an. Detta möjliggör en mycket snabb ankomst till försöksområdet oavsett var i världen man befinner sig. Närheten till Uppsala gör det också möjligt att fortlöpande underhålla och bedriva intensiva mätningar vid huvudmätplatserna. Militärflygplatsen i Uppsala är hemmabasen för det svenska flygplan som är avsett att användas för flödesmätningar i det turbulenta gränsskiktet. Det finns vidare permanenta vädertjänster såväl på Arlanda som på flygplatsen i Uppsala. Detta möjliggör en god planering av de mest intensiva experimenten under NOPEX. På Arlanda finns även en väderradar. NOPEX-området är unikt välutrustat med infrastruktur jämfört med andra områden som använts i liknande storskaleexperiment. Risken är sålunda liten för att experimentet skulle misslyckas av praktiska skäl, mot bakgrund av ett stort antal affärer och verkstäder som hanterar elektronik, mekanik, datorer, elektromekanik etc. Hotell, campingplatser och uthyrningsstugor finns i tillräcklig mängd för att kunna härbärgera även det största tänkbara deltagarantal. Vissa av de tilltänkta mätplatserna kan till och med nås med buss.

VILKA MÄTNINGAR KOMMER ATT SKE I NOPEX?

Projektet kommer att omfatta tre typer av mätningar. Intensivmätningar kommer att ske under Koncentrerade FältSatsningar (KFS) och som en del av den Fortlöpande KlimatRegistreringen (FKR). Extensiva mätningar handhas via den Regionala KlimatDatainsamlingen (RKD). KFS- och RKD-programmen kommer att pågå i hela NOPEX-regionen, medan FKR-programmet kommer att försiggå på en (eller möjligen två) huvudmätplats.

Stor vikt kommer att läggas vid kvaliteten på de data som samlas in. I början av projektet kommer energi att läggas på jämförande mätningar med olika system och instrument. Interkalibreringar kommer att ske inom ramen för alla KFS-program och för vissa flödes- och strålningsmätningar kommer flyttbara standarder att finnas till hands.

Koncentrerade FältSatsningar, KFS

Mätningar av avdunstning, CO_2-utbyte och de egenskaper som normalt studeras inom gränsskiktsmeteorologin (impuls, flöde av förnimbar värme och strålning) tillsammans med flöden och tillstånd av vatten och värme i mark och vegetation kommer att vara centrala inom NOPEX. Dessa egenskaper skall mätas under KFS-programmen på flera olika platser i NOPEX-regionen; över skog, åkermark, sjö och våtmark. Luftburna flödes- och fjärranalysmätningar kommer att ske under några lämpliga dagar samtidigt som alla andra mätningar förutsätts vara igång. Flygburen mikrovågsradar kommer att tillåta kartläggning av såväl markvatten, vattenvärde i snö som skogsbiomassa. De mest intensiva mätperioderna kommer att synkroniseras med passage av satelliter som ger information om olika ytegenskaper. Under dessa mest intensiva perioder skall också ett nät av ballongsonderingar, lidar- och sodarmätningar komplettera de flygburna mätningarna för att kunna förse atmosfäriska mesoskalemodeller med initierings- och valideringsdata.

Fortlöpande KlimatRegistrering, FKR

Detta program kommer att koncentreras till en hundra meter högt mast i skogen på Norunda häradsallmänning, 25 km norr om Uppsala. Turbulens- och strålningsbudgetmätningar kommer att ske på tre höjdnivåer. Dessa flödesmätningar kommer att kompletteras med profilmätningar i mark, bestånd och atmosfär av värme, (ofrusen) vattenhalt eller vattenånga samt koldioxid. Vidare skall nederbörd, interception, genomfall och vattentransport i trädstammar mätas med hög tidsupplösning.

Regional KlimatDatainsamling, RKD

De intensiva KFS- och FKR-mätningarna måste kompletteras med RKD-mätningar av avrinning från huvudavrinningsområdena och från ett antal mindre experimentområden. RKD-programmet kommer även att innefatta data från SMHIs synoptiska nät, liksom från Vägverkets automatstationer. Grundvattennivåerna inom NOPEX-området och i dess randområde kommer att fås från SGUs nät, varvid en ny station kommer att upprättas centralt inom området. Kompletterande data från andra nät kommer också att infogas i RKD, t ex vattenkvalitetsdata och vattenståndsregistreringar från länsstyrelser och kommuner.

NOPEX databas

Det mest påtagliga resultatet av NOPEX-projektet kommer att bli den databas som byggs upp. Exakt hur denna skall fungera är ännu inte bestämt, men följande punkter har diskuterats av projektets exekutivkommitté:

- Alla data måste följa en viss minimistandard vad gäller dataformat, databeskrivning och kvalitetskontroll.
- Den centrala databasen kommer att innehålla en kopia av varje mätning. En direktåtkomlig databas kommer att finnas tillgänglig som innehåller beskrivningar av (a) mätningar, (b) modeller och (c) projektdeltagare.
- Alla data skall vara tillgängliga för alla deltagare så snart de själva levererat mätdata eller modellinformation. Alla data beräknas bli fritt tillgängliga efter projektets slut.

TIDSPLAN

NOPEX startade officiellt med ett arbetsmöte i Helsingfors 12-13 november 1991. Fram till 1994, när de första mätningarna skall starta, kommer tiden att åtgå till planering och förberedelse. NOPEX' huvudfas skall pågå i tre år under perioden 1994-96. Under perioden t o m 1994 kommer olika typer av bas- och bakgrundsdata (ex vis topografi, markanvänding, markegenskaper, bladyteindex några gånger per år) att samlas in och sammanställas. Olika typer av modeller, speciellt mesoskalemodeller beräknas komma att spela en betydande roll under planeringsskedet. En kvalitetssäkringsplan kommer att utarbetas under planeringsperioden. Under hösten 1992 kommer tilltänkta deltagare att mera formellt få inkomma med förslag på delprojekt. Relevansen av dessa förslag för NOPEX kommer att granskas av projektets exekutivkommitté och godkända projekt kommer att få besked om dess relevans, som kan användas i samband med reguljära ansökningar om medel. Exekutivkommittén kommer också att lämna förslag på förbättringar och förändringar som t ex kan öka samordningsvinsterna och chanserna att erhålla medel från EG eller nordiska fonder.

Mätfasen beräknas kulminera 1995, vilket möjliggör för forskare som är engagerade i andra stora landyteprojekt att delta (EFEDA 1993; BOREAS, 1994). Under NOPEX' huvudfas kommer tre (och möjligen flera) KFS att genomföras. Dessa skall pågå ungefär en månad vardera. Beroende på väderförhållandena kommer några dagar under dessa månader att väljas ut för speciellt intensiva mätningar. Tre KFS är för närvarande tilltänkta:

- Vinter - sällan studerad och dåligt förstådd
- Vår - den period när växttäcket förändrar sig som mest
- Sommar - när markvattenstress kan inträda

Årliga möten, vilka skall cirkulera mellan olika platser i Norden, kommer att hållas mellan 1992 och 1997. Dessemellan kommer ett antal olika specialgrupper att sammanstråla för att diskutera specifika problem.

FINANSIERING AV NOPEX

NOPEX-projektet har mycket av sina vetenskapliga mål gemensamma med tidigare och planerade storprojekt som HAPEX och FIFE. En betydande skillnad mot dessa är finansieringssättet, som i NOPEX grundar sig på två huvudidéer. För det första att hålla nere kostnaderna genom att använda sig av existerande resurser och infrastruktur på ett intelligent sätt. För det andra att hålla nere centrala kostnader till ett minimum. Detta sker genom att varje deltagare själv måste ansvara för de medel som skall täcka hans/hennes medverkan, även om insatsen bedöms som vital för hela projektets genomförande. Viss administrativ hjälp planeras dock finnas till hands för att hjälpa deltagare från det tidigare Sovjetblocket att få fram medel för resor och uppehälle i och till NOPEX-aktiviteter.

Svenska forskningsorgan (FRN, NFR och SNV) beräknas ansvara för den fasta utrustning som krävs för att få projektet att fungera, liksom för en del av kostnaden för att driva NOPEX centralkontor. Medel från Nordiska Ministerrådets miljöforskningsprogram 1993-97 beräknas täcka resterande kostnader för drift av centralkontoret, liksom även för ett antal specifika forskningsprojekt. För deltagare utanför Norden beräknas främst EGs miljöforskningsprogram, men även olika nationella forskningråd, komma att finansiera deltagande.

ORGANISATIONEN AV NOPEX

För samordning av de olika aktiviteterna inom NOPEX har två olika styrgrupper börjat verka. Den vetenskapliga bedömningen handhas av en internationell exekutivkommitté bestående av:

- Reinder Feddes, Nederländerna
- Sven-Erik Gryning, Danmark
- Sven Halldin, Sverige
- Ulf Högström, Sverige
- Anne Jochum, Tyskland
- Juhan Ross, Estland
- Juhani Virta, Finland
- eventuell kontaktperson inom BOREAS-projektet

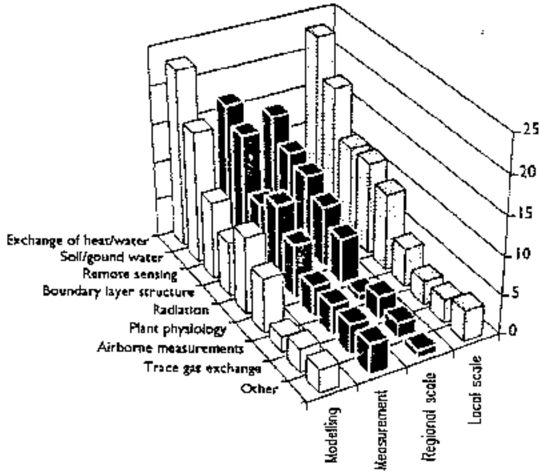
Ansvaret för allehanda praktiska arrangemang handhas av den grupp som ansvarar för NOPEX såsom NHP-projekt:

- Sven Halldin, Sverige
- Sofus Linge Lystad, Norge
- Sirkka Tattari, Finland
- Anton Thomsen, Danmark
- Halldor Thórgeirsson, Island

NHP-gruppen skall bl a ansvara för de cirkulerande, årliga mötena. Vidare planeras en serie intensiva nordiska doktorandkurser, vilka skall synkroniseras med mätkampanjer och större möten. Om medel beviljas för detta utbildningsprogram kommer NHP-gruppen att ansvara för genomförandet.

För att kunna genomföra de intensiva KFS-programmen måste de olika forskarna och forskargrupperna delas upp i ett antal hanterbara grupper. Den indelning som är tänkt baserar sig på kompetensprofilen hos de mer än femtio forskare från tio olika länder som konstituerade NOPEX i Helsingfors i november 1991 (Figur 4). Fyra grupper har ansetts som en rimlig uppdelning, nämligen:

- Utbyten av värme, vattenånga, koldioxid och övriga spårgaser
- Mark- och grundvattenförhållanden. Växternas vattenförhållanden
- Fjärranalys och strålningsbudgetar
- Gränsskiktsmeteorologi och flygburna flödesmätningar



Figur 4. Kompetensprofilen hos forskare som konstituerade NOPEX-projektet i november 1991

Efter mötet i Helsingfors har det tillkommit ytterligare forskargrupper som anmält sitt intresse och sökt medel för deltagande i NOPEX. På detta sätt har kompetensen inom fjärranalyssidan stärkts påtagligt. Förfrågningar har under början av 1992 också tillkommit i betydande grad från forskare som intresserar sig för växtfysiologiska och växtbiologiska frågor, liksom från forskare med inriktning mot atmosfärskemi och näringsämnesbudgetar. En liknande tillströmning från andra vetenskapsgrenar kan komma att modifiera organisationen av forskargrupper inom NOPEX, sannolikt genom att kräva skapandet av ytterligare specialistgrupper.

För det praktiska genomförandet har NOPEX centralkontor påbörjat sin verksamhet. Kontoret består för närvarande av tre personer:

- Sven Halldin, projektkoordinator
- Lars-Christer Lundin, organisationsansvarig
- Iréne Johansson, sekreterare

Under huvudfasen beräknas centralkontoret utökas med ytterligare två personer. En med ansvar för centralt beslutade och genomförda mätningar samt en som ansvarar för uppbyggnad och underhåll av projektets databas. Som stöd för sin verksamhet backas centralkontoret upp av sex institutioner vid Uppsala Universitet, Sveriges Lantbruksuniversitet och Sveriges Geologiska Undersökning.

COMPARISON OF TWO MODELS TO SIMULATE SOIL-VEGETATION-ATMOSPHERE INTERACTION ABOVE A BARLEY CANOPY

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T. Tourula M. Heikinheimo	Finnish Meteorological Office, Helsinki	Finland

ABSTRACT

Two different models (Deardorff, SOIL) were used to simulate the surface energy fluxes above a barley field in southern Finland. The models were compared against the ground truth data measured with Bowen ratio system. The measured data has been investigated with a quality control model. Approximately 60 per cent of the measured daytime latent heat flux data can be considered reliable.

Both of the models simulate satisfactorily the latent heat fluxes during a short time period e.g., a few days. SOIL tends to overestimate the latent heat flux during late afternoon, while Deardorff model slightly underestimates them. Both of the models start to deviate from the measured values when simulation period increases.

INTRODUCTION

Evidence from general circulation model experiments shows that the climate is strongly sensitive to soil moisture changes and the representation of the evaporation process in the models (Walker and Rowntree, 1977). Recently, many experiments studing the soil-vegetation-atmosphere interface has been launched firstly to develope better representations of the complex nature of land surface processes and secondly to test the validity of these models.

In the literature there are many detailed evapotranspiration procedures which include soil water movement, vegetation storage and evaporation from soil surface as well as intercepted precipitation including dew formation (e.g. Sellers et al., 1986). On the other hand, in practice, the evapotranspiration is typically formulated in conceptual models mainly as an empirical function of the soil water storage (Bergström, 1992). In the first mentioned example, the models depend on adequate description of physical and biological characteristics of land surface and vegetation.

Accurate initial conditions are important for short time modelling purposes but become less significant for long time modelling studies. The driving varibles, e.g., air temperature, relative humidity, wind velocity and radiation components should be accurately measured in the reference site. These govern the flows at the boundaries between atmosphere and soil and between plant and atmosphere. The most crucial part of model includes the parametrization of the processes involved. The soil water flow is characterized with water retention curve and functions for saturated as well as unsaturated hydraulic conductivity. Plant properties include the parameters describing the functions of plant aerodynamic and surface resistances, the root water uptake and how it is regulated by the soil stress.

The model calibration is usually done against the micrometeorologically measured fluxes. In mesoscale the water balance equation inside a drainage basin can be applied. In this case the components are calculated typically over the period of one month or more. In both cases the accuracy of the used method should be critically examined.

SITE AND MODEL DESCRIPTIONS

In this study two different models were used to estimate the surface fluxes above a barley field in Jokioinen (Lat 60°49' Long 23°30'). The Jokioinen observatory is well provided with different meteorological standard measurements including all radiation components. The Bowen ratio system (Campbell Scientific, Logan, US) was established in the middle of the barley field, introducing a fetch considerable greater than 100 x maximum canopy height (in meters).

The soil-vegetation-atmosphere model used in this study has been described by Taconet (1986). It is based on the formalism of Deardorff (1978). The energy budget equations are simultaneously solved in the ground level as well as on the canopy level. The vegetation is described by one layer only, which shields the ground more or less depending on the leaf area index. The soil compartment is divided into two parts, the upper surface layer (0-0.10 m) and the whole root zone (0-1.2 m). The water which reaches the soil surface infiltrates first to the upper layer and the lower layer is filled after the upper layer becomes saturated. The stomatal resistance is calculated as a fuction of radiation, soil water status and minimum resistance to transpiration, which describes the seasonal dependance on the physiology of the vegetation (Sucksdorff et al., 1990).

The model parameters has been tested through a sensitivity analysis. Soarès et al. (1988) have shown that over a bare soil the model is most sensitive to three parameters, which are the heat conductivity, hydraulic diffusivity and so called limiting evaporation based on the soil properties. Over dense canopies the leaf are index, height of vegetation and minimun resistance to transpiration become more important. Over partial canopies the model is sensitive to all six above mentioned parameters.

The SOIL model is described in detail by the author of the model, Jansson (1991). On the contrary to Deardorff model, the basic structure of the SOIL model is a depth profile of the soil. Two coupled differential equations for water and heat flow represent the basis for the model. The most important functions to cover the soil water flow include the determination of water retention curve and the unsaturated hydraulic conductivity. Evaporation process can occur as transpiration and root water uptake, as soil surface evaporation and evaporation of intercepted water. Reduction of transpiration occurs when the soil dries and also because of low soil temperature. As the Deardorff model, the SOIL model requires information on the plant canopy height, leaf area index and resistance between the atmosphere and vegetation.

Jansson (1986) concludes that the complicated sensitivity patterns of the model parameters demonstrates the problem of estimating parameters with fitting techniques to models where many parameters can be changed. Anyhow, the unsaturated conductivity was found to be important when simulating water tensions. When simulation water balances saturated hydraulic conductivity was of minor importance. According to Ahonen et al. (this report) the tortuosity factor affected mostly the amount of percolated water while the pore size distribution was important in soil water storage amounts. The lack of long time reliable flux measurements e.g. sensible and latent heat fluxes, has been the limiting factor in comparing the model sensibility on the evapotranspiration compartment.

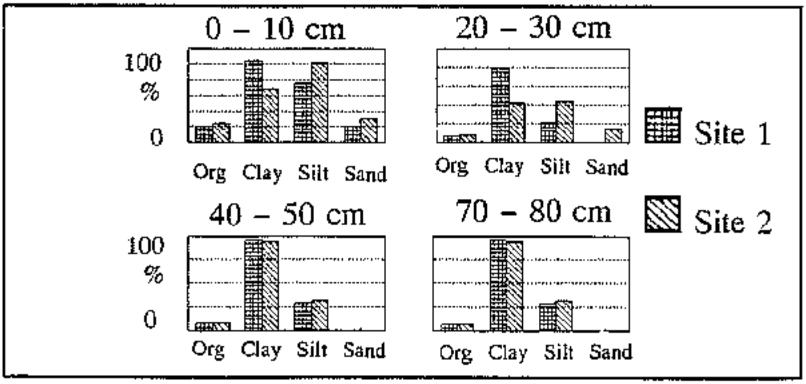

Fig. 1. The soil texture measurements at different depths at two sites inside the barley field.

INITIAL AND PHYSICAL PARAMETERS

In this study the initial state variables were based on the measurements made in the field. Some of the soil properties such as texture, saturated hydraulic conductivity and porosity were measured while some other, e.g., pore size distribution, tortuosity factor, were taken from literature. An example of the soil texture variability is shown in figure 1. The soil samples were taken in the vicinity of the study area from two different sites. The textural variability is most evident in the surface layer, but decreases considerably by depth. The parameters describing the plant development, such as leaf area index and canopy height, were measured in the field and an estimate for stomatal resistance (r_s) was solved from the Penman-Monteith equation using the Bowen ratio value for evapotranspiration. In figure 2 the estimated leaf area index (LAI) development is presented. The LAI value reaches the maximun (3.2) at the end of July.

Stomatal resistance and aerodynamic resistance play an important role, because they control the partitioning of the available energy between the sensible and latent heat flux. The r_s typically increases to a very large value as soil moisture becomes limiting and plants approach wilting point. Turner (1991) claims that in many species, closure only begins when approximately one-half to two-thirds of the extractable water in the soil has been utilised. In figure 3 the daily variability of r_s in barley field is presented during four consecutive days after an initially dry and wet soil water status. The meteorological conditions during the periods were nearly similar. Figure shows that the increase in r_s during a day is fairly moderate and similar in dry and wet soil conditions. The difference, approximately 100 s/m, between the r_s values between these two groups is obvious, reflecting the closure of the specie in dry soil situation.

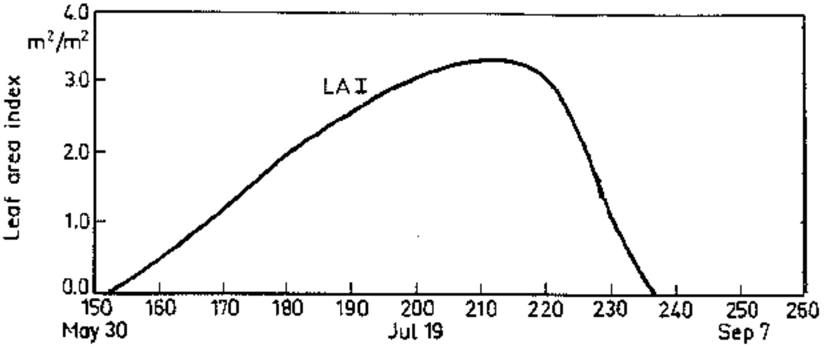

Fig. 2. The estimated leaf area index in barley field in Jokioinen.

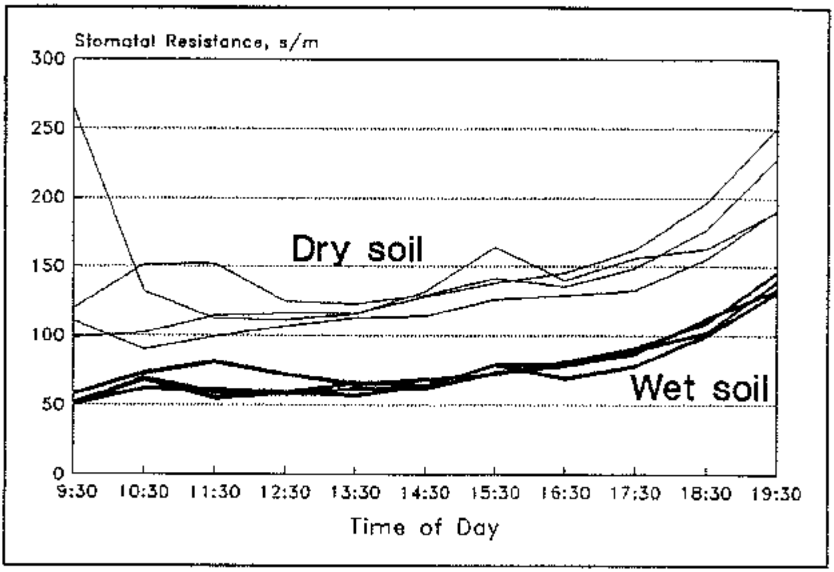

Fig. 3. The 'big leaf' stomatal resistance obtained from Penman-Monteith equation during 4 consecutive days after an initially dry and wet situations.

ACCURACY OF FIELD FLUX MEASUREMENTS

The Bowen ratio system was used to estimate the sen$ible and latent heat fluxes above the canopy. The method utilizes the flux gradient relationships and is based on the surface energy balance. The assumption of the similarity between the turbulent exchange coefficients is made. In addition to the gradients of temperature and vapour pressure, net radiation, soil heat flux and soil surface temperature are variables needed in determining.evapotranspiration.

The micrometeorological measurement devices are typically sensitive to weather conditions, e.g., rainfall events and wind direction. Moreover, the interception of precipitation is seldom observed because of condensation of water on the tubes after the precipitation or after dew formation (Tattari, 1991). The quality control of the field data is essential for evapotranspiration estimates. In figure 4 the calculated latent heat flux is shown together with the quality control status data for a period of one week. The figure shows that approximately 60 per cent of the daytime data of latent heat flux can be considered accurate (Status is one). This has to be taken into account, when comparing the measured and modelled flux quantities. Unfortunately, the quality control status does not include measurement errors in net radiation nor in soil heat flux. Further, it does not include the instrumental errors. This problem can be overcome by instrumental calibration.

MODEL COMPARISONS AND DISCUSSION

The modelling results were compared during one week period starting 25th of July (Fig 5). Initial soil water content varied from 30 volume per cent in the upper layer to a saturated value in lower layers. Net radiation reached values around 500 W/m^2 during midday decreasing sligthly towards the end of the week. Wind speed was low, appr. 2 m/s during the first day increasing to 4 m/s at the end of the week. Wind direction was favourable during the whole period.

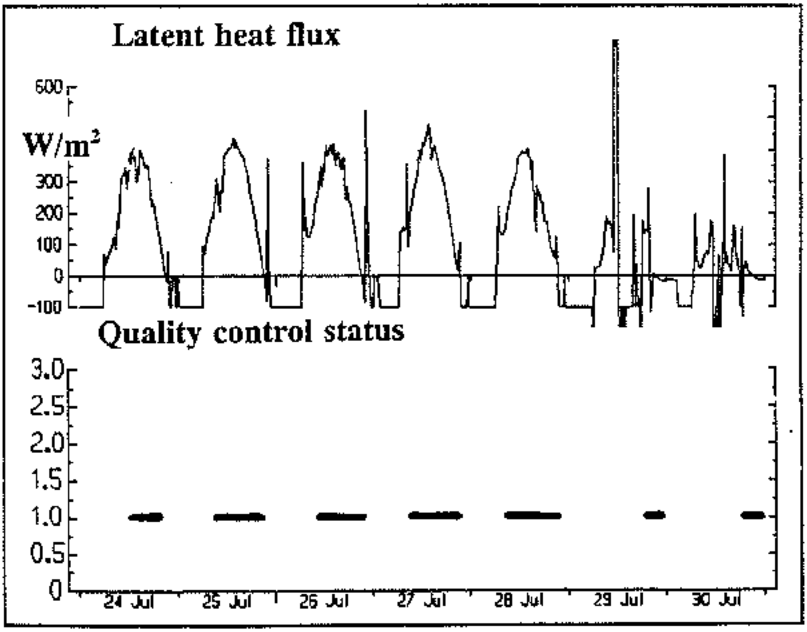

Fig. 4. The measured latent heat flux in Jokioinen provided with the error status, where number 1 corresponds to reliable data.

In figure 5 the modelled and measured latent heat fluxes are shown. The measured latent heat flux values seem to indicate that the soil water content is not a limiting factor during the period. SOIL tends to overestimate the latent heat flux during late afternoon, while Deardorff model slightly underestimates it. Both of the models start to deviate from the measured values when simulation period increases.

Both of the models introduce a great amount of model parameters. The models seem to be able to simulate the latent heat fluxes during short time periods satisfactorily. Anyhow, longer simulation periods in different climatic and soil conditions are needed to test the validity of the used parametrizations. One of the factors that affects the stomatal resistance is the physiological age of the crop (Taconet et al., 1986). For longer simulation runs, provided the age developed is known, the proper parametrization of r_s could improve the modelling results. The measured flux values has to be investigated critically by using quality control techniques and the comparison performed only with reliable data or periods.

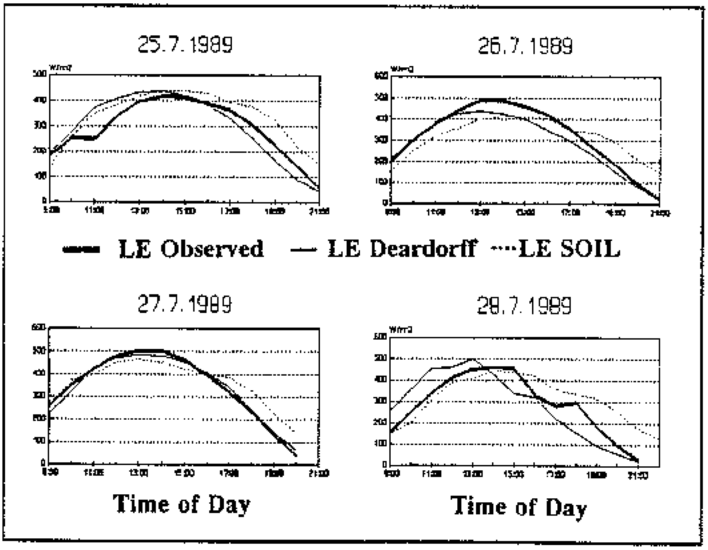
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Fig. 5. Daily variability of latent heat flux simulated with Deardorff and SOIL models and measured with Bowen ratio system.

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IMPROVED EVAPOTRANSPIRATION ROUTINE IN THE HBV RAINFALL-RUNOFF MODEL

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ABSTRACT

This paper adresses the calculation of evapotranspiration losses and soil moisture deficits in the conceptual HBV model. Evapotranspiration losses are in the HBV model calculated as the sum of water lost from the soil water zone and direct lake evaporation. The potential values are normally given as standard monthly values. The loss of water through evapotranspiration is in this study related to the variation in low flow, quantified through recession parameters. Four different versions of the HBV model which differ in the calculation of evapotranspiration have been incorporated, including calculations using the AMOR model. The AMOR model is based on the Penman-Monteith equation for calculating evapotranspiration and accounts for the effect of vegetation and soil properties in the calculations. This work focuses on the difficulties involved in modelling the observed variation in the recession rate using the different versions of the HBV model. This includes both the seasonal variation as well as the trend in the recession rate itself, and is also reflected in lower recession variability and lower correlations with evapotranspiration than found in the observed case. Improvements in the model structure seem necessary in order to evaluate the performance of the different estimates of evapotranspiration. The results do however, point to important issues which will govern further modelling work.

INTRODUCTION

In conceptual models the catchment processes are given a mathematically description inspired by consideration of the physical processes involved. Many conceptual models are designed for a specific purpose, for instance flood modelling, which is reflected in the choice of model representation. Two important issues should be considered in this context. First, the choice of model representation depends on which processes are thought to be most important, giving other "less" important processes a very simple representation or none at all. Secondly, care should be taken applying the model outside the design area. However, if a conceptual model is to be used as an all year model it might be necessary to include processes that dominate at different times on an equally level.

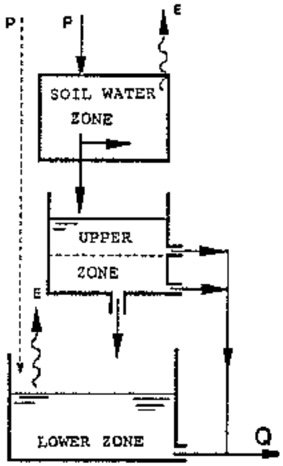
The conceptual HBV-model which originally was designed for flow forecasting, has been widely used for hydrological simulations and forecasting in Norway and Sweden, and its application today comprises more than 27 countries (Harlin, 1992). This paper adresses the calculation of evapotranspiration losses and soil moisture deficits in the HBV model. The loss of water through evapotranspiration is in this study related to the variation in low flow, quantified through recession parameters. A prior study (Tallaksen, 1991) has found a clear seasonal dependence in the recession rate. Of equal importance is the influence of evapotranspiration losses on the soil moisture deficit, which in turn determines the runoff response to precipitation. In a recent study, Bergström (1992) shows how the traditional HBV model with monthly standard values of potential evapotranspiration, fails during summers with extremely bad weather. Under such conditions the model simulation of soil moisture deficit is too high as a result of evapotranspiration losses being overestimated.

The HBV model is in this study tested on data from the Sæternbekken catchment. Four successively more complicated representations of evapotranspiration are incorporated, including estimates calculated using the AMOR model. The AMOR model is based on the Penman-Monteith equation for calculating evapotranspiration and accounts for the effect of vegetation and soil properties in the calculations. The model does however, only account for soil moisture variation and does not model runoff. The need for a better representation of the soil moisture routine in the AMOR model has lead to the formulation of this study, where the AMOR model is extended to also include the soil moisture and drainage components of the HBV model. The HBV model on the other hand, could benefit from a better representation of evapotranspiration losses and thereby soil moisture status. The overall model performance is evaluated using standard measurements of model fit, whereas the model's low flow performance is evaluated using recession analysis.

The study is part of on ongoing project, and therefore only limited conclusions can be drawn. The results do however, point to important issues which will govern further modelling work. The project is supported by the Norwegian National Committee for Hydrology (NHK) and Fund for Licensing Fees - as a national contribution to the Nordic project "Climate change and Energy production".

THE HBV MODEL

The main components of the dynamic part of the HBV model are a nonlinear soil moisture submodel and a piecewise linear storage system, Figure 1. This part of the model has eight model parameters. The three main modules are the soil water zone, upper zone (surface flow and interflow) and lower zone (ground water). Lakes are regarded as an integrated part of the lower zone.



MODEL PARAMETERS (selected values)

Beta (3.0): nonlinearity root constant
FC (150): zone water content at saturation (mm)
LP (60): threshold value for potential evapotranspiration(%)
UZ1 (15.0): threshold value for rapid response, upper zone (mm)
KUZ1 (0.80): drainage coefficient,upper zone, rapid response (1/d)
KUZ (0.12): drainage coefficient,upper zone, slow response (1/d)
PERC (0.40): percolation to lower zone (mm/d)
KLZ (0.04): drainage coefficient, lower zone (1/d)

Figure 1 HBV model structure (P: Precipitation, E: evapotranspiration, Q: discharge, T: temperature).

The soil water zone has a nonlinear retention that is governed by two parameters, FC (zone water content at saturation) and BETA (nonlinearity constant). Water is removed from the zone by throughflow to the upper zone provided that there is precipitation, and by evapotranspiration. The ratio of actual evapotranspiration to potential, varies linearly with zone water content. Potential evapotranspiration is given as standard monthly values, whereas precipitation and temperature are given as daily inputs. The upper zone drains at a constant rate, PERC, to the lower zone. Runoff is generated from the upper zone through a piecewise linear response where KUZ and KUZ1 are runoff coefficients for slow and rapid response respectively, and UZ1 the threshold value for rapid response. The lower zone generates runoff at a linear rate, KLZ, with maximum lower zone water content LZmax, given by PERC/KLZ and maximum drainage by PERC.

The model was calibrated combining a subjective judgement with standard measurements of model fit, i.e. volume differences, summed squared relative deviation and model efficiency, R^2, which is the proportion of the initial variance accounted for by the model (Nash & Sutcliffe, 1970). In the initial calibration emphasis was put upon the general catchment behaviour, whereas later modifications were limited to alterations in the lower zone parameters as well as in the calculation of evapotranspiration losses. The HBV model was not developed for use at very small catchments, where responses are fast and the effect of integration of processes in time is small. Consequently, small catchments will be more difficult to calibrate using the simple HBV model concept. The main model parameters finally selected are given in Figure 1. Important considerations regarding the choice of parameters are presented later in the text.

Three years were used for calibration, whereas the simulation period comprises 10 years (1977-1986). It was not possible to obtain a high model fit, R^2 equals 0.70 for the calibration period, which could be related to some particular difficult areas of calibration. The same set of values for the two snow temperature threshold parameters (melting/no melting & snow-/rain precipitation), did not permform equally well throughout the winter season.

There was also found to be a contradiction between making a good model fit in both summer and autumn. The soil moisture deficits during summer time are generally high, and the base flow is low, but rarely zero. It was only during the warm summer of 1976, that the catchment ran dry for an extensive period. The same parameter set did not manage to reproduce both the low summer base flow, disrupted by minor, but steep floods, and at the same time produce sufficiently high autumn floods and slow recession rate at low flows. A reduction in summer base flow and an increase in the recession rate can be obtained by increasing the potential evapotranspiration in this period. However, in order to achive this effect we had to assume unrealisticly high values for potential losses. The drainage parameters selected in the model were chosen as a compromise between the summer and autumn flow patterns.

METHOD

The different HBV model representations are tested on data from the Sæternbekken research catchment (Erichsen & Nordseth, 1985), situated about 10 km west of Oslo. Catchment area is 5.8 km^2, and the altitude ranges from 110 to 422 mas. Lake area is less than 1 %, bog and cultivated land accounts for 7 and 6 % repectively, whereas the rest (87%) is forested. Apart from a minor glaciofluvial deposit in the valley bottom (5%), the area has a thin cover of till. The climate station is situated about 5 km south-west of the outlet, at an altitude of 59 mas. The catchment responds quickly to precipitation, lagtime is between 6 and 12 hours. Evapotranspiration losses have shown to have pronounced influence on the water yield during the summer period in this area (Tallaksen & Erichsen, 1992). Summer base flow is low, but the river seldom runs dry. Due to the extensive forest cover, comprising mainly conifers, the interception loss during summer time is expected to be high.

Four different versions of the HBV model which differ in the calculation of evapotranspiration have been included in this study, Table 1.

Table 1 Different versions of the HBV model.

	HBV-1	HBV-2	HBV-3	HBV-4
EPOT, time	monthly	monthly	daily	daily
EPOT,model	standard	standard	temp-index	Pen-Mon.
Uptake	NO	YES	YES	YES

The original model, labelled HBV-1, operates with standard monthly potential values for evapotranspiration labelled Epot1 in Table 2. The Epot3 values are monthly indexes included as part of the calculation in the HBV-3 model version.

Table 2 Monthly standard values for evapotranspiration.

Epot1	0.0	0.0	0.1	1.0	2.0	3.0	2.5	2.0	1.0	0.5	0.1	0.0
Epot3	0.6	0.6	0.6	1.0	1.3	1.4	1.3	1.0	0.6	0.6	0.6	0.6

Andersson (1989) tested the use of individual calculated mean monthly potential evaporation values using the Penman formula and only found marginal improvements in the simulations using standard measurements of model fit. However, in areas with shallow groundwater table, different estimates of potential evapotranspiration will only have limited effect on the low flow simulations unless the model allows for capillary uptake.

By introducing a transport from the groundwater to the soil moisture zone, this effect is in the HBV-2 version, modelled as a function of the maximum uptake (OPPT), the soil moisture deficit (SMdef) and the low zone water content (LZ). The uptake to the soil moisture zone, OLZ, is given as a function of the maximum uptake (OPPT):

$$OLZ = OPPT * LZ/LZmax * SMdef/FC \tag{E.1}$$

OPPT has in this study been given a value of 0.5 mm/day. Mørk (1989) found in case of silt and fine sand, that the capillary transport might become as large as the potential evapotranspiration for groundwater depth less than 0.8 meter. In a study on morainic soils, Myhr (1982) indicates that the transport may reach the order of 0.5-1.0 mm/day during the summer, even when the groundwater table lies deeper than 1 meter. Capillary transport functions have also been introduced in other versions of the HBV model, for example in the PULSE model (Bergström et al., 1985).

In another modification of the HBV model, labelled HBV-3 in this study, the evapotranspiration is made temperature dependent; potential evapotranspiration is assumed to be proportional to temperature above freezing (Sælthun et al., 1990). In the HBV-3a model version the multiplying factor is 0.11, and in version HBV-3b 0.25 mm/day °C. In both cases the potential evapotranspiration is modified by a seasonal index, labelled Epot3 in Table 2, to account for variation in transpiration activity.

Daily estimates of evapotranspiration calculated by the Penman-Monteith equation, are given as input data in the HBV-4 model. Capillary uptake is included in all the models except the HBV-1 model. The Penman-Monteith equation includes factors which depend on the characteristics of the vegetation type. The calculations are done using the AMOR model (Tallaksen, 1991), which also accounts for soil properties in the calculations. The AMOR model has been tested on data from this area (Tallaksen & Erichsen, 1992), and is also given a short presentation in Erichsen & Tallaksen (1992; this volume).

In addition, recession analysis has been incorporated to test the low flow behaviour of the model versions. The analysis considers recession flow below average daily flow. Using an automatic method for calculating recession characteristics (Tallaksen, 1989), variability due to model limitations is reduced by calculating a standard recession where both initial discharge and the length of the recession period are given as constants. The recession rate is quantified through the recession mean value, C-mean, calculated as the arithmetic mean of the recession constants of individuals segments. The segments are automatically selected from the flow series given the initial discharge and the length of the recession in days. It is required, however, that the first value is at least two days from peak of discharge. A recession sequence continues as long as the next flow value is less than or equal to the last value. No limit is put on precipitation during the recession period at this time. To each segment the simple exponential equation (E.2) is fitted by a least square procedure, and the recession constant C, calculated. The recession variability is represented by the coefficient of variation of the sample of segments, C-var.

$$Q_t = Q_0 \exp(-t/C) \qquad \text{(E.2)}$$

Recession mean and variance values are calculated for up to nine different starting levels, all given as percentages of average flow. Recession length is seven days. Due to low resolution in discharge measurements at low flows, the data are frequently recorded in a staircase manner. Steps in the flow series complicate the use of recession analysis, and the steps have therefore been modified by fitting an exponential decay curve between decreasing neighbour points in the series.

RESULTS AND DISCUSSION

A varity of model simulations and corresponding recession analysis have been performed. The general model performance has been evaluated using standard measurements of model fit, whereas its recession behaviour and related seasonal variation have been analysed by looking at the recession mean and variance values, obtained by the procedure described above. The recession parameters have been calculated over a 10 year period, however, only data from the period June to October are included in order to avoid the influence of snow and ice.

In order to investigate possible relationships between the recession rate and the seasonal variation in evapotranspiration, a correlation analysis is performed including the recession constant C of the observed series, along with the different models' estimate of potential evapotranspiration summed over the recession period. In addition, estimates of evaporation calculated using the Penman equation (Penman, 1948) are included. Correlation coefficients have been calculated for six successively lower starting levels, and the results are presented in Table 3. EPmnd and EPtemp relates to the HBV-1 & 3 model estimates, respectively. No refers to the number of recession segments in each case.

Table 3 Correlation coefficients between the observed recession rate and four different model estimates of potential evapotranspiration.

QSTART	No	P-48	P-Mon	EPmnd	EPtemp	temp	prec
100%	19	-.83**	-.81**	-.71**	-.69**	-.76**	-.26
75%	16	-.83**	-.79**	-.68*	-.70*	-.79**	-.32
50%	16	-.79**	-.75**	-.73**	-.75**	-.79**	-.26
30%	12	-.69*	-.64	-.54	-.62	-.68*	.02
20%	7	-.71	-.67	-.35	-.55	-.66	-.03
10%	7	.03	-.07	-.07	-.24	-.33	.71

1-tailed Signif. * .01 ** .001

As it can be seen from the table, the seasonal variation in evapotranspiration has a marked influence on the observed recession rate, particulary for the highest starting levels. Slightly higher values are obtained for the Penman-48 and Penman-Monteith estimates. The analysis is repeated when segments influenced by precipitation are removed from the sample. Only minor deviations are found using a precipitation limit of 1 mm a day in average.

There is a generally increase in the recession constant, i.e. slower recession rates, for the observed series as the flow decreases. This trend is shown in Figure 2, where the mean recession constant is plotted agaist starting values.

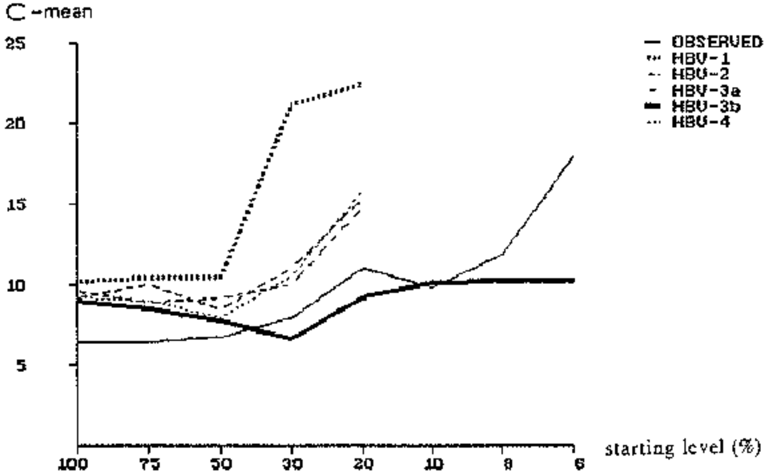


Figure 2 Trends in the mean recession constant for observed and simulated series.

The question is now to what degree the different versions of the HBV model are capable of reproducing the observed trend in the recession rate, as well as the high variance encountered, and if so, can the variability be related to a seasonal varying evapotranspiration as found in the observed case?

Figure 2 shows that the recession rate for high starting levels is generally faster than in the simulated series. It is, however, important to be aware that the model parameters have been selected in order not only to resemble the recession rate, but also to give a general acceptabel model fit for both high and low flows. It is only the HBV-1 model that produces a steady increase in the mean recession constant as starting level decreases. The increase is however, overestimated, and governed by the lower zone drainage coefficient, KLZ. KLZ is recommended to be within the range 0.01 to 0.05, which corresponds to a recession constant C, of 100 and 20, respectively. These values are generally too high for the summer recession of small catchments, unless water is lost otherwise. The introduction of a capillary uptake from the groundwater to the soil water zone as in the HBV-2 model, leads to a clear reduction in the recession rate. A similar trend in the mean recession constant is found for the HBV-3a and HBV-4 model versions. The HBV-3a model version has the same lower zone drainage parameters as HBV-1,2 & 4, whereas in HBV-3b an increase in the drainage coefficient (KLZ=0.05), is combined with a lower zone water content (PERC=0.30), in order to yield faster recessions.

The structure of the HBV model will often produce a minimum in the recession constant when the upper zone empties. This minimum becomes more pronounced by introducing a capillary uptake. The minimum is for the chosen parameter values, typically found at the 50 % starting level. Its location depends, however, on the parameter values and there will be a shift towards lower levels for lower water capacities, as can be seen for the HBV-3b simulations.

The coefficient of variance, C-var, is in the range 0.4-0.6 for the observed series, whereas values for the simulated series typically varies between 0.1 and 0.4. As to the question of how the different model versions can account for the observed effect of evapotranspiration, analyses show that it is not possible to detect any relationships between the recession rate and corresponding evapotranspiration losses, unless a precipitation limit is imposed. The high correlations found between the simulated recession constant and even minor amounts of precipitation, indicate the need for calculating interception losses. Particularily during periods with high evaporative demand, losses due to interception might be considerable. Table 4 presents the correlations found between the simulated recession rates and the related estimate of potential evapotranspiration provided a precipitation limit.

Table 4 Correlation coefficients between simulated recession rate and related estimate of potential evapotranspiration provided a precipitation limit. Number of segments are given in brackets.

QSTART	HBV-1	HBV-2	HBV-3a	HBV-3b	HBV-4
100%	-.40(12)	-.58(13)	-.18 (13)	-.84**(11)	-.32 (11)
75%	-.09(12)	-.46(13)	-.49 (19)	-.85**(16)	-.29 (14)
50%	.38(9)	-.42(10)	-.74*(10)	-.81**(14)	.06 (12)
30%	.46(9)	.65(11)	.67 (8)	-.32 (16)	.43 (7)
20%	(3)	-.76(6)	-.59 (5)	-.12 (17)	(3)
10%				-.72* (11)	

1-tailed Signif. * .01 ** .001

Table 4 shows significantly lower correlations with potential evapotranspiration than found in the observed case (ref. Table 3). The higher correlation figures found for the HBV-3b series are due to more than a doubling of the potential evapotranspiration losses in this case, which was introduced to obtain higher recession rates during summer time. Consequently, the correction factor for precipitation had to increase in order to ensure a correct water balance. However, the new estimates for potential evapotranspiration were much higher than the Penman-Monteith estimates which are thought to give reasonable values. It may in this context also be necessary to focus on the calculation of actual evapotranspiration in the model, and perhaps allow for increased losses by imposing a lower threshold value for potential evapotranspiration (LP), accomplished by larger water storages available for evapotranspiration. Further modelling work and simulations will focus on these issues.

Special features of the model structure related to the calculation of evapotranspiration losses can clearly be recognized in the simulated HBV-3b series, where high correlations are found at high and very low recession levels. Similar variation in the correlations is not found in the observed case. Only minor variations are found between the standard measurements of model performance of the different simulated series. The only exception is the HBV-3b simulation, which shows a significant lower model fit than the others.

FURTHER RESEARCH AND CONCLUDING REMARKS

This analysis has focused on the difficulties involved in modelling the observed variation in the recession rate using the different versions of the HBV model. This includes both the seasonal variation as well as the trend in the recession rate itself, and is also reflected in lower recession variability and lower correlations with evapotranspiration than found in the observed case.

So far the interaction between the HBV and the AMOR models has been limited to include potential estimates of evapotranspiration as input values to the HBV model. The model performance is similar to using more rough estimates of evapotranspiration. However, neither of the model versions are able to reproduce the observed relationship found between evapotranspiration losses and recession rates. This is primarily related to features of the model stucture, and improvements here seem necessary in order to evaluate the performance of the different estimates of evapotranspiration.

In the AMOR model, estimates of potential evapotranspiration is converted to actual evapotranspiration by adjusting the bulk surface resistance according to the soil moisture deficit. Up to a soil moisture deficit of 40% the evapotranspiration is potential, below this limit it reduces progressively to very small values. The same threshold value has been chosen for the HBV model versions in this study. The HBV model, however, uses a linear reduction with soil moisture content. Further work will evaluate different algorithms for calculating actual evapotranspriation.

The analysis has also shown that the model response to minor precipitation events during summer time is too high, and it is important to account for interception losses. In future model runs precipitation will be corrected by including the AMOR model calculation of interception losses. It is generally recommended to model evaporation of intercepted water and transpiration separately in forested areas.

The advantage of the Penman-Monteith equation as compared to the traditional Penman equation, is primarily related to the possibility to calculate actual evapotranpiration by adjusting the bulk surface resistance. As vegetation are represented explicit in the calculations, it also allows for an evaluation of possible consequences due to land use and climate changes.

The linked HBV-AMOR model will also be evaluated for use at the regional scale, by applying it for different physiographic and climatic conditions. Selected catchments from the FRIEND data base (Flow Regimes from International Experimental and Network Data (UNESCO, 1991)) will be included in the analysis. A joint project in the FRIEND group 2 (low flows) will study the effect of land use and climate change on the low flow regime, and compare low flow indices simulated using different rainfall-runoff models.

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BRUK AV EN DIGITAL TERRENGMODELL I SNØSMELTEMODELLER

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ABSTRACT

This article describes a project investigating the use of a geographical information system (GIS) in snowmelt runoff forecasting. A digital terrain representation aids modelling the spatial variation of meteorological input data. The project includes a field study of two small catchments in Telemark, Central Norway. Preliminary results from multiple regression analysis show substantial differences in the energy components' relation to the melt rate when comparing a mainly north-facing catchment to a catchment facing the opposite direction.

INNLEDNING:

Denne artikkelen beskriver det arbeide som gjøres i forbindelse med en hovedfagsoppgave i naturgeografi ved Universitetet i Oslo. Formålet er å undersøke nytten av en GIS-basert, arealfordelt snøsmeltemodell der de meteorologiske variablene fordeles ut fra variasjonen i topografiske parametre. En terrengmodell i rasterformat konstruert fra digitaliserte høydekoter representerer topografien, og danner samtidig enkeltcellene i den fordelte smelterutinen. De fleste leddene i energibalanseligningen representeres i smelterutinen. Meteorologiske variable måles med tidsoppløsning på en time.

Hvorfor en fordelt modell?

Sammenligninger mellom snøsmeltemodeller av ulik kompleksitet er gjort av en rekke forfattere, for eksempel Bengtsson (1976), Kuusisto (1978, 1984), Harstveit (1984) og Sand (1990). Til dels er det trukket svært ulike konklusjoner om nytten av mer komplekse modeller enn rene graddagsmodeller. Det er funnet store variasjoner i graddagsfaktorer, særlig mellom åpne og skogdekte områder.

Zuzel & Cox (1975) har analysert de ulike meteorologiske faktorers relative betydning for smelting, og konkluderer med at temperatur trass i å være den best egnede enkeltvariabelen ikke bidrar til økt forklaringskraft i en modell der vindhastighet, nettostråling og damptrykk inngår. Bengtsson (1986) relaterer optimal modellkompleksitet til den valgte tidsoppløsningen, og hevder at en graddagsmodell gir tilstrekkelig forklaring på døgnbasis, men at et strålingsledd er nødvendig for å simulere smeltingen fra time til time. Lang & Braun (1990) påviser at sammenhengen mellom målt lufttemperatur og smelting varierer betydelig i tid og rom, og med aktuell skala og tidsoppløsning.

Smelteprosessen er avhengig av en rekke variable, de fleste med betydelig romlig variasjon. En fordelt modell betrakter et nedbørfelt som en mengde av mindre delfelt eller fragmenter, og beregner smeltevolumet i hver del separat. På denne måten simuleres smelteprosessen som funksjon av stedsspesifikke variable. Ulempen er at en må angi meteorologiske variable og andre parametre for hver enkelt del. Vesentlige fremskritt i modellering av snøsmelting avhenger imidlertid av at en løser problemene med å koble fordelte meteorologiske og hydrologiske modeller (Morris 1991).

Det finnes en rekke interpolasjonsrutiner av ulik kompleksitet (kriging, trendflater, osv.) som estimerer en variabels verdi på et gitt sted. Beregningene baseres på stedets koordinater, målt verdi på en eller flere målestasjoner med kjente koordinater, samt en antagelse om romlig korrelasjonsstruktur. Basert på et nettverk av målestasjoner kan en god fordeling av variabelen oppnås. Målenettets "maskevidde" gjør at slike teknikker som oftest er best egnet til å modellere variasjoner i stor skala. Isaritmekart for trykk, temperatur og nedbør er eksempler på representasjon av fordelte variable som kan brukes som input i en GIS-basert modell.

Til dels uavhengig av interpolasjonsteknikk kan en nyttiggjøre seg korrelasjonen mellom den valgte variabelen og parametre der en kjenner den romlige fordelingen i detalj. I første rekke er topografien egnet til et slikt formål, men også vegetasjons- og løsmasseparametre har sterk samvariasjon med viktige hydrologiske variable. Bruk av slike korrelasjoner gir grunnlag for å modellere romlige variasjoner også i liten skala.

TERRENGMODELLER OG SNØSMELTING

Topografien har sterk innvirkning på de fleste av de variable som styrer snøsmeltingen. Den direkte kortbølgete strålingen er avhengig av terrengets vinkel i forhold til strålingens retning, og dermed av terrengets eksposisjon og gradient. I områder med sterkt relieff vil omkringliggende terreng delvis skygge for denne strålingen.

Snødekkets albedo minker med snøens aldring, som er avhengig av bl.a. temperatur, nedbør og mottatt stråling. Dette medfører at snødekkets albedo øker med høyden, og er størst i nordvendte hellinger.

Den diffuse strålingen varierer mindre med topografien enn den direkte. Variasjonsmønsteret er resultatet av et komplekst samspill mellom topografi i ulike skalaer, værtype og snødekning, og svært vanskelig å estimere sikkert (Obled & Harder, 1978).

Netto langbølget stråling representerer som regel et energitap, fordi utstrålingen fra jorden er mye større enn den innkommende atmosfæriske strålingen. Der en vesentlig del av himmeldomen er dekket av omkringliggende terreng reduseres imidlertid tapet fordi langbølget stråling mottas fra terrenget rundt.

Hva angår de turbulente energibidragene er temperaturens høydeavhengighet godt kjent. Fuktigheten er vanskeligere å fordele, og det er vanlig å anta at den er konstant over et område (Morris 1991). Disse to størrelsene er sterkt gjensidig avhengige, og den romlige variasjonen estimeres best der målinger i ulike høyder støtter berengingen av gradienter.

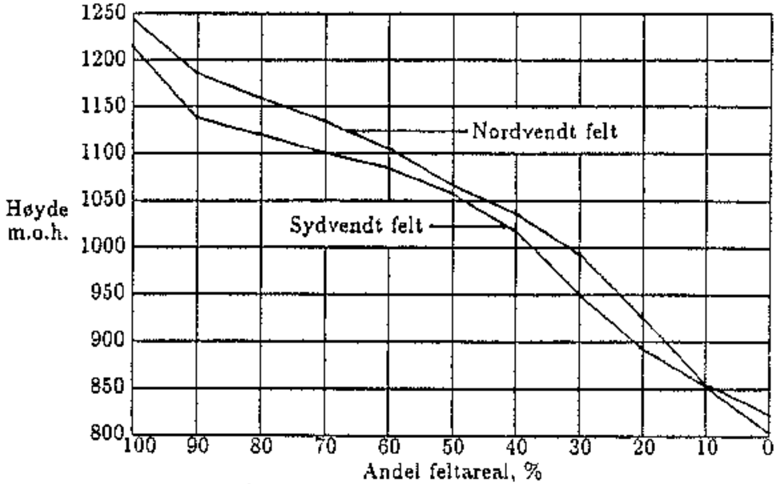
Vind varierer sterkt med topografien, samtidig er denne variasjonen svært vanskelig å simulere kvantitativt. Det er rimelig å anta at vindhastigheten er større på losiden av en forhøyning enn i le, og at konvekse terrengformer er mer utsatt for vind enn senkninger. Imidlertid vil turbulens ofte endre bildet og blant annet introdusere vertikale hastighetskomponenter med stor betydning for turbulent energiutveksling.

Fra et topografisk kart kan en generere fordelte verdier for høyde, terrengets eksposisjon og gradient, samt ulike mål på kurveform eller konveksitet, horisontens høydevinkel i ulike retninger osv. En høydematrise (digital elevation model, DEM) representert ved et regulært gridnett er ofte et første stadium i beregningen av topografiparametre, men det eksisterer også datastrukturer der terrenget representeres ved lineære triangler med kjente hjørnekoordinater, eller irregulære rutemønstre der rutegrensene faller sammen med høydekoter og terrenggradienter (Moore et al, 1991). Enkeltelementene i terrengmodellen brukes også som grunnenhet i den hydrologiske modellen, når disse koples sammen.

PROSJEKTBESKRIVELSE

Feltet:

To små nedbørfelt undersøkes mhp avrenning under vårsmeltingen. Feltene ligger i Tokke kommune i Telemark, ca. seks kilometer fra hverandre. Det ene er overveiende nordvendt, det andre overveiende sørvendt. Feltareal er hhv ca. 1.5 og 2.3 kvadratkilometer. Hypsografiske kurver for de to feltene er gitt i fig. 1. Økonomisk Kartverk i målestokk 1:5000 og ekvidistanse 5m. er grunnlaget for en rasterbasert terrengmodell. Rutestørrelsen er valgt til 50 m., og ut fra en høydematrise beregnes terrengets gradient, eksposisjon og kurvatur.



Figur 1: Hypsografiske kurver beregnet fra høydematrisen

HYDROLOGISKE OG METEOROLOGISKE MÅLINGER

Timesverdier for meteorologiske variable måles på tre ulike steder mindre enn 15 kilometer fra begge feltene, dels ved egne instrumenter, dels på Skafså Kraftverks målestasjon ved Borsæ demning. Måleseriene i 1991 angis i tabell 1.

Tabell 1: Måleserier

Stasjon	Borsæ	Berehommen	Kjønnesvik
Høyde	760 moh	805 moh	825 moh
Lufttemperatur	1/4 - 10/6	5/4 - 11/6	12/4 - 21/6
Luftfuktighet	1/4 - 10/6	16/5 - 21/6	12/4 - 21/6
Vindhastighet	1/4 - 10/6	3/4 - 21/6	
Globalstråling		5/4 - 11/6	
Nedbør	1/4 - 10/6		
Vannføring		26/4 - 21/6	26/4 - 21.6

Data fra limnigrafer i hvert felt regnes om til vannføring i mm/time. På grunn av snøfylte bekkefar er ikke vannføringskurvene, og dermed ikke dataene, brukbare før 26. april. De meteorologiske og hydrologiske dataene danner en tidsserie på 46 døgn fram til 11. juni, da strålingsmålingene opphørte.

Tilrettelegging av data

De tre klimastasjonene ligger med små innbyrdes avstander, og høydeforskjellen mellom dem er liten. Av denne grunn gjøres det ikke forsøk på å trekke slutninger om romlig variasjon i meteorologidata ut fra målingene. Parallelle måleserier for temperatur, fuktighet og vind midles for å gi stabile anslag med få manglende observasjoner. Damptrykket beregnes under antagelse om konstant lufttrykk, og forenklede ligninger basert på en lineær vindfunksjon brukes for å estimere de turbulente energikomponentene:

$$Qh = (3.1 u + 2.3) (Ta - Ts) ,$$

$$Qe = 1.7 (3.1 u + 2.3) (Ea - Es)$$

der Qh er energibidrag fra følbar varme, Qe energibidraget fra latent varme, u vindhastighet, Ta luftttemperatur og Ea damptrykket. Ts og Es er hhv temperatur og damptrykk umiddelbart over snødekket, satt til 0 grader C og 6.11 mbar. De empiriske konstantene er i høy grad avhengige av lokale forhold. De anvendte verdier er optimalisert av Harstveit (1984), som påviser godt samsvar med verdier funnet i andre undersøkelser.

Ut fra målt vannføring beregnes døgnlig tilsig etter en enkel resesjonsalgoritme: Det fastsettes ett og bare ett resesjonstidspunkt pr. kalenderdøgn, 4 timer før døgnets første lokale minimumsvannføring, dog ikke senere enn kl. 20:00. En resesjonsfaktor Kr velges ut fra en vurdering av observerte resesjonsrater. Denne faktoren minker ettersom magasineringen i snøpakka reduseres, og for til en viss grad å ta hensyn til dette, er resesjonskonstanten Kr for begge felt satt til 0.96 ved smeltesesongens begynnelse, og deretter redusert med 0.0006 pr. døgn. Ved hvert resesjonstidspunkt blir det fra den momentane vannføringen Qr beregnet et summert resesjonsvolum Vr, som inngår i beregningen av døgnets smeltevolum.

$$Q(t) = Kr\ Q(t-1) \quad ; \quad Vr = Qr / (1-Kr)$$

FORELØPIGE RESULTATER FRA SMELTESESONGEN 1991

Det er gjort statistiske analyser på sammenhengen mellom de beregnede energibidragene og smelteverdiene. På grunn av redusert snødekning ble seriene stoppet 28. mai, og danner en tidsserie på 31 døgn. For å vurdere energikomponentene i relasjon til et mer heterogent felt er gjennomsnittet av smeltingen i enkeltfeltene tatt med som ny avhengig variabel. Enkel korrelasjonsmatrise er gitt i tabell 2. Multippel regresjon er utført mellom hver av de tre smelteverdiene og de tre mulige kombinasjonene av to energikomponenter, resultater i tabell 3.

Tabell 2: Enkel bivariat korrelasjonsmatrise

Korr.:	temp	damptr.	vind	stråling	følbar	latent
Temp	1.0000	.6574**	.1251	.2741	.8250**	.6084**
Damptr.	.6574**	1.0000	.3499	-.3796	.6793**	.9438**
Vind	.1251	.3499	1.0000	-.0419	.5911**	.1675
Stråling	.2741	-.3796	-.0419	1.0000	.2461	-.3739
Følbar	.8250**	.6793**	.5911	.2461	1.0000	.5946**
Latent	.6084**	.9438**	.1675	-.3739	.5946**	1.0000
Sme/sydv	.7352**	.5203*	.1337	.4338	.6583**	.5409**
Sme/nordv	.8097**	.7477**	.3302	.1156	.8703**	.7097**
Sme/total	.8548**	.7247**	.2809	.2559	.8650**	.7071**

Antall observasjoner: 31 1-sidig signif: * = .01 ** = .001

Tabell 3: Regresjonskoeffisienter mellom smelteverdier og kombinasjoner av to energikomponenter

	Sydvendt	Nordvendt	Summert
Følbar, latent :	0.43	0.80	0.79
Latent, stråling :	0.75	0.65	0.80
Følbar, stråling :	0.48	0.75	0.73

Som det går fram av tabellene er det vesentlig forskjell i de ulike komponentenes forklaringskraft i de to feltene. Korrelasjonsmatrisen viser at den følbare varmeutvekslingen er den enkeltkomponenten med høyest korrelasjon til smeltingen, uansett felt. Legges stråling til økes forklaringskraften 5% i det sørvendte, men bare marginalt i det nordvendte. Latent varme gir motsatt effekt, +5% idet nordvendte, ingen endring i det sørvendte. Velger en stråling og latent varme øker forklaringskraften i det sydvendte feltet radikalt, mens dette er den dårligste kombinasjonen i det nordvendte feltet.

Det er også utført multippel regresjonsanalyse der signifikansgrenser styrer utvelgingen av uavhengige variable. Som metode er benyttet trinnvis inkludering og ekskludering av variable basert på en F-test på samvariasjon. Signifikansnivå på 5% og 10% er valgt for hhv inkludering og ekskludering av variable i regresjonsligningen. Resultatet av analysen for hvert av feltene samt summert avløp fra de to er gitt i tabell 4a til 4c.

Tabell 4a: Multippel regresjon, sydvendt felt. R2 = 0.75

Inkludert:	B	SE B	Beta	T	Sig T
Stråling	.05189	.00696	.73946	7.453	.0000
Latent	.28736	.03488	.81741	8.239	.0000
Konstant	1.01384	1.78078		.569	.5737
Ikke inkludert:	Beta In	Partial	Min Toler		
Følbar	-.02473	-.03177	.35830	-.165	.8700

Tabell 4b: Multippel regresjon, nordvendt felt. R2 = 0.80

Inkludert:	B	SE B	Beta	T	Sig T
Følbar	.34111	.04979	.69350	6.851	.0000
Latent	.17607	.05994	.29732	2.937	.0066
Konstant	-.21938	1.92510		-.114	.9101
Ikke inkludert:	Beta In	Partial	Min Toler		
Stråling	.10770	.18048	.35830	.953	.3488

Tabell 4c: Multippel regresjon, summerte felt. R2 = 0.87

Inkludert:	B	SE B	Beta	T	Sig T
Følbar	.14775	.03803	.41209	3.885	.0006
Latent	.26085	.04785	.60429	5.451	.0000
Stråling	.03279	.00792	.38046	4.138	.0003
Konstant	-.46847	1.58235		-.296	.7694

I begge enkeltfeltene er to komponenter signifikante på 5% - nivå. I det sørvendte feltet utelates følbar varme, mens det i det nordvendte feltet er strålingen som ikke er signifikant. I de to feltene sett under ett gir variasjonen grunnlag for inkludering av samtlige komponenter. Det er da den latente varmen som er viktigst i beskrivelsen.

Videre arbeid

Studiet fortsetter i smeltesesongen 1992, og måleprogrammet er sterkt utvidet. Den ene klimastasjonen er flyttet opp i 1070 meters høyde, i tillegg vil data fra nok en automatstasjon tas i bruk. Denne ligger mindre enn 25 kilometer fra begge feltene, og ca. 450 moh. Når også observert lufttrykk tas inn i datamatrisen vil dataene fra de tre stasjonene gi viktig informasjon om temperaturens og damptrykkets høydegradient gjennom døgnet og gjennom sesongen.

Ut over at smeltingen beregnes fra observert avløp fra feltene, er det vinteren 1992 plassert ut et 30-talls staker som markerer faste punkter med gitte topografiske egenskaper. Gjentatte taksering av snømagasinet ved disse punktene vil gi observerte smelteverdier, som kan tjener som kontroll under tilpasningen av en topografi-avhengig smeltemodell.

Oppsummering

De foreløpige resultatene viser at de ulike energikomponentenes betydning for smelting, og dermed nytten av å inkludere dem i en modell, i stor grad varierer med topografiske parametre. At så klare forskjeller gjør seg gjeldende for felt av denne størrelsen oppmuntrer til videre arbeid med topografi-avhengige fordelte modeller.

Etterord

Hovedoppgaven er en del av et prosjekt der også modellering av snøakkumulasjonen inngår. Prosjektet utføres av av Hydro Nova A/S, og er finansiert av Konsesjonsavgiftsfondet. Veileder for oppgaven er Bredo Erichsen, Hydro Nova A/S.

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MONITORING AND MODELLING SNOW STORAGE IN SWEDISH MOUNTAIN BASINS

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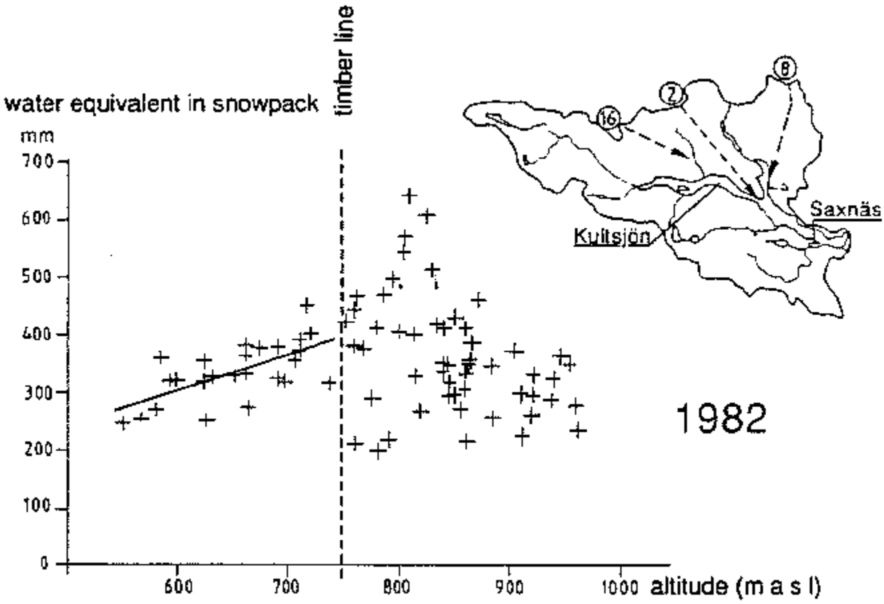
ABSTRACT

A correct estimate of the snow storage in a basin is important for spring flood forecasting. In Sweden the HBV runoff model, based on precipitation measurements, is normally used for forecasting but in mountain areas the precipitation stations are few and sometimes not representative. Therefore two projects with the aim of finding new and better areal snow measurements methods in combination with models have been carried out. The first project was based on snowpack monitoring with airborne gamma-ray spectrometry and the second with helicopter-borne georadar. Both these projects were run for five years. The results show that these methods are suitable for snow monitoring of large areas but that also a relatively dense network of flight lines require empirical corrections to arrive at basin snow water equivalents compatible with the HBV model. An updating of the snow storage in the model can improve the forecast, especially for those winters when the snow distribution is not correctly described by the ordinary precipitation network. Long series of manual snow surveys as input data to the model have also been tested. It was found that manual snow surveys often failed to give a correct picture of the total snowpack in a basin and were therefore of limited value for updating the HBV model. A project aiming to show the possibility of using snow cover data from satellites image analysis is going on at SMHI.

INTRODUCTION

Half of the Swedish electric power demand is covered by the hydroelectric power system, and it is therefore important with good hydrological forecasts during the spring flood period. A conceptual runoff model, HBV, has been used since the later half of the 1970's. The model is based on standard daily observations from the national climatological networks. The areal precipitation is calculated by weighting point measurements from several stations and is increased with respect to basin altitude. One problem is the lack of representative climatological stations and another is measurement errors, especially in the winter, when the wind wirls the snow around the instrument.

The precipitation and the snowpack increase normally with altitude but above the timber line the snowpack is more dependent on the location in the terrain than by the altitude alone (Figure 1). Therefore, new ways of determining actual areal snowpack over large areas before the melting season have been tested by SMHI with financial support from the Swedish Association of River Regulation Enterprises. These were snow water equivalent mapping by airborne gamma-ray spectrometry and by helicopter-borne georadar. Snow cover mapping by different satellites and by conventional snow-courses have also been carried out and compared with HBV model results.



Figur 1. Relationship between snow water equivalent and altitude measured along three lines in the Kultsjön Basin.

SNOW MEASUREMENTS WITH GAMMA-RAY SPECTROMETRY

The experiment with gamma-ray spectrometry was carried out in the Kultsjön Basin during 1980-84 (Bergström and Brandt, 1985). The so-called two-flight method was used. First the natural bare ground radiation was measured along selected flight lines in the first autumn (1979), and then new flights were done when the snow accumulation reached its maximum every spring. The snow water equivalent could then be calculated from the attenuation, that is, the difference between radiation from bare ground and winter flights.

The sensitivity of the gamma method was tested with respect to the number of flight lines (totally sixteen). The bare ground flight was repeated and evaluated, and the differences between two successive flights was also checked. The results are sensitive to variations in background activity, but the repeatability is good.

Gamma radiation is recorded from a strip below the flight path as shown in Figure 2. It was found that any comparison against ground measurements must be based on average values over at least 2 km due to the different way of measuring the snowpack. A comparison is summerized in Figure 3. The reason for the deviation of the 10b record is probably due to rugged terrain with large percentage of shallow snow coverings that will dominate and lead to an underestimate of the snow water equivalent.

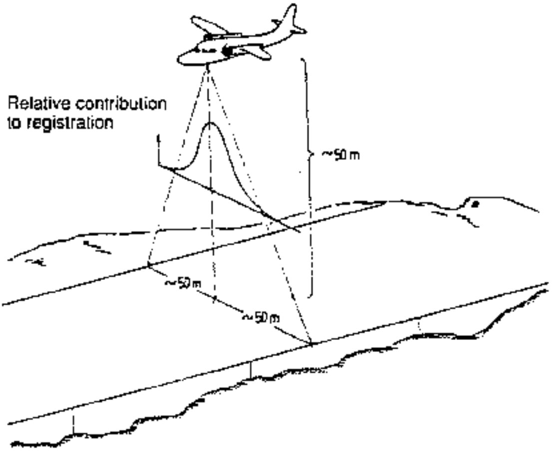


Figure 2. Schematic presentation of the distribution of relative contribution from the ground to the airborne instrument.

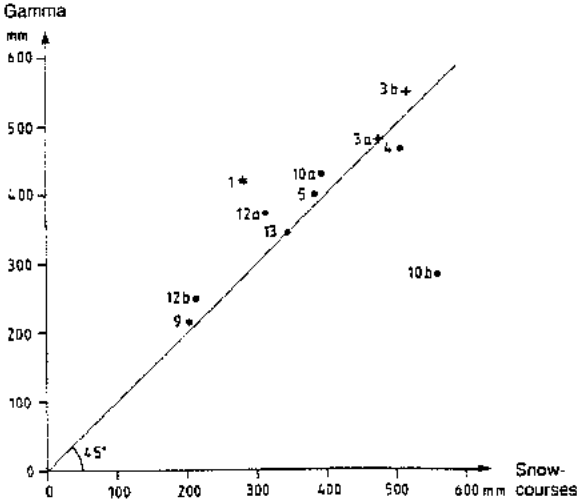


Figure 3. Comparison between conventional snow-courses and results from gamma measurements. Each point represents a 2 km line or longer.

The method was also compared with the snowpack calculated by the HBV model. The model snowpack was updated after the spring season for volume errors during the floods. There is a strong correlation between this corrected snow water equivalent and the gamma method but it doesn't fall along the 1:1 line (Figure 4). The relationship can be used to correct the snow water equivalent as computed by the HBV model. This will affect the volume error over the snowmelt season, as summerized in Table 1. Especially for 1982 with an unusal snow distribution, the performance of the HBV model was improved. However, it has to be emphasized that the results are not based on an independent data set.

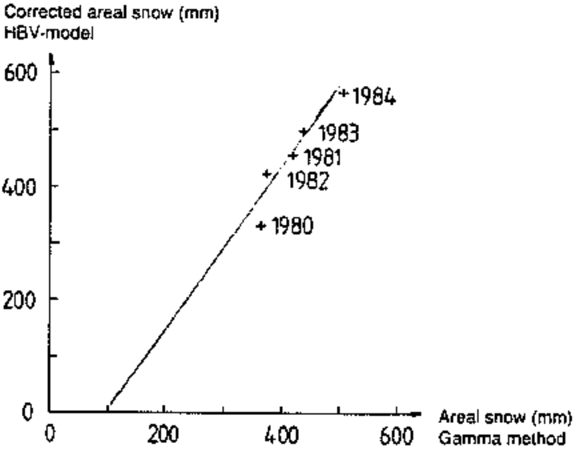


Figure 4. Comparison between the areal snow water equivalents measured by the HBV model and the gamma method in the Kultsjön Basin.

Table 1. The effect of snow corrections from gamma-measurements on the simulated volume error over snowmelt season.

Year	Volume error (mm)	Volume error with correction (mm)
1980	+ 20	+ 42
1981	+ 5	+ 1
1982	- 90	- 34
1983	- 31	- 16
1984	- 5	+ 4
Mean error	30	19

The conclusions from the project are that the gamma method has an obvious potential for estimate of the snowpack in large areas, but that it must be empirical corrected and is expensive to carry out.

SNOW MEASUREMENTS WITH GEORADAR AND CONVENTIONAL SNOW-COURSES

Impulse georadar for determination of the snow storage was tested 1986 to 1990 in the upper part of the River Luleälven (Brandt, 1991). This method gives the delay time through the snowpack which has to be converted to water equivalent through calibration.

The lines flown are shown on Figure 5. The total distance is nearly 400 km which can be flown in one full day if the weather is fine. The area was divided into different sub-basins for which the HBV model was set up.

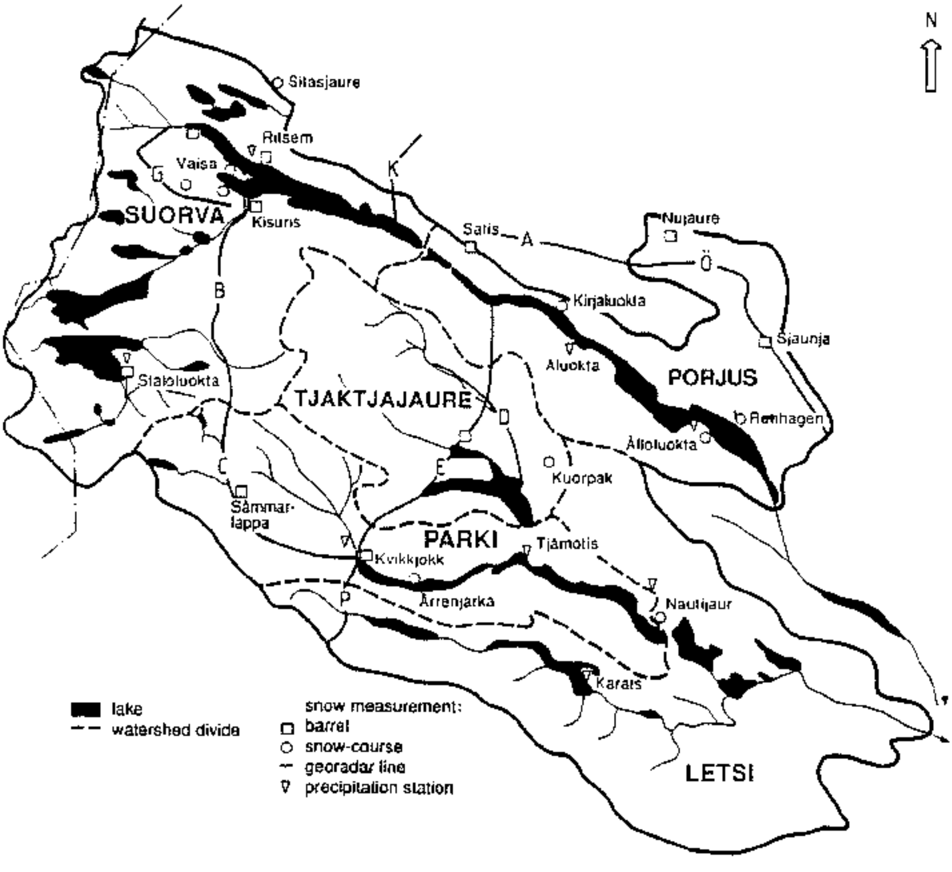


Figure 5. The flight lines for georadar measurements and other snow measurements in the upper part of the River Luleälven.

Results are given for the sub-basin Suorva in the west which is more than 4 000 km^2 and mostly covered by mountain. The georadar line B has been flown all five years and one way to use the information from the flights is to test if there is a stable relationhip, factor, between the snowpack measured by the georadar and the snowpack measured by the HBV model (corrected after the snowmelt season). The georadar line B is about 50 km. The average snowpack measured by georadar in line B is only about half of the areal snowpack in the basin due to a large gradient to the west, but it seems fairly stable. In Table 2 the factors for different years are shown, and also the mean value and the standard deviation. The factors for the four different 2 km snow-courses in the area are also calculated, but they are much more instable. If the relationship for georadar is used to correct the snow storage in the model, it will improve the results four years of five, but destroy the results nearly every year if the factor from the snow-courses are used.

Table 2. Factors between snow pack calculated by the HBV model (corrected for volume error during the snowmelt season) and snow pack according to georadar mesurements and conventional snow-courses.

Year	1986	1987	1988	1989	1990	Mean value	Standard dev.
Factor HBV/ georadar	2.08	2.12	2.19	2.06	2.14	2.12	0.05
Factor HBV/ snow-course:							
Vaisa mountain	1.12	1.03	1.18	1.66	1.23	1.24	0.22
Vaisa forest	2.98	4.16	2.95	2.46	3.71	3.25	0.60
Vaisa cottage	3.25	3.74	2.93	2.42	2.54	2.98	0.48
Sitas	1.25	1.50	1.58	1.84	1.45	1.52	0.19

SNOW MAPPING FROM SATELLITE IMAGERIES

Three types of satellite informations have been tested. 1987 four SPOT imageries were ordered covering the Kultsjön Basin during the snowmelt period, but were not supplied due to too much cloud at all passages. So then Landsat TM was tested but also here there were problems with cloudiness. It was found that Landsat or SPOT imageries could be useful for calibration but not for near real-time use (Moberg and Brandt, 1988).

Presently, the most interesting satellite is the NOAA that is received and classified into different types of clouds and areas covered by water, ice, snow, and bare snowless ground, several times per day at SMHI. They have been tested for snow mapping since 1989. The main disadvantage of satellite data is that it gives the snow cover but not the snow water eqiuvalent. Relationships between the snow storage as % of maximum storage, snow cover from the HBV model and the snow cover from the satellite imageries are being established (Häggström et al, 1992).

CONCLUSIONS

The conclusions from the different areal snowpack monitoring projects in larger basins are that these techniques have their greatest potential in areas where the climatological data coverage is poor, such as in the mountainous areas.

The costs to integrate gamma-ray spectrometry monitoring into operational forecasting are high. Both the gamma and the georadar technique require an empirical correction to arrive at a basin snow storage even with a relatively dense network of flight lines. Snow measurements from conventional snow-courses seem difficult to integrate into operational forecasts.

Finally, it was difficult to compare the integrated HBV modelled snow with the spatially distributed remote sensing data from satellites, gamma and georadar measurements. It is time to restart the model development to make better use of the areal input data available today.

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SNOWMELT DEGREE-DAY VALUES FOR HBV-MODEL IN FINLAND

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Abstract

Watershed models based on HBV-model structure are in use for over 20 watersheds in Finland. The number of calibrated sub-basins within these watershed models is over 70 covering more or less the whole Finland. In this paper is presented the calibration results concerning degree-day values from all these sub-basins with discussion of changes between different districts and land use in Finland. The results published from Sweden suggested, that the degree-day values do not change markedly from north to south. The same seems to be true also in Finland.

TEMPERATURE INDEX SNOW MODEL

The most used method in operational watershed forecasting is the temperature index approach, of which there are many different versions. In the temperature index models, the energy balance of snowmelt is substituted by a function where snowmelt M (mm d^{-1}) depends only on air temperature T (°C):

$$M = KM\,(T - TM) \quad , T > TM$$
$$M = 0 \quad , T \leq TM$$

KM = the degree-day constant (mm $°C^{-1} d^{-1}$)
TM = the threshold air temperature for snowmelt (°C)

The melt function is usually calculated with a one-day time step, as revealed by the other name of the temperature index method - i.e. the degree - day method. The degree-day method is not valid for a time period shorter than one day. In Fig. 1 is presented the used snowmelt model where are also included the refreezing of melted water and water retention storage of snow for melted water. In Fig.2 are presented the constant degree-day values of operational watershed models. According to these results there is some tendency for smaller degree-day values in northern basins.

VARIABLE DEGREE-DAY FACTOR

During the snowmelt period, the physical properties of snow change considerably. Snow becomes more granulated, its density increases and, most important, the albedo of the snow surface drops from about 0.8 to about 0.5 owing to the increase of density, water in snow and debris accumulated on melting snow. Finally the shallow snowpack allows solar radiation to penetrate into the ground, which increases the energy available for snowmelt. Further, patches of bare ground increase the melt rate particularly when the sky is clear and solar radiation is intense, because the melting is promoted by advective transport of sensible heat from the warm soil patches. Flooded water can cause a sudden decrease of snow albedo and increase of snowmelt. A sudden increase in the intensity of melting in the aapa-mire following flooding of the mire has been reported by Nisula (1988). The approximation for the combined effect of these processes is to increase the degree-day factor as a function of cumulative snowmelt (Bergström 1975):

$$KM = KMIN\ (1 + KC\ SM)$$
$$KM = KMAX \qquad ,KM > KMAX$$

KMIN = the value of KM at the beginning of snowmelt ($mm\ °C^{-1}\ d^{-1}$)
KMAX = the value of KM at the end of snowmelt ($mm\ °C^{-1}\ d^{-1}$)
KC = parameter (mm^{-1})
SM = cumulative snowmelt (mm)

According to the results from 76 watersheds and sub-basins, the mean value for the increasing degree-day factor was 1.4 $mm\ °C^{-1}d^{-1}$ and the standard deviation (S.D.) 0.52 $mm\ °C^{-1}d^{-1}$ at the beginning of the snowmelt period. At the end of the snowmelt period, the mean degree-day factor was 4.7 $mm\ °C^{-1}d^{-1}$ and S.D. 1.9 $mm\ °C^{-1}d^{-1}$. The maximum value of the degree-day factor is reached after 77 mm of snowmelt on the average.

At Tables 1-3 the results from calibration have been divided into three groups: southern, central and northern Finland in order to find out some differences in degree-day values from south to north. According to these results there was some tendency for smaller degree-day values in northern Finland as was suggested in the results of Fig. 2.

SNOWMELT IN OPEN AREAS AND IN FORESTS

Both the accumulation of snow and snowmelt in open areas differ from those in forested areas. During the accumulation period, forests have two main effects, which influence the accumulation of snow in different directions. The shielding effect of the forest prevents wind from transferring and redistributing snow. This increases the water equivalent of snow in the forest as compared to a large open area, where snow is transferred and accumulated at the edges of the forest and near other obstacles which prevent further transport of snow. This shielding effect is at its peak in sparse spruce and pine forests and in deciduous forests, where the interception effect of snow is small.

During snowmelt, the main effect of forest is to shield the snow cover from direct solar radiation and from the effect of wind, i.e. turbulent exchange of sensible heat. On the other hand, the forest crown emits long-wave radiation after it is warmed up by solar radiation, so that the effect of solar radiation does not altogether disappear owing to covering by the forest crown. However, the overall effect of the forest on snowmelt is that melting proceeds more slowly the denser the forest is. The degree-day factor in the forest is thus clearly smaller than in open areas. Vehviläinen and Kuusisto (1984) obtained the following results for a small experimental basin in southern Finland by calibration of a temperature index model over data for 42 years:

	Forest	Field	Bog
Degree-day factor KM	1.73	4.08	4.69
Threshold temperature TM	0.1	0.1	0.1

Due to the good results obtained for separate open/forest snowmelt modelling, this approach was taken into use in new operational watershed models. The calibration results from operational watershed models with a separate degree-day model for open and forested areas are presented in Tables 4-6. The mean initial degree-day values were 1.7 mm°C^{-1}d^{-1} for open areas and 1.4 mm°C^{-1}d^{-1} for forests, and the final values were 7.8 mm°C^{-1}d^{-1} for open areas and 4.7 mm°C^{-1}d^{-1} for forests. On the average, the final degree-day value is reached after 109 mm of cumulative melt in open areas and after 83 mm of melt in forests.

The obtained degree-day values were divided into two groups: southern and central Finland and northern Finland. This division did suggest the same differences from south to north in Finland for open areas as results presented before i.e that the degree values are smaller in north. But the opposite was true for forested areas.

Experiences of this version of the degree-day snowmelt model for operational flood forecasting have been good. Field observations have shown that the simulation of snow melt and snow cover separately in open and forested areas has been correct. Open areas are free of snow approximately two weeks earlier than forested areas.

CONCLUSIONS

All the presented results show that the degree-day values do not change markedly from south to north in Finland. However, some tendency for smaller degree-day values in northern basins can be seen from part of the results. The need for different degree-day values for open and forested areas was clear.

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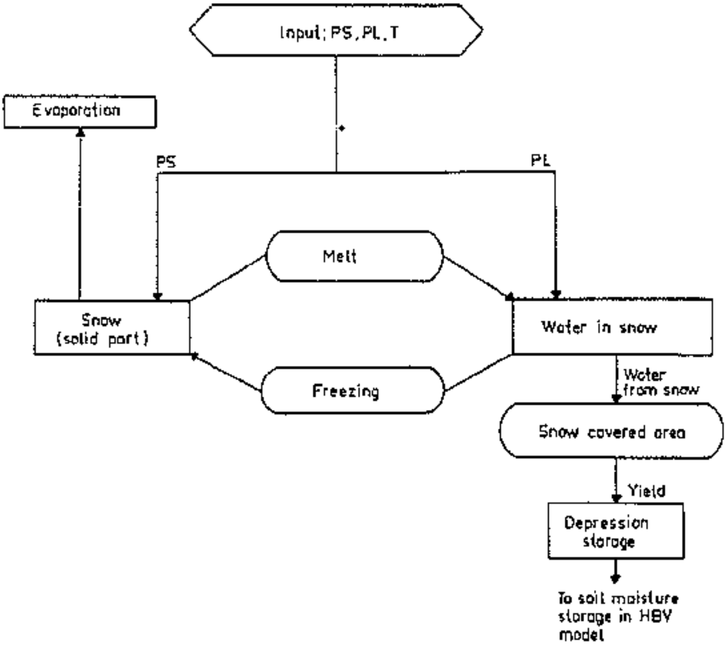

Fig. 1. The used temperature index snowmelt model.

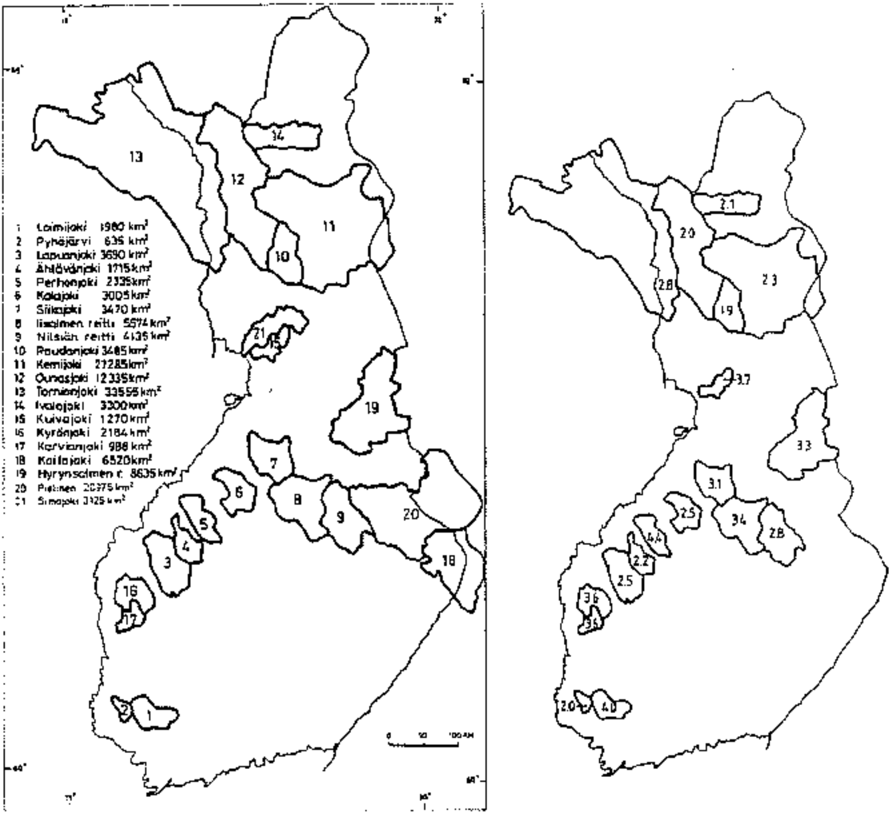

Fig 2. The watershed used in this study and the constant degree-day values for these watersheds.

Table 1. Variable degree-day values from calibration of the temperature index model for sub-basins in operational watershed models in southern Finland.

SOUTHERN FINLAND

	TM	KMIN	KMAX	KC
Säkylän Pyhäjärvi				
-Ylaneenjoki	-0.3	1.3	2.6	0.033
-Pyhäjoki	-0.3	1.3	2.6	0.033
Loimijoki	0.7	3.5	4.5	0.005
Ylä-Karvianjoki				
-Nummijoki	2.1	1.0	3.3	0.049
-Karviänjärvi	0.1	1.1	6.0	0.033
-Suomijärvi	0.3	1.1	5.2	0.041
-Vahokoski	0.1	0.8	5.8	0.075
-Vatajankoski	0.3	1.4	10.7	0.047
Kyrönjoki				
-Pitkämö	0.6	1.4	6.5	0.027
-Ala-Jalasjoki	0.5	1.2	8.0	0.046
-Hirvijoki	0.5	1.0	7.4	0.077
-Mustajoki	0.6	1.0	5.6	0.077
-Ala-Kauhajoki	0.2	1.4	8.0	0.033
-Ikkelänjoki	0.4	1.4	3.6	0.022
-Hyypänjoki	0.8	1.7	3.9	0.024
-Pääntäneenjoki	0.7	2.0	3.2	0.033
-Kainastonjoki	0.8	1.6	5.2	0.023
Lapuanjoki				
-Kuorasjärvi	-0.2	1.1	4.0	0.036
-Hirvijärvi	-0.3	1.1	4.0	0.037
-Kuortane	-0.2	1.1	3.8	0.038
-Pappilankari	-0.2	1.1	3.9	0.038
Mean	.34	1.4	5.1	0.039
Standard deviation	.56	.56	2.1	0.018
Number of values	21	21	21	21

Table 2. Variable degree-day values from calibration of the temperature index model for sub-basins in operational watershed models in central Finland.

CENTRAL FINLAND

	TM	KMIN	KMAX	KC
Ähtävänjoki				
-Alajärvi	-0.3	1.1	3.2	0.037
-Lappajärvi	-0.1	1.1	3.2	0.037
-Evijärvi	0.1	1.1	3.7	0.032
Perhonjoki				
-Venetjärvi	-0.2	1.1	5.8	0.037
-Tunkkari	-0.2	1.1	4.7	0.032
-Ullavanjoki	0.4	1.8	6.9	0.031
-Köyhänjoki	0.1	1.2	14.0	0.090
-Vissavesi	0.1	1.4	5.2	0.042
-Pelo	-0.3	1.2	8.1	0.110
Kalajoki				
-Reis-Vuohtojärvi	0.0	1.3	4.3	0.036
-Hautaperä	0.0	1.1	4.2	0.032
-Settijärvi	0.1	1.2	3.6	0.027
-Haapajärvi	0.1	1.2	3.4	0.029
-Pidisjärvi	0.0	1.2	3.8	0.027
-Niskakoski	0.2	1.2	4.2	0.027
Tujuoja	0.4	1.0	3.8	0.042
Siikajoki				
-Iso-Lamujärvi	0.6	1.7	3.8	0.030
-Kortteinen	0.3	1.4	5.4	0.037
-Lamujoki	0.3	1.2	4.6	0.043
-Uljua	0.1	1.2	4.0	0.046
-Harjunniva	0.3	1.3	6.0	0.039
Iisalmen reitti				
-Salahminjärvi	0.2	1.4	4.2	0.024
-Iisalmen reitti	0.5	1.3	6.5	0.036
Nilsiän reitti				
-Laakajärvi	1.4	2.2	4.7	0.044
-Kiltuanjärvi	0.4	1.1	4.2	0.060
-Sälevä	0.3	1.2	3.3	0.026
-Ala-Tiilikanjoki	0.5	1.2	4.5	0.029
-Ylä-Tiilikanjoki	0.6	0.8	5.3	0.063
-Keyritynjoki	0.8	0.9	4.0	0.072
-Luostanjoki	0.3	0.8	4.9	0.073
-Syväri	1.2	1.2	4.4	0.062
-Vuotjärvi	0.5	0.8	5.5	0.074
Mean	.27	1.2	4.9	0.046
Standard deviation	.38	.28	2.0	0.021
Number of values	32	32	32	32

Table 3. Variable degree-day values from calibration of the temperature index model for sub-basins in operational watershed models in northern Finland.

NORTHERN FINLAND

	TM	KMIN	KMAX	KC
Kuivajoki				
-Ala-Kuivajoki	0.3	1.3	5.8	0.036
-Hamarinjoki	-0.0	0.8	9.2	0.057
-Kivijoki	-0.2	1.5	3.4	0.065
Hyrynsalmen reitti				
-Hossa	0.2	1.0	8.4	0.046
-Ämmäkoski	0.3	1.4	6.7	0.046
-Aittokoski	0.3	1.3	6.1	0.018
-Seitenoikea	0.2	2.5	3.2	0.059
-Koirakoski	0.5	1.1	3.0	0.054
-Iso-Pyhäntä	0.4	1.2	4.6	0.024
-Uvajärvi	0.6	1.4	3.4	0.055
-Leppikoski	1.6	1.6	3.7	0.031
-Alanteenjärvi	0.3	1.4	6.3	0.012
Kemijoki				
-Kummaniva	-0.5	1.3	2.7	0.031
-Ylä-Kemijoki	-0.3	0.9	4.2	0.021
Ounasjoki				
-Köngäs	0.4	1.3	2.7	0.061
-Kaukonen	-0.4	1.2	3.1	0.029
-Marraskoski	-0.3	1.1	3.0	0.020
Raudanjoki	-0.3	1.0	2.8	0.036
Tornionjoki				
-Käresuvanto	0.5	2.7	2.9	0.025
-Muonio	1.2	2.5	2.9	0.089
-Kallio	1.1	3.0	3.5	0.089
-Pello	0.6	3.0	3.0	-
Ivalonjoki	1.5	1.1	3.0	0.033
Mean	.35	1.5	4.2	0.043
Standard deviation	.57	.67	1.9	0.022
Number of values	23	23	23	22

Table 4. Variable degree-day values for open areas in southern and central Finland.

Basin	Open areas			
	TM	KMIN	KMAX	KC
SOUTHERN AND CENTRAL FINLAND				
Loimijoki	0.9	4.9	9.0	0.021
Ylä-Karvianjoki				
-Nummijoki	0.1	1.0	4.2	0.055
-Karvianjärvi	-0.1	1.1	7.5	0.053
-Suomijärvi	0.3	1.1	5.2	0.064
-Vahokoski	-0.1	0.8	8.6	0.075
-Vatajankoski	-0.3	1.4	12.7	0.047
Kyrönjoki				
-Pitkämö	0.1	1.5	9.3	0.029
-Ala-Jalasjoki	0.3	1.2	13.4	0.056
-Hirvijoki	0.0	1.4	14.0	0.077
-Mustajoki	-0.3	1.5	13.4	0.077
-Ala-Kauhajoki	0.1	1.4	9.2	0.033
-Ikkelänjoki	0.1	1.4	6.4	0.022
-Hyypänjoki	0.0	1.7	9.3	0.025
-Päntäneenjoki	0.0	3.7	6.2	0.057
-Kainastonjoki	0.3	2.0	9.3	0.023
Nilsiän reitti				
-Laakajärvi	1.1	3.0	5.7	0.068
-Kiltuanjärvi	0.2	1.4	4.7	0.069
-Sälevä	0.3	1.2	12.7	0.074
-Ala-Tiilikanj.	0.1	2.0	6.4	0.023
-Ylä-Tiilikanj.	0.4	0.9	4.7	0.056
-Keyrityjoki	0.7	1.0	6.8	0.074
-Luostanjoki	0.0	0.8	8.1	0.068
-Syväri	1.2	1.3	4.7	0.063
-Vuotjärvi	0.3	1.0	13.0	0.086
Mean	0.2	1.7	8.5	0.054
St. deviation	0.39	0.97	3.2	0.021
Number of values	24	24	24	36

Table 5. Variable degree-day values for open areas in northern Finland.

Basin	Open areas			
	TM	KMIN	KMAX	KC
NORTHERN FINLAND				
Kuivajoki				
-Ala-Kuivajoki	0.2	1.3	8.7	0.065
-Hamarinjoki	0.0	0.9	11.6	0.057
-Kivijoki	-0.2	1.5	4.6	0.043
Hyrynsalmen r.				
-Hossa	0.0	1.0	11.0	0.043
-Ammäkoski	0.0	3.6	7.1	0.090
-Aittokoski	0.1	1.3	6.1	0.018
-Seitenoikea	0.9	2.5	3.5	0.076
-Koirakoski	0.0	2.3	3.6	0.088
-Iso-Pyhäntä	0.2	1.2	6.2	0.049
-Uvajärvi	0.4	2.9	5.3	0.094
-Leppikoski	0.0	2.2	6.0	0.089
-Alanteenjärvi	0.2	1.4	8.8	0.017
Mean	0.15	1.8	6.9	0.061
St. deviation	0.28	0.85	2.7	0.027
Number of values	12	12	12	12

Table 6. Variable degree-day values for forested areas in southern and central Finland.

SOUTHERN AND CENTRAL FINLAND

Basin	Forested areas			
	TM	KMIN	KMAX	KC
Loimijoki	0.9	3.0	3.9	0.015
Ylä-Karvianjoki				
-Nummijoki	0.2	1.0	2.9	0.045
-Karvianjärvi	-0.1	1.1	5.2	0.021
-Suomijärvi	0.3	1.1	5.2	0.025
-Vahokoski	0.2	0.8	4.6	0.075
-Vatajankoski	0.5	1.4	10.0	0.047
Kyrönjoki				
-Pitkämö	1.0	1.3	4.6	0.021
-Ala-Jalasjoki	0.5	1.1	5.7	0.042
-Hirvijoki	0.7	0.9	5.8	0.077
-Mustajoki	0.8	0.9	3.9	0.077
-Ala-Kauhajoki	0.2	1.4	7.5	0.032
-Ikkelänjoki	0.5	1.4	2.9	0.029
-Hyypänjoki	0.9	1.6	2.5	0.023
-Päntäneenjoki	0.8	1.5	2.4	0.027
-Kainastonjoki	1.0	1.4	3.4	0.023
Nilsiän reitti				
-Laakajärvi	1.6	1.7	4.2	0.032
-Kiltuanjärvi	0.5	0.8	3.8	0.053
-Sälevä	0.3	1.1	6.7	0.019
-Ala-Tiilikanj.	1.2	1.3	2.5	0.022
-Ylä-Tiilikanj.	0.5	0.8	4.7	0.055
-Keyritynjoki	0.9	0.9	2.7	0.070
-Luostanjoki	0.5	0.8	3.2	0.068
-Syväri	1.2	1.2	4.4	0.062
-Vuotjärvi	0.5	2.8	6.8	0.070
Mean	0.65	1.3	4.6	0.043
St. deviation	0.39	0.6	1.8	0.022
Number of values	24	24	24	24

Table 7. Variable degree-day values for forested areas in northern Finland.

NORTHERN FINLAND

Basin	Forested areas			
	TM	KMIN	KMAX	KC
Kuivajoki				
-Ala-Kuivajoki	0.4	1.3	8.7	0.015
-Hamarinjoki	0.0	0.7	7.5	0.057
-Kivijoki	-0.2	1.5	4.5	0.029
Hyrynsalmen r.				
-Hossa	0.2	1.0	7.6	0.043
-Ammäkoski	0.4	0.9	6.7	0.038
-Aittokoski	0.4	1.3	6.1	0.018
-Seitenoikea	1.3	2.5	3.1	0.052
-Koirakoski	0.6	1.0	3.0	0.050
-Iso-Pyhäntä	0.4	1.2	4.0	0.015
-Uvajärvi	0.6	0.8	2.7	0.040
-Leppikoski	1.7	1.5	3.5	0.026
-Alanteenjärvi	0.4	1.4	5.4	0.011
Mean	0.52	1.3	5.2	0.033
St. deviation	0.52	0.5	2.1	0.016
Number of values	12	12	12	12

MODELLING OF SOIL MOISTURE AND RADIO-TRACER TRANSPORT IN A CULTIVATED FIELD

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ABSTRACT

A mechanistic model of water movement and transport of a non-reactive solute has been used to simulate moisture movement and movement of injected HTO as a tracer of moisture in a cropped agricultural field. In two micro plots, each 1 m^2 in size, HTO was injected at nine points, 30 cm apart and at 30 cm depth in a square grid, in an experimental cultivated field 45 km north west of Helsinki Finland, in early June 1988.

The main features of the model are that it can simulate moisture and solute movement in one flow domain using Richards and convection dispersion equations or in two domains where fluxes of water and solute through macropores are coupled to flow in micropores by empirical interaction terms.

It was found that the one domain model was sufficient to explain the moisture and tracer movement since the simulated values of soil moisture and tracer activity in the soil agreed fairly well with those observed experimentally. This implies a piston-like movement of moisture and tracer and that bypass of the older soilwater by new water derived from precipitation either did not occur or was not significant.This was also observed experimentally since the ^3H concentration profiles showed a unimodal distribution of the tracer cloud.
In model sensitivity analysis, a proper choice of parameters such as dispersivity and diffusion coefficient of tritiated water in soil, was found to be important.

1 INTRODUCTION

Tracer techniques offer a direct method to trace the movement of soil moisture. In ^{3}H tagging, a soil layer below the root zone is spiked with ^{3}H as HTO. Since HTO behaves more or less like ordinary water, it is generally not retarded or adsorbed in the soil matrix and moves with the same velocity as ordinary water. Assuming a piston like flow, the ^{3}H tagged moisture layer acts like a boundary between the old soil moisture and the fresh incoming water and cannot be by-passed in the vertical direction. The piston flow concept was demonstrated by Zimmermann et al. (1967), pioneers in tritium tagging, in central European forest soils. The piston flow concept was later validated by Datta and Goel (1977), Bahadur et al. (1977) and Athawale et al (1980) in sub tropical alluvial soils in India. In a cultivated field in Denmark, Butts et al. (1988) successfully used tritium as a reference tracer to evaluate the performance of ^{60}Co and ^{51}Cr.

In contrast, in most of the Scandinavian till soils, the ^{3}H tracer method did not prove to be equally successful. Very often, the tracer could not be located in the soil at all, (Lundin 1982 and Dressie 1987). Lundin's experiments in till soils showed the presence of preferential flow paths taken by soil moisture and large variations in observed flow rates were attributed to field heterogeneity. Even in glaciofluvial deposits in central Sweden, the tagged layer was swept away laterally due to the presence of clay lenses, (Saxena and Dressie 1984). However, in a homogeneous glaciofluvial sand, Saxena (1984, 1987) successfully monitored the temporal displacement of injected tritium and environmental ^{18}O. Thus, the inherent heterogeneity of till soils, the occurrence of clay lenses, cracks due to freezing and thawing and frost heaving etc, make tracer monitoring rather difficult and mostly inapplicable.

Tracer movement may be affected by field heterogeneity and preferential flow paths. The latter may occur during large inputs at the surface (heavy showers) if the soil is cracked and fissured.

In this paper, the movement of tritiated water in a cultivated field has been simulated by a matrix/macropore model (Jarvis et al. 1991a). The main objective is to test whether the soil moisture movement in a clay dominant till soil is predominantly by piston flow and if not, then to quantify the role played by macropore flow.

2 EXPERIMENTAL METHODS

2.1 Site description

The present study was carried out in an experimental agricultural field at Vihti in southern Finland 45 km north west of Helsinki. The soil is sandy clay down to 30 cm depth from the soil surface. Between 30 to 60 cm,, the soil is fine textured with a clay content of 59%. The crop in 1988, was spring wheat, sown on 14 May. Precipitation, class A pan evaporation and temperature data were recorded at a meteorological station 4 km from Vihti.

2.2 Tritium Injections

Two microplots 1 m^2 each, were treated with HTO. Each micro-plot contained 9 injection points in a square grid, 20 cm inside the boundaries of the plots. HTO injections were done on 3 rd. June,1988. Each of the 9 points was injected with 8 ml HTO, 30 cm below the soil surface. ^3H activity was 0.065 μCi/ml and total ^3H activity applied to each plot was 4.7 μCi. Soil samples were collected down to 1 m depth by a corer, each soil core being 10 cm in length. Soil sampling was carried out in July, August, September and October 1988. The micro-plots are hereafter termed as plots A and B.

2.3 Extraction of Soil Moisture

Soil samples were heated electrically in desiccators and moisture was collected in cold traps continuously kept at -55 °C. The traps were further connected to a rotary pump. In this arrangement 6 desiccators can be operated simultaneously. This vacuum distillation technique is described in detail by Saxena and Dressie (1984). By measuring the wet and dry weight of the soil samples the moisture content by volume of the soil samples was also determined

2.4 Tritium Assay

10 ml of extracted soil moisture was mixed with 10 ml of a scintillation cocktail and the samples were counted for 60 minutes each, on a liquid scintillation spectrometer. The figure of merit of the instrument was 740. The error in measurements at the observed levels of ^3H activity was < 2%.

3 MODEL DESCRIPTION

The model considers water and solute transport in a soil profile divided into layers which may be of varying thickness, with an upper boundary at the soil surface and a lower boundary at a specified depth. A detailed description of the model is given in Jarvis et al. (1991a) and an improved version in Jarvis (1991). An important feature of the model is that it may either be run in one or two flow domains using the same values for hydraulic properties characterizing the soil. In two flow domains, the total soil porosity in each layer is divided into interacting flow regions here termed as micropores and macropores, each of which is characterized by a water content and a flux. Water and solute movement in the micropores is calculated with the Richards and convection-dispersion equations, which are coupled to fluxes of water and solute in the macropores by empirical interaction terms. These interaction terms are superfluous in the one domain case, which then simply reduces to the non-steady state convection-dispersion equation.

3.1 Soil hydraulic properties

Two hydraulic functions are required to predict transient unsaturated water flow: the water release characteristics (the relationship between water content θ and soil water pressure head ψ) and the hydraulic conductivity function (hydraulic conductivity K as a function of θ or ψ). In the model it is assumed that the total porosity in each soil layer may be partitioned into two components, micropores and macropores with a specified boundary hydraulic conductivity at a given water content and potential.If the model is run in two flow domains, micropores and macropores operate as semi-independent interacting flow regions, each characterized by a degree of saturation, conductivity and flux. In one domain, each soil layer is represented by only single values of water content and conductivity and the model calculations of water flow reduce to a numerical solution of Richards equation.

3.2 Water and solute flow in micropores

Solute flow in micropores is calculated using the convection-dispersion equation: where c_{mi} is the solute concentration, θ is the soil water content, t is time, z is vertical distance, q is the Darcy water flux density and D is the dispersion coefficient given by:

$$\frac{\partial\ (\theta\ c_{mi})}{\partial t} = \frac{\partial}{\partial z}\left(D \frac{\partial c_{mi}}{\partial z} - q c_{mi} \right) \tag{1}$$

where D_o is the diffusion coefficient in free water, f is the impedence factor assumed constant, D_V is the dispersivity and v_{mi} is the pore water velocity which is given by q/θ. Water flow is calculated using the extended Richards equation:

$$D = (\ D_v v_{mi} + D_o\ f\ )\ \theta \tag{2}$$

where S is a sink term accounting for water uptake by roots, ψ is soil water potential and K_{mi} is the unsaturated hydraulic conductivity.The water release characteristic is based on the function suggested by Brooks and Corey(1964) and the unsaturated hydraulic conductivity function in the micropores is given by Mualem's (1976) equation.

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z} \left\{\ K_{mi} \left(\frac{\partial \psi}{\partial z} + 1 \right) \right\} - S \tag{3}$$

3.3 Water and solute flow in macropores

Water flow in macropores is calculated using Darcy's law assuming a unit hydraulic gradient (laminar flow under gravity) and a simple power law function to characterize the unsaturated hydraulic conductivity in the macropore domain (Beven and Germann, 1981). With respect to solute transport, the model neglects processes of hydrodynamic dispersion and diffusion in the macropores as convection is assumed to dominate.

4. DRIVING VARIABLES, INITIAL CONDITIONS AND PARAMETER ESTIMATION

Daily precipitation data and daily potential evaporation estimated from class A pan evaporation were used as driving variables in this study. Actual evaporation was calculated from potential evaporation using the simple model described by Jarvis (1989). Evaporation demand within the day was estimated assuming an even distribution over a calculated daylength, which was obtained from the site latitude and day number in the year. Climatic data were obtained from a weather station 4 km from Vihti.

Data on soil physical and hydraulic properties was missing and had to be estimated from literature data and measurements made in a Swedish soil of similar texture and structure (Jarvis et al. 1991b).The molecular diffusion coefficient of tritiated water was kept as 1.5×10^{-9} cm^2/s (Munnich 1983). Observed soil moisture and tritium concentrations from plot (A) on 6 th. July were used as initial input values for the simulations.

5. RESULTS AND DISCUSSION

5.1 Observed tritium profiles

The temporal displacements of the centre of mass of tritium activity in the soil profile was monitored, instead of peak ^{3}H concentrations. Choice of the former reduces the errors caused by vertical diffusion of the tracer due to its concentration gradient. The positions of centre of mass (C.M) during different sampling occasions are shown in table (1). Observed tritium profiles in plot (A) from July to October 1988 are shown in Fig(1). Similar profiles were observed in plot (B).From the temporal displacement of the centre of mass of the tracer cloud, the average water particle velocities from the injection date to last sampling in October are 1.3 and 1.5 mm/d for plots (A) and (B) respectively. The corresponding values from August to October are 2.3 and 2.4 mm/d. Observations from plot (B) in July are unreliable as this profile was the first to be distilled and used for standardizing the distillation for clay rich soils.

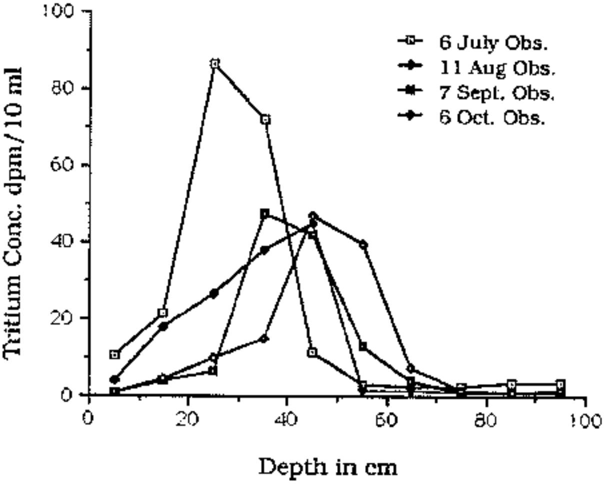

Fig. 1 Observed tritium profiles in plot (A).

Table (1). Positions of centre of mass (C.M) of tritium activity in the soil profiles.

Location	Date->	6 July	11 Aug.	7 Sept.	6 Oct.
Plot A	C.M. in cm	39.0	33.7	41.5	46.3
Plot B	C.M. in cm	31.0	36.7	38.0	49.9

The remaining samples were properly distilled. It is interesting to note that during July and August in plot (A), the centre of mass moved upward by 5.3 cm i.e. moisture movement was upward where as in plot (B) there was an apparent downward movement of 5.7 cm although it should be remembered that the results in July may be unreliable (see above discussion). This observation may indicate indicate field heterogeneity.

5.2 Simulation of tritium and moisture movement

Using the one domain model, a reasonable agreement between observed and D_v set to 7 cm, Fig(2).

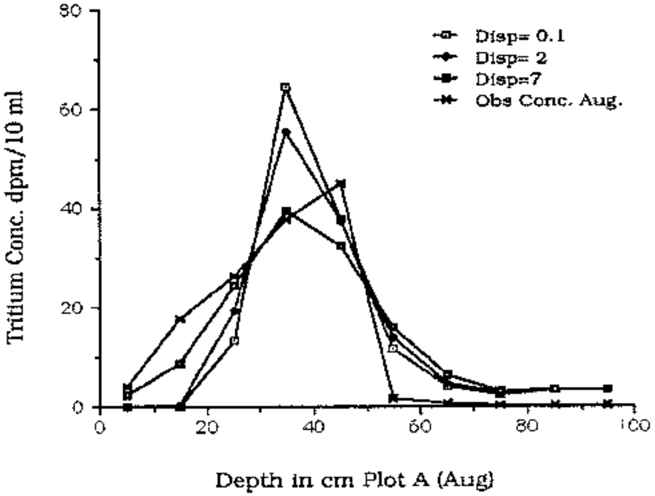

Fig.2 Simulated tritium profiles using different values of dispersivity.

However the agreement between observed and predicted tritium profiles keeping D_v= 7 cm becomes less good later in the year Fig(3). This may indicate limitations in the convective-dispersive equation in that the dispersivity may not be spatially and temporally constant. Another reason for the poorer model performance later in the season may be the lateral diffusion of the tracer away from the injection and sampling locations.The centre of mass (C.M) calculated from one and two flow domains are given in table (2). Average particle velocities obtained from simulations in one and two domain flow (keeping D_v =7) from August to October were 2.0 and 1.8 mm/d respectively as compared to observed values 2.3 and 2.4 mm/d for plot A and B.

Table (2). Positions of centre of mass (C.M) of tritium activity in the soil profiles. simulated by one and two flow domain models.

Simulations		Date->	11 Aug.	7 Sept.	6 Oct.
1 domain	C.M. in cm		41.0	45.9	52.3
2 domain	C.M. in cm		42.7	46.6	52.6

It was found that both the one and two domain simulations gave very similar concentration depth profiles Fig.(3). This suggests that under the prevailing summer/early autumn conditions of low net downward water fluxes, macropore flow either did not occur, or did not significantly affect the tritium profiles.

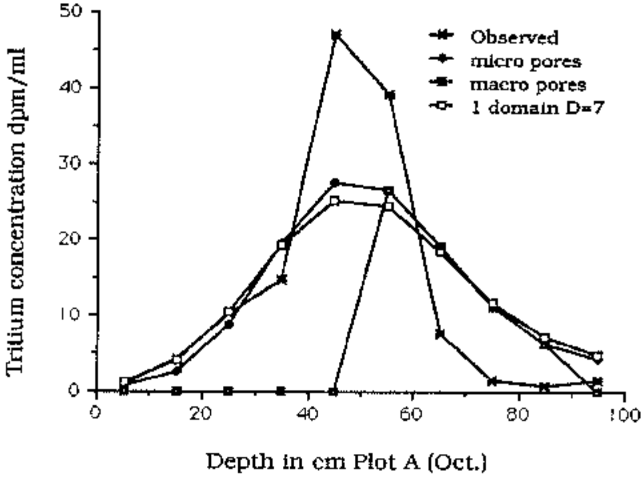

Fig.3 A comparison between simulated tritium profiles calculated from one and two domain models.

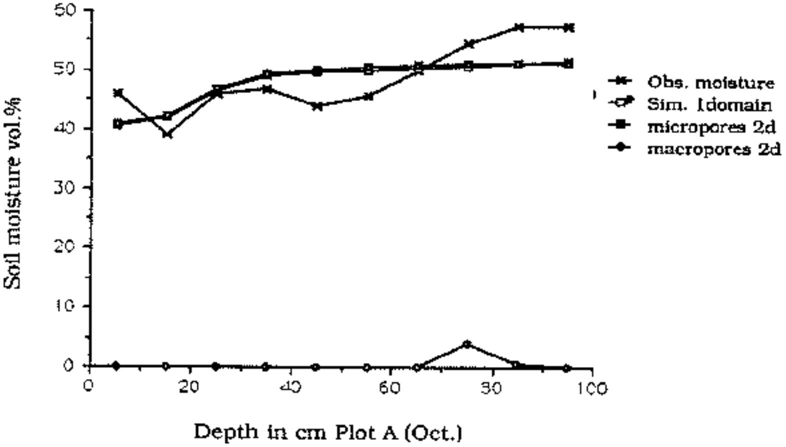

Fig.4 Observed and simulated moisture profiles in one and two domains:"d" signifies domain.

Concerning the soil water balance, both the models again gave very similar results.Observed and simulated moisture profiles agreed reasonably well and are shown in Fig(4).

6 CONCLUSIONS

Experience gathered from world wide tritium tagging experiments shows that the method is only applicable in homogeneous soils.The problem of dispersion of the tritium cloud is reduced when the vertical soil moisture movement is faster than the longitudinal diffusion, but slow enough to smooth out lateral concentration gradients created by interstitial water. The simulations may have been more successful if the tritium sampling had been done within the injection area instead of at the edges of the micro plots. This caused a continuous flow of the tracer from the centre of the plots toward the edges on account of lateral concentration gradients.The model does not account for this.
The one domain model seems to describe fairly well the movement of tritium and soil moisture. This indicates that the movement of tracer and soil moisture was Darcy-like and that under the prevailing field conditions, macropore flow apparently did not occur. This is also corroborated by the observed tritium profiles. However a more rigourous test of the occurrence or otherwise of macropore flow can be made if water and tracer fluxes are also measured, as is possible for example, in Lysimeters.

ACKNOWLEDGEMENTS

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THE USE OF LYSIMETERS IN SOIL PROCESS STUDIES

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ABSTRACT

Four lysimetres in the Central and Southern Finland are used to study the lysimeter percolation. The aim was to find out the factors that explain best the amount of percolation. Model simulations were done in order to replace firstly the missing values of percolation water and secondly the soil moisture storage variation. The sensitivity of the 1-dimensional model to the parameters, which were not measurable, was tested.

Precipitation and percolation are correlated in long term analyses. In shorter periods, the initial soil moisture content and the intensivity of the rain event become dominating. The relative water storage variation in lysimeter can be modelled. The simulated daily values of percolation could not be used to complete time series.

INTRODUCTION

The groundwater monitoring network of the National Board of Waters and the Environment in Finland consists of 56 stations representing different geological and climatological conditions of the country (Soveri 1985). At each station there is equipment for measuring groundwater level, lysimeter percolation (at 12 stations) and soil moisture content. The main objective of this study is to improve the understanding of the water flow in the unsaturated zone and to find out the factors that influence mostly on the amount of the percolation water. The time series of percolated water are not always complete which makes problems in calculating the water balance. An attempt was made to replace the missing values with modelled ones on the daily basis.

Four lysimeters representing typical groundwater recharge areas were selected to study the soil water flow processes. The time period of this research was limited to two years, 1983 and 1984. Two one dimensional soil water models were used to simulate the water flow processes, the emphasis being on the amount of percolation water of the lysimeters. The results of the model were compared with the measured ones and the goodness of the fit was estimated. The sensitivity of the model for certain parameters was analysed.

SITE DESCRIPTION AND INSTRUMENTATION

The four lysimeters selected for the research are Oripää (60°55'N, 22°41'E) Pistohiekka (61°34'N, 28°01'E), Kangaslahti (63°25'N, 28°05'E) and Pesiöjärvi (64°57'N, 28°33'E) (Fig. 1). All are situated in natural pine forest areas. Oripää and Pistohiekka lies on eskers, which represent sandy and gravelly areas. The texture in the lysimeter container in Pistohiekka is some finer than that in Oripää (Fig. 2). In Oripää, there are two rain gauges located near to the lysimeters. The climatological data is taken from the nearest observation station, Jokioinen. For Pistohiekka, all climatological data is taken from the observation station situated 3 kilometers from Pistohiekka.

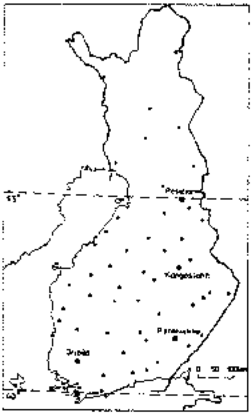

Figure 1 The situation of the groundwater stations in Finland.

Two other lysimeters, Kangaslahti and Mäntyniemi, are situated on glasifluvial sandy soils. The texture in the lysimeter vessel of Mäntyniemi is obviously finer than in the others (Fig. 2). In Mäntyniemi, there is a precipitation gauge, but the other data is taken from an observation station of Suomussalmi village, 20 kilometers from Mäntyniemi. All the climatological data for Kangaslahti is taken from an observation station about 29 kilometers from Kangaslahti.

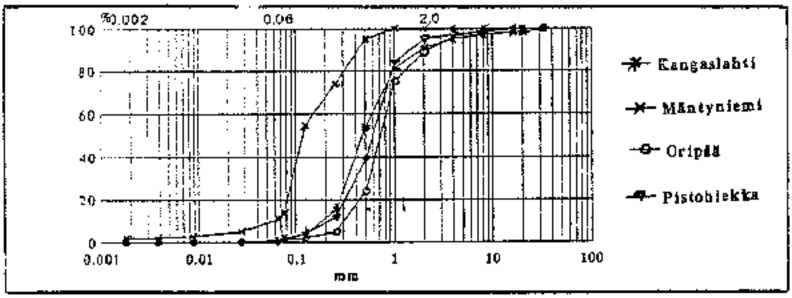

Figure 2 Grain size curves of the lysimeters.

THE MANAGEMENT OF LYSIMETERS

The lysimeters used in this study consist of a round metallic container with 1,6 m diameter. They are 1,7 meters deep and in the bottom of the container, there is an outlet pipe, leading the percolated water down to the automathic recorder (Fig. 3c).

The percolated water is normally observed during the frost free season, eg between May and October, because the frost causes problems in instruments. Winter percolation is measured only in Oripää. The less the percolation, the bigger is the error in the recorded value compared to the observed one. The timer of the recorder may cause some inaccuracy. In two-week's period the recorded time can exceed even 4 to 5 hours that of the observed one. Some inaccuracy can occur in vertical movement of the plotter pen, too. In the optimal conditions the measuring accuracy is ± 0.1 mm/d, while if some disorder occurs, the accuracy will be ± 0.2-0.5 mm/d.

The time of disfunctions compared with the operating time of the lysimeters reaches from 5 to 25 % in one year's period. One of the most difficult problems to detect is that the lysimeter is partly clogged or it is leaking resulting that the percolation is unnormally small. Anyway, one must be carefull in studying the results later on and not consider all the exceptions as faults.

Soil water content is measured in lysimeters with the neutron scattering method. It's accuracy is about 0.7

volume per cent (Tattari and Granlund 1989) which means in the scale of a lysimeter about 10 millimeters error. Inside the lysimeter, the moisture content is typically some lower down to 30-40 centimeters depth than that measured outside. On the contrary, in the bottom layers, it is higher (Fig. 3). Moisture profile inside the lysimeter can differ a lot, too. For example in Mäntyniemi (Fig.3), in the depth of 80-100 centimeters, the moisture decreases inside the lysimeter while it increases outside of it. It results that water flow processes inside the lysimeter differ from those outside of it. That may be because the stratification of the lysimeter is disturbed during the installation. Clogging of the outlet pipe by fine soil particles can cause the moisture increase in the bottom. While soil water models are not made especially for lysimeter simulations, some uncertainties in modelling results can be expected.

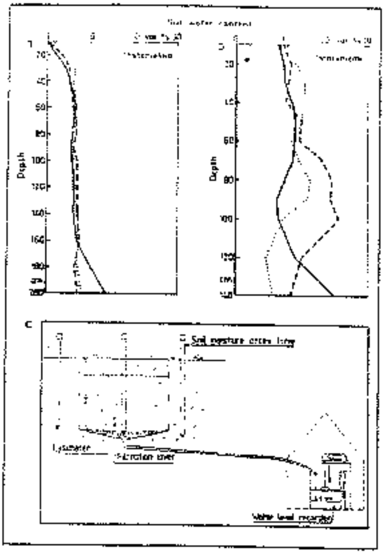

Figure 3 Moisture profiles inside (line) and outside (plotted lines) of the lysimeters of a) Pistohiekka and b) Mäntyniemi. c) The construction of a lysimeter and the location of the soil moisture tubes.

THE MODELLING

Two soil water models were used to simulate the percolation through the lysimeter. The PROBE model is developed by Svensson (1985) and the other, SOIL model, by Jansson and Halldin (1979) in Sweden. The principal difference between these two models is that the calculation of water flow in PROBE is based on the moisture diffusion and in SOIL on the continuity equation. There are also some differences in parameters for solving the hydraulic conductivity (K). In PROBE the K value and the matric potential are solved by using the relations by Clapp and Hornberger (1983):

$$K = K_s \ (\Theta/\Theta_s)^{2b+3}$$

$$\Psi = \Psi_s \ (\Theta/\Theta_s)^{-b}$$

where K is hydraulic conductivity, Θ is moisture, b is empirical coefficient, Ψ is matric potential and index s means saturation.

In SOIL the K-value is solved by using the empirical equations by Brooks and Corey (1964) and the analytical solution by Mualem (1976):

$$K = K_s \ (\Psi_a/\Psi)^{2+(2+n)\lambda}$$

where Ψ_a is air entry tension, n is tortuosity factor and λ is pore size distribution.

The meteorological data used in PROBE simulations were daily values of precipitation and evaporation. The initial values of soil moisture and the saturated hydraulic conductivity were used as input. The b value was taken from the literature (Clapp & Hornberger 1978).

The PROBE model was calibrated by estimating the missing parameters (eg saturated moisture content, saturated matric potential and porosity) so that the percolation through the lysimeter during one summer became as correct as possible. Then the other years were simulated using the same parameter values. First the constant value of evapotranspiration, 2 mm/day was used. Then, the evaporation was calculated with the Penman-equation and multiplyed by a soil moisture correction factor to get the actual evapotranspiration. The simulations were repeated to find out if these values improved the results.

In SOIL model, transpiration was calculated with Penman-Monteith equation, while soil evaporation was based on the surface energy balance approach. The parameters λ and n were taken from the literature (Karvonen 1988). The hydraulic conductivity of the lowest soil layer is taken as the lower boundary condition in both models.

Previous studies on the sensitivity of the SOIL model (Jansson 1986) showed that the water tension was mostly influenced by the unsaturated hydraulic conductivity. In this study the sensitivity analysis was done for the parameters needed in calculating unsaturated hydraulic conductivity and the resulting influence on the amount of percolation water and soil water storage. In the analysis, one parameter at time was altered 5 per cents of its nominal value. The analysis was done for the lysimeter of Mäntyniemi. The profile is slightly layered and the saturated hydraulic conductivity grows downwords as the coarseness of the soil raises.

MODELLING RESULTS

Both models simulated succesfully the amount of percolation water when the flow was average during the summer time (Fig. 4). Anyway, the models failed to simulate the situations, when the observed percolation varied a lot (Fig. 5). PROBE tended to give a smooth percolation or it exaggerated the peaks. SOIL gave more daily variation but often allowed too little water to come through.

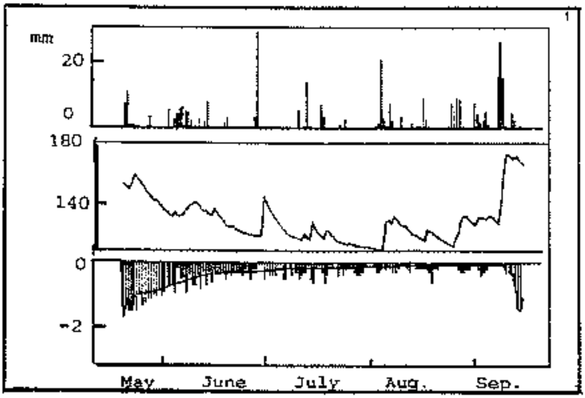

Figure 4 (Up) The precipitation, (middle) the soil water storage and (down) the measured (needle) and estimated by PROBE (line) percolations in Pistohiekka 1983.

The models succeeded well in simulating the soil water storage (Fig. 4 and 5). In some cases the calculated water storage was lower than the observed one but the relative changes in the storage between two observation times were successfully simulated. The calculated evapotranspiration didn't effect the percolation or soil water storage results remarkably.

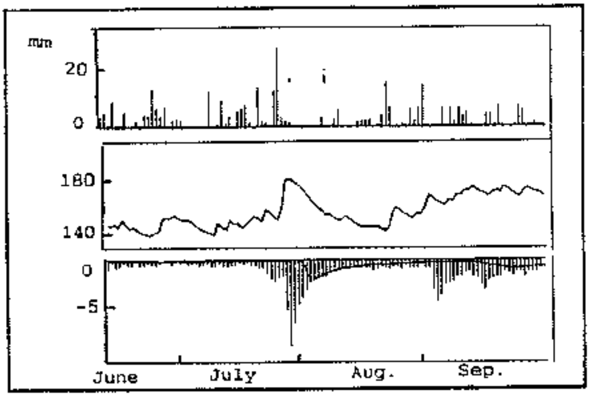

Figure 5 (Up) The precipitation, (middle) the soil water storage and (down) the measured (needle) and estimated by PROBE (line) percolations in Mäntyniemi 1984.

The sensitivity analysis of SOIL model showed that the percolation water was mostly influenced by the tortuosity factor. The daily differences between the values calculated with the nominal and the altered parameters were from 0 to 13%, which means from 0 to 1.2 mm/d. The sensitivity for the pore size distribution index was strongest in the topsoil where it caused deviation from 0 to 0.2 mm/d. The sensitivity for saturated hydraulic conductivity was negligible.

The soil water storage was mostly influenced by the pore size distribution index. The tortuosity factor caused some variation, too. The sensitivity was strongest in topsoil

and in the depth of 60 cm. This may be due to sharp decrease in the fine matter content in this layer. The sensitivity of soil water storage for the saturated hydraulic conductivity was negligible. However, the results of the sensitivity analysis have to be compared with the measur ement accuracy.

THE DISCUSSION OF THE RESULTS

The soil grain size curves of Kangaslahti and Pistohiekka are quite similar. In Oripää, the soil type is some more coarse. The soil in Mäntyniemi is obviously finer than the others. All the profiles are layered. That may have been the reason for the difficulties in simulations by PROBE. The differences in parameter values between the layers had to be minimized to prevent the model dumping. In addition, the coarseness of soil caused problems, because of steep wetting fronts and dry initial conditions (Hills et al. 1989).

Even if the modelled cumulative values of percolation water coincided well with the measured ones, there were large deviations on daily values. While comparing the daily deviations, the percolation water was best simulated in Pistohiekka. In some situations, SOIL managed to simulate even the peak flows relatively well (Fig. 6). Anyway, as a result of this research, missing values of percolation water can not be replaced by the modelled ones.

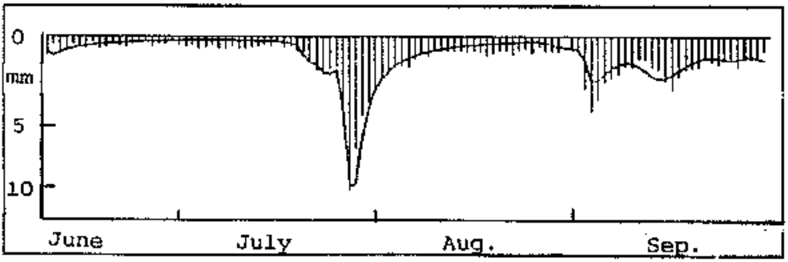

Figure 6 Measured (needles) and simulated by SOIL (line) percolation in Mäntyniemi 1984.

Both models were sensitive and reacted in the same way for rain events so that changes in water storage occured easily. While comparing the simulated values to the measured ones, in half of the cases they were approximately the same. In the other half, soil water storage diminished sharply in the beginning of the simulation period and therefore stayed too low during the whole period. That may be because of too high evapotranspiration or uncorrect water retention curve. However, changes in water storage may still be simulated satisfactorily by the models.

In long term analysis the precipitation and the lysimeter percolation are correlated. In shorter time periods the soil moisture before the rain events and the intensity of the rainfall becomes dominating. In Oripää and Pistohiekka the soil moisture retains normally under 25 volume per cent. In the profile, there exists a low permeable layer under the topsoil. In Kangaslahti and Mäntyniemi moisture reaches sometimes to values of 30% and more, which in Mäntyniemi can be explained by the finer soil texture. However, according tomeasurements, the value of saturated hydraulic conductivity does not differ between these four lysimeters remarkably. Therefore the layer construction and the macropores must have a dominating influence on percolation.

THE WATER BALANCE

The water balance method was used to calculate the evapotranspiration between june and september. For example in Mäntyniemi 1983 it seemed to have realistic values, varying from 25 to 48 mm/month. The values calculated by Penman-Monteith equation and water balance differed only 4.0 mm (Fig. 6) during whole summer. Anyway, in most of the cases, the Penman-Monteith evapotranspiration was much higher than that calculated by water balance.

Some similarities can been seen in water balances between the four lysimeters. Soil water storage typically decreased during august and it increased during september. August was generally the most rainy month and the evapotranspiration was very high in that month too (except in Kangaslahti). The high evapotranspiration rate can be cause to the decrease in soil water storage. Even if the soil type is coarse, the low percolation during this month may be explained by a relatively thick organic matter layer in the topsoil, which stores efficiently water. In two stations percolation was highest in august too, which gives an additional explanation to the decrease.

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ELECTRICAL CONDUCTIVITY IN SOIL SOLUTION OF FROZEN AND UNFROZEN SOILS MEASURED BY TIME DOMAIN REFLECTOMETRY

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ABSTRACT

The electrical conductivity of the soil solution is a measure of its ion concentration. *In situ* measurements are cumbersome, especially during frozen conditions, and often involve destruction of the soil volume sampled. In time domain reflectometry (TDR) a cable tester is applied to monitor the *in situ* dielectric and conductive properties of the soil. The dielectric properties are used to evaluate water content in both frozen and unfrozen soils since the early 80´s. Evaluation of the conductive properties is a recent undertaking. The advantages of using TDR to measure electric conductivity are that it is done simultaneous with the water content measurements, using the same probe, and that measurements can be made continuously, at a high temporal resolution. The objective of this study was to evaluate this method for measuring electric conductivity and to test whether existing TDR records made for water content evaluation could be used to estimate electrical conductivity. The data set tested consisted of TDR and temperature records. Bulk electrical conductivity and, using the temperature measurements and a regression model, electrical conductivity were evaluated. Although problems arose using TDR recordings intended for water content analysis, the method was considered promising.

INTRODUCTION

Ions in soil solution in connection to soil freezing are interesting from three viewpoints: 1) The concentration affects the freezing point depression in the soil solution and thus the unfrozen water content, 2) increased concentration reduces soil heave and 3) the freezing causes a redistribution of ions resulting in an increased concentration in the unfrozen water. The latter could be of importance for ion transport processes in the soil profile. The concentration of ions in the unfrozen water can be very high; Gray & Granger (1986) measured a five-fold increase of the salt concentration at the freezing front. Chemical and biological reactions involving these ions would be affected. An increased concentration could partly compensate the reduction in the chemical and biological reaction rates caused by low temperatures; see, *e.g.*, Christianson & Cho (1983) concerning denitrification. Research in this area has developed slowly because of difficulties in measuring concentrations in the unfrozen water in frozen soils. The methods available has been destructive (*e.g.* Cary & Mayland, 1972; Gray & Granger, 1986) or have required extraction of very small quantities of water during a long time (*e.g.* Cary *et al.*, 1979).

During recent years a new technique, time domain reflectometry (TDR), has been developed which makes it possible to simultaneously measure both the bulk electric conductivity (BEC) and the dielectric constant of the soil using the same equipment. The relationship between the dielectric constant and the water content of the soil under both unfrozen and frozen conditions was established in the early 80's (Topp *et al.*, 1980; Patterson & Smith, 1981; Stein & Kane, 1983) and has been extensively used. A good correlation between BEC and water content has also been observed (Dasberg & Dalton, 1985; Hayhoe & Balchin, 1988). Recently, van Loon *et al.* (1990) also found a good correlation between BEC and the electrical conductivity of the soil solution (measurements in soil solution made by extracting water samples from the soil). The electrical conductivity of the soil solution is a measure of the ion concentration since they are directly proportional to each other. Theories and models to describe the relationship between BEC, soil solution electrical conductivity and soil water content has also been proposed (Rhoades *et al.*, 1989; van Loon *et al.*, 1991). To determine the soil solution electrical conductivity (and the ion concentration) simultaneous measurements of temperature, liquid (unfrozen) water content and BEC are required. For a general model it is also necessary to know the soils own electrical conductivity (due to surface charges of soil particles). So far, studies of BEC and soil solution electrical conductivity has only been made in soil samples in the laboratory under unfrozen conditions.

During a winter season in 1985/86 measurements of temperatures and unfrozen water content using TDR was made in four profiles in an agricultural field in central Sweden (Lundin, 1990; Johnsson & Lundin, 1991). The period covered a whole freezing-thawing cycle. In this study, we have re-evaluted the readings from the TDR device to calculate the BEC values. The BEC values were used together with simultaneous measurements of water content and temperatures to calculate the solution electrical conductivity in both frozen and unfrozen soil. An existing regression model (van Loon *et al.*, 1990a; b) was used for this purpose.

MATERIAL AND METHODS

The experimental site

The experimental field was located at Kjettslinge in central Sweden, 40 km north of Uppsala, and was the main experimental site for the 'Ecology of Arable Land' project (Steen *et al.*, 1989). The area consists of glacial and postglacial sedimentary deposits overlying till and precambrian bed-rock. The climate in the region is temperate and humid. The average annual precipitation is about 600 mm, and the mean annual temperature is about 5 °C. A detailed description of the field is given in Steen *et al.* (1984; 1989), while meteorological and hydrological measurements are presented in Alvenäs *et al.* (1986). Measurements were made from 1981 to 1985.

The soil, a Mollic gleysol (FAO classification system), is characterized by distinct textural horizons: a loam topsoil with a mean thickness of 0.27 m overlays a loamy sand layer of varying thickness (0 - 0.50m) and a clay layer several meters thick. The clay content of the clay layer increases with depth. The organic matter content is about 5% in the topsoil and about 0.5% in the subsoil.

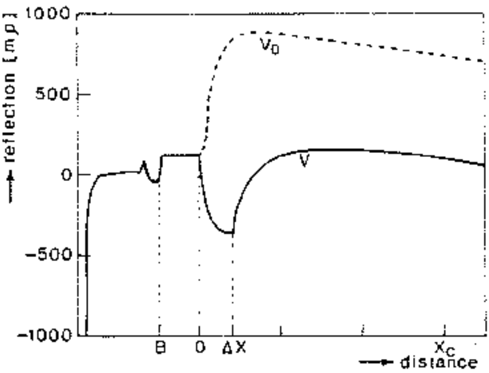

Fig. 1. Schematic TDR trace for a soil, V, and for air, V_0. B indicate the balun (not used in this study and 0 the start of the probes. From van Loon *et al.* (1990b).

Measurements

Measurements of soil temperature and TDR-recordings were made during winter 1984/85 in four soil profiles, two of them snow cleared, at depths of 5, 10, 20, 25, 30, 40, 50, 60, 70 and 100 cm (Lundin, 1990; Johnsson & Lundin, 1991)). Soil temperatures down to a depth of 40 cm were measured every 3 hours using thermocouple sensors (Pt-500) connected to a data logger. At deeper levels, temperature readings were made weekly, using thermistor sensors. Unfrozen water content was evaluated using time domain reflectometry (TDR; see Patterson & Smith, 1981; Stein & Kane, 1983). The method is based on measuring the dielectric constant of the soil which is a function of the volumetric liquid water content (Topp *et al.*, 1980). Stainless steel, 17-cm-long, measuring probes were installed horizontally in pairs, 2.5 cm apart. The probes were connected to the time domain reflectometer Tektronix Model 1502 through coaxial cables (50 Ω).

Electrical conductivity

The evaluation of BEC and electrical conductivity of the soil solution followed van Loon *et al.* (1990a; b; 1991) and is based on determining the signal attenuation of the reflected TDR-pulse. A reflection measurement in soil is compared with a reference measurement in air (Figure 1).

The attenuation of the signal is a function of the bulk electric conductivity of the soil. According to the method proposed by van Loon *et al.* (1990b) the electrical attenuation, α, of the soil sample can be expressed by

$$\alpha = \frac{1}{2L} \ln \frac{V_0(x_{c0})}{V(x_c)}, \qquad [1]$$

where L is the probe length, $V_0(x_{c0})$ is the reflection at a distance x_{c0}, in a measurement taken in vacuum or dry air, and $V(x_c)$ is the reflection at the distance x_c, in a measurement taken in the soil. The distances were in our case chosen so that x_c was as close to the reflection maximum of the signal as possible. The number of reflections, N, at the selected point was calculated using the relation

$$N = \frac{x_c}{L\sqrt{\varepsilon_c}}, \qquad [2]$$

where ε_c is the relative dielectric constant of the soil. From the evaluation of water content from the TDR trace the relative dielectric constant was already determined as

$$\varepsilon_c = (\frac{\Delta x}{L})^2, \qquad [3]$$

where Δx is the apparent probe length given by the TDR trace. The number of reflections can thus be calculated as

$$N = \frac{x_c}{\Delta x}, \qquad [4]$$

van Loon *et al.* (1990b) always performed the evaluation at N=10. In this study the number of reflections was different for each evaluation, normally varying between 8 and 30. A certain N-value gave a corresponding distance x_{c0} given by

$$x_{c0} = NL\sqrt{\varepsilon_{c0}}, \qquad [5]$$

where ε_{c0} is the relative dielectric constant of vacuum (equal to unity), so that eq. [5] reduces to $x_{c0} = NL$.

Having obtained the distances the related reflections were measured. The reflection in the soil was measured on the TDR print-out using a ruler. The reflection in vacuum was taken from a table function generated from two measurements in dry air.

The relation between signal attenuation and bulk electric conductivity, σ, is given by Yanuka *et al.* (1988) as

$$\sigma = \frac{2\alpha\sqrt{\varepsilon}}{\eta_0} - \omega\varepsilon_0\varepsilon_y, \qquad [6]$$

where η_0 is the square root of the ratio between magnetic permeability and dielectric constant (equal to $120\pi\ \Omega$), ω is the wave frequency, and ε_0 is the real part and ε_y is the imaginary part of the dielectric constant in vacuum. The last term is normally neglected, *e.g.*, Dalton & van Genuchten (1986).

Finally, the bulk electric conductivity can be related to the ratio between the reflections in soil and in vacuum and the apparent length of the trace in soil:

$$\sigma = \frac{\Delta x}{L^2 \eta_0} \ln \frac{V_0(x_{c0})}{V(x_c)}. \qquad [7]$$

The BEC is the sum of the electrical conductivity of the soil solution and of the surface of the soil particles. Furthermore, it is a function of both temperature and water content. To be a useful measure of ion concentration in the soil solution an electrical conductivity related to, *i.e.*, saturated soil and 20 °C must be formed.

Following van Loon *et al.* (1990a), a quasi-theoretical model was applied:

$$\sigma(T, \theta_w, \sigma_w) = \left[\sigma_s(1+3\theta_w) + \frac{\theta_w{}^2(2-\theta_w)\sigma_w}{\theta_s(2-\theta_s)}\right]\nu(T), \qquad [8]$$

where σ_w is the electrical conductivity of the soil solution, σ_s is the electrical conductivity of the soil particles, θ_s is the porosity, θ_w is the liquid water content, and $\nu(T)$ is the temperature dependent viscosity. Rearranging, and solving for σ_w yields,

$$\sigma_w(T) = \frac{\theta_s(2-\theta_s)}{\theta_w{}^2(2-\theta_w)}\left[\frac{\sigma}{\nu(T)} - \sigma_s(1+3\theta_w)\right]. \qquad [9]$$

van Loon *et al.* (1990a) used a second order power expansion for this purpose. Note that temperature should be in °C. Thus,

$$\sigma_w(20\ ^\circ\mathrm{C}) = \frac{\theta_s(2-\theta_s)}{\theta_w{}^2(2-\theta_w)}\left[\frac{\sigma}{0.5584+0.0193T+0.00014T^2} - \sigma_s(1+3\theta_w)\right]. \qquad [10]$$

They generated a regression model to determination electrical conductivity of the soil particles. We measured soil-particle electrical conductivity in air-dried soil using a Terrameter. Since the electrical conductivity was very low in the air-dried soil ($\sigma_s < 1\ \mu S/m$) we neglected the last term in Eq. [10]. This result was in contradiction to the results presented by van Loon *et al.* (1991) who find values between 12 and 26 mS/m for the soil-particle electrical conductivity in their regression. However, their values are very close to the standard error obtained in the regression and were not safely demonstrated to be non-zero.

The final expression used could thus be simplified to

$$\sigma_w(20\ ^\circ\mathrm{C}) = \frac{\sigma\theta_s(2-\theta_s)}{\theta_w{}^2(2-\theta_w)(0.5584+0.0193T+0.00014T^2)}. \qquad [11]$$

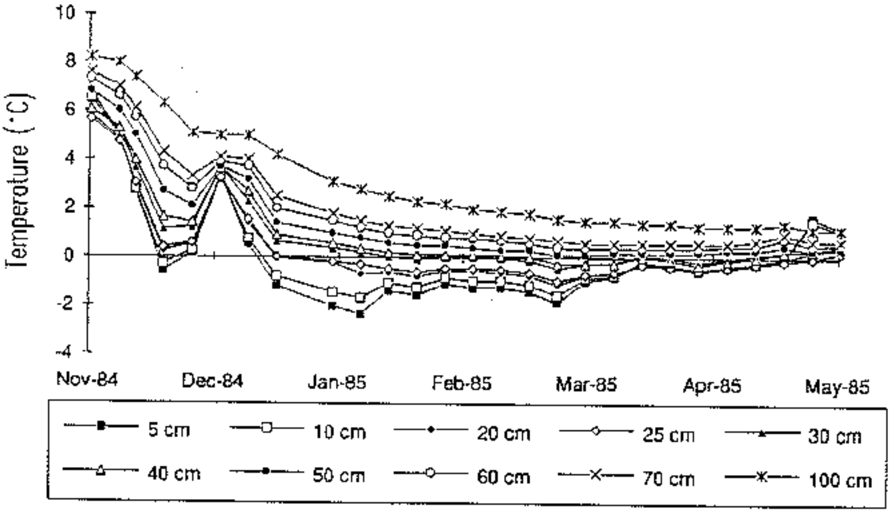

Fig. 2. Soil temperatures at the different levels for one of the snow covered plots at Kjettslinge.

RESULTS AND DISCUSSION

When evaluating the TDR print-outs, the estimated error in the ruler readings of the heights of the traces (*i.e.*, the reflections) and the distances was 0.5 mm. The error in the measurements was, during unfrozen conditions, normally in the range of 2-4 %. However, for low values of reflections the relative error was sometimes considerable because most of the signal was attenuated. For high values the same was sometiomes true as the difference between the reflection in vacuum and the one in the soil was small. For some of the higher values, it was only when the minimum estimations were used that an non-infinite value could be obtained. It was also found that the error was dependent on the amplification selected on the cable tester. An increase in error often coincided with the freezing of the soil. This was probably an artefact created by the lower liquid water content, leading to a decreased apparent length of the probe, causing the TDR operator to increase the horizontal amplification of the print-out. Sometimes this led to the print-out of the TDR trace being too short to make an evaluation possible. These measurements have been left out. The errors inherited in the TDR-technique itself were not investigated

In addition, a sensitivity analysis was performed to investigate the sensitivity in the soil solution electrical conductivity to errors in temperature and liquid water content. It was found that an error of 2 % in water content and an error of 0.1 °C in temperature caused an error of 1 per mil in the conductivity.

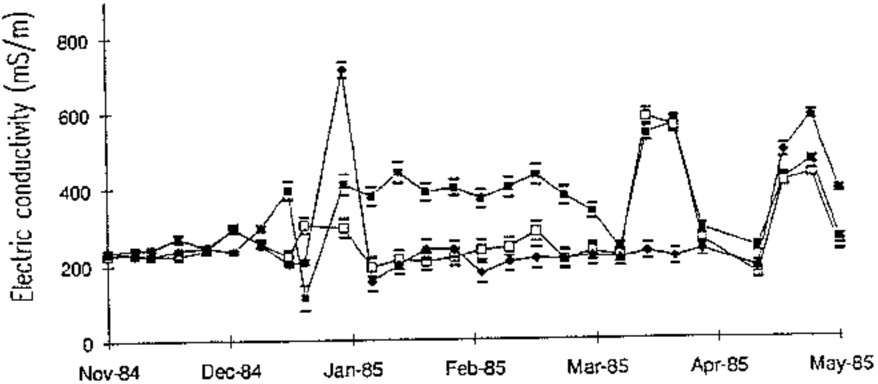

Fig. 3. Electrical conductivity of the soil solution for the top soil (5, 10, and 20 cm) at one of the snow covered plots in Kjettslinge. Evaluation error limits are given as horizontal bars. The legend is shown in Figure 2.

From the error analysis we could conclude that there does not seem to be any important errors due to the evaluation technique. .

The results presented include measurements from the ten levels in one of the snow covered plots investigated (Figures 3-5) and the temperature for each level (Figure 2). The main differences between the plots were caused by the different temperature regimes, created by snow clearing, and showed basically the same patterns but at somewhat different occasions and more or less pronounced.

The most characteristic features seen were that the highest values occurred in the clay soil at depth, whereas the lowest values occurred in the sand horizon.

An interesting feature occurred as the freezing front passed the level. At first the electrical conductivity values increased, sometimes with a factor four or more, then they returned to more or less there original value. Although the measurement interval was a bit too long to study this phenomena it seems that the levelling off took about a week. The observation of the phenomena was based on single valued peaks, but they were frequent and always coinciding with the passing of the freezing front.

The explanation to the rising part is quite simple; it is an increase in solute content due to the freezing-out of salts. The following decline is more difficult to explain. It can not involve an increase in liquid water content since no such was observed. Thus, it must be a decrease in ion content, either by ion transport downwards or by some type of immobilisation of ions, *e.g.*, by precipitation. Little is known about the types of reactions and the diffusion processes connected to freezing. A downward transport of nitrate is reported by Kay & Groenevelt (1983) in connection with freezing, although reports of accumulation of ions at the surface

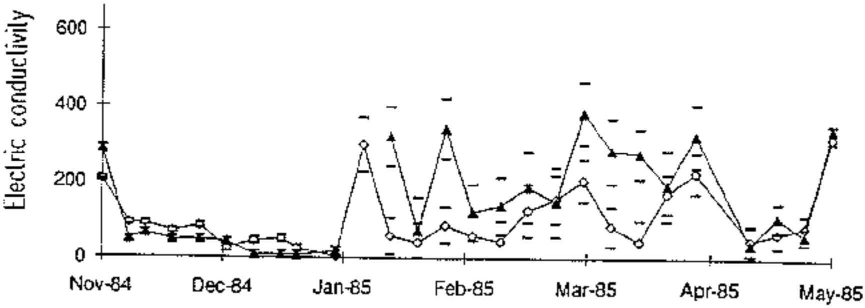

Fig. 4. Electrical conductivity of the soil solution for the sand horizon (25 and 30 cm) at one of the snow covered plots in Kjettslinge. Evaluation error limits are given as horizontal bars. The legend is shown in Figure 2.

and in the top soil is more common (*e.g.*, Campbell *et al.*, 1970, Gray & Granger, 1986). Various chemical reactions are also reported, *e.g.*, hydrolysis, polymerisation of iron ion, aluminium, and silicon (Florence, 1982).

Another regularly occurring feature was the increase in electrical conductivity in connection with thawing. In the top soil the increase was followed by a decrease some two weeks later. At the sand horizon the measurements were aborted before a similar decrease could be detected. The most plausible reason for this increase is infiltration of melt water with a high ion content. However, this does not explain that the highest concentrations (the highest conductivity) was found at the 20 cm depth. If the ions were immobilised in connection with freezing, it could be speculated that what is seen is actually a mobilisation of ions, *e.g.*, a solution caused by the infiltration.

In mid March 1985 a distinct increase was observed at the depths of 5 and 10 cm. After about two weeks a decrease followed. This feature coincided with an increase in total water content (*i.e.*, ice content) and with a short period of tile drainage observed in the field (Johnsson & Lundin, 1991). Johnsson & Lundin (1991) interpret there findings as infiltration into the frozen soil. Thus, the peak found in this investigation is likely to be caused by infiltration of melt water. It is interesting to note that these findings gives the third independent indication of infiltration through the frozen soil for this field. However, a peculiarity was that whereas the infiltration indication for the profile (Fig. 3) shown was the most developed, the total water content records for the same profile showed little indication of an increase. In addition, the profile with the most developed increase in total water content showed no indication of a peak in electrical conductivity. A reason for this could be the spatial intermittancy at which infiltration was occurring. The measurements of the total water content and the TDR-measurements were carried out a few dm apart, thus if infiltration is occurring in cracks and other large pores, as suggested by Johnsson & Lundin (1991), then it is only indicated by sensors penetrating those active pores or cracks.

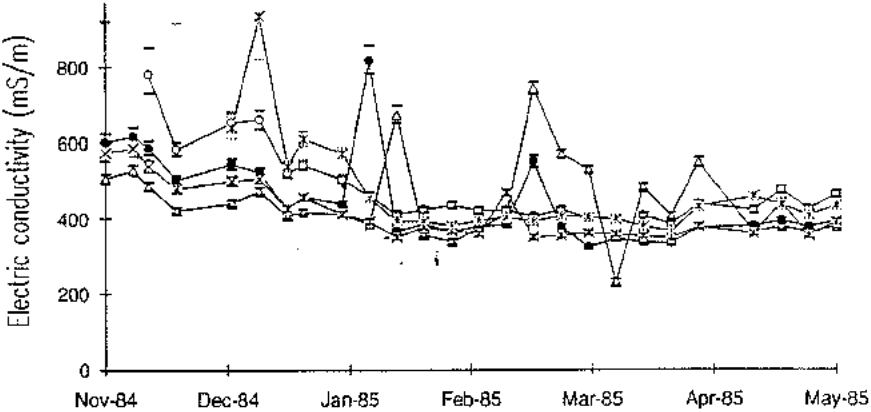

Fig. 5. Electrical conductivity of the soil solution for the clay soil (40, 50, 60, 70, and 100 cm) at one of the snow covered plots in Kjettslinge. The legend is shown in Figure 2.

The electrical conductivity of the soil solution is related to the ion concentration by

$$\varepsilon = QC, \qquad [12]$$

where Q is the specific conductivity of the ion and *C* is the ion concentration. Since the soil solution contains a number of ions it is difficult to distinguish a change in solute concentration from a change in ion constituents. However, for periods or situations when the ion constitution is constant, or changing slowly, the electrical conductivity can be used as a measure of ion concentration. Such a situation could be created in connection with tracer experiments. Further developments in this area are expected.

CONCLUSIONS

It was concluded that the TDR technique is promising also in determining the electrical conductivity of the soil solution. The technique worked in both unfrozen and frozen soil conditions. When using TDR-traces obtained for the purpose of evaluating liquid water content problems caused by inadequate amplification was sometimes found. In the water content evaluation a high horizontal amplification is necessary, whereas a high vertical amplification is needed for the electrical conductivity evaluation. The inherent conflict has to be recognised when doing dual evaluations.

The features observed indicated that further studies of electrical conductivity of the soil solution, especially related to freezing and thawing, are a fruitful means of obtaining a better understanding of the chemical reactions and the diffusion processes going on in the field.

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VERTICALLY DISTRIBUTED SOIL MOISTURE SIMULATIONS

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ABSTRACT

This paper presents a development of the PULSE-model for vertically distributed simulation of water flow and moisture in a soil profile. If the pF-curve and average distance to groundwater is known the soil moisture routine does not need any calibration. The precipitation and snow routine should, however, be calibrated against discharge measurements. The model has been tested at three catchments in Sweden. It was also compared with a physically based model (SOIL), with data from one of these catchments.

The PULSE-model produced good reproductions of measured soil moisture content in most cases. Both the level of soil moisture and the variation pattern are described satisfactory. In a comparison with the physically based SOIL-model, this model did not produce better simulations than PULSE. The SOIL-model simulations were, however, hampered by the lack of sufficient input data and parameter values.

The conclusion from this study is that the vertically distributed version of the PULSE-model can produce sufficiently accurate soil hydrology for hydrochemical simulations in a soil profile. The model has the advantage of limited input data demand and a moderate number of parameters.

INTRODUCTION

The chemical processes in the soil are strongly affected by the soil profile. The different soil horizons show large differences in chemical properties. A chemical model, which attempts to describe the reactions in soil must take this differences into consideration. The principal mediator of chemical constituents between the soil horizons is the water. The water flow from one horizon to another is therefore essential, as is the soil moisture content within the horizon.

The Swedish Integrated Groundwater Acidification project was initiated to assess the risk for groundwater acidification in Sweden. The project's main objective was to develop a model for groundwater acidification to be able to make regional assessment of sensitive areas. The main hypothesis of the present part of the project is that a vertically distributed modification of the PULSE model (Bergström *et al.*, 1985) can provide satisfactory simulations of water flow, soil moisture and transit times for input to hydrochemical models of the unsaturated zone.

The proposed model was tested against soil moisture measurements at three catchments in Sweden. Further analysis of the behavior of the modified PULSE model has been obtained by a comparison with the SOIL model (Jansson and Halldin, 1979). The SOIL model is a physically based model for simulation of water and heat transport in a layered soil profile. The same sets of input data were applied to simulations with both the PULSE and the SOIL model. Transit times simulations using ^{18}O measurements in soil lysimeters was also carried out. The result from these are presented separately (Lindström and Rodhe, 1992).

MODEL STRUCTURE

The PULSE model (Bergström *et al.*, 1985) forms the hydrological modelling framework for the modified model. The model is a conceptual rainfall-runoff model based on the HBV model (Bergström and Forsman, 1973, Bergström, 1975).

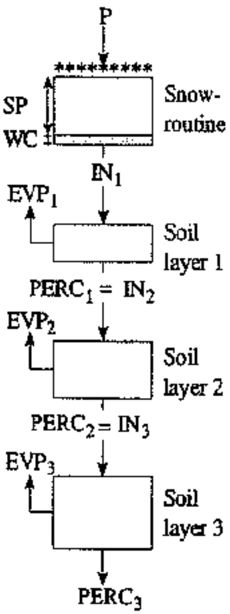
In contrast to the original PULSE model the soil moisture accounting routine of the modified PULSE model is distributed vertically according to the different soil horizons. Daily estimates of soil moisture content, evapotranspiration, water flux and residence time in the different horizons are calculated. The chosen structure of the modified PULSE model, with equations and explanation of the parameters, is shown in Figure 1. A daily time step was used in the model calculations, except in the soil moisture routine where the calculations within one day were made mm by mm.

The snow routine is identical to the one developed for the HBV model. The observed precipitation (PREC) can be adjusted by a factor (CPREC) to eliminate systematic errors in the observations. Precipitation is accumulated as snow, if the air temperature is lower than a threshold value (TTPREC). A snowfall correction factor (CSF) accounts for winter evaporation, aerodynamic losses at the precipitation gauge and its representativeness. The melt routine is essentially a degree-day approach where the melt volume is determined by a degree-day melt factor (CMELT) and a threshold temperature for snowmelt (TTMELT). A liquid water holding capacity (CWH) of the snow has to be exceeded before any meltwater can leave the snowpack.

In the soil moisture accounting routine, the water balance is calculated individually for each layer according to:

$$\frac{\Delta SM_i}{\Delta t} = IN_i - PERC_i - EVP_i \tag{1}$$

where SM_i is soil moisture in layer i,
IN_i is inflow to layer i,
$PERC_i$ is percolation from layer i,
EVP_i is evapotranspiration from layer i.

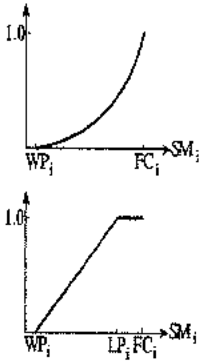


$$
\begin{cases}
P = CPREC \cdot PREC & \\
SP = SP + CSF \cdot P & T < TTPREC \\
WC = WC + P & T \geq TTPREC \\
MELT = CMELT \cdot (T - TMELT) & SP > 0 \\
MELT = 0 & SP = 0 \\
MELT = SP & MELT > SP \\
MELT = CFR \cdot MELT & MELT < 0 \\
MELT = -WC & MELT < -WC \\
SP = SP - MELT & \\
WC = WC + MELT & \\
IN_1 = WC - CWH \cdot SP & WC > CWH \cdot SP \\
IN_1 = 0 & WC < CWH \cdot SP \\
WC = WC - IN_1 &
\end{cases}
$$

$$PERC_i = K_i \; IN_i$$

$$K_i = \left(\frac{SM_i - WP_i}{FC_i - WP_i} \right)^{\beta}$$

$$\frac{EVP_i}{PET_i} = \begin{cases} \dfrac{SM_i - WP_i}{LP_i - WP_i} & SM_i < LP_i \\ 1.0 & SM_i \geq LP_i \end{cases}$$



$$PET_i = \gamma_i \cdot PET$$

$$\gamma_i = \frac{e^{-\alpha \cdot l_i} \cdot s_i}{\sum_{j=1}^{n} e^{-\alpha \cdot l_j} \cdot s_j}$$

Parameters

CPREC	Correction factor for precipitation
CSF	Correction factor for snowfall
CMELT	Degree-day factor (mm $°C^{-1}$ day^{-1})
CFR	Refreezing factor for meltwater in snow (% day^{-1})
TTPREC	Threshold temperature for snow accumulation (°C)
TTMELT	Threshold temperature for snow melt (°C)
CWH	Water holding capacity of snowpack (mm)
FC_i	Field capacity of soil layer i (mm)
WP_i	Wilting point for soil layer i (mm)
LP_i	Limit for potential evapotranspiration from soil layer i (mm)
β	Coefficient for soil moisture routine
α	Coefficient for evapotranspiration routine
s_i	Thickness of soil layer i (cm)
l_i	Depth of soil layer i (cm)
n	Number of soil layers

Variables

PREC	Observed precipitation (mm day^{-1})
T	Observed temperature (mm day^{-1})
PET	Monthly average potential evapotranspiration (mm day^{-1})
P	Corrected precipitation (mm day^{-1})
SP	Water equivalent of snowpack (mm)
WC	Liquid water content in the snowpack (mm)
MELT	Snow melt (mm day^{-1})
IN_i	Inflow to soil layer i (mm day^{-1})
SM_i	Soil moisture in soil layer i (mm day^{-1})
$PERC_i$	Percolation from soil layer i (mm day^{-1})
PET_i	Potential evapotranspiration from soil layer i (mm day^{-1})
EVP_i	Evapotranspiration from soil layer i (mm day^{-1})

Figure 1. Model structure for simulation of unsaturated flow in a soil profile. Example with three soil layers.

The downward flux is assumed to be dependent only on the inflow to and water content in each soil layer. The flow in the model is thus not driven by a gradient in the soil moisture potential based on Darcy's law and Richards equation (Richards, 1931), as is most common in the modelling of flow in the unsaturated zone (e.g. Jansson and Halldin, 1979). In earlier descriptions of the PULSE model the FC parameter represented only water available for evapotranspiration. Thus the FC parameter in this description is larger by the amount of WP and represents the total water volume in the soil.

Evapotranspiration is calculated as a fraction of the potential evapotranspiration depending on the current soil moisture status. The potential evapotranspiration from the unsaturated zone is distributed between the different soil layers according to an exponential expression, in which the evapotranspiration decreases with soil depth.

Andersson and Harding (1991) achieved a significant improvement in the performance of the PULSE-model by introducing a simple temperature regulation of the potential evapotranspiration. The routine uses daily mean air temperatures to determine the reduction in transpiration rates. Below 5 °C the potential evapotranspiration is put to zero, between 5 °C and 10 °C there is a linear increase in the evapotranspiration factor, and above 10 °C there is no temperature regulation of the evapotranspiration. This modification was also included in the present model.

Each daily inflow into a soil horizon are stored in separate pulses. For each water pulse, the model keeps track of the age, i.e. the time that has elapsed since the moment of inflow. The transit time was calculated as the volume-weighted mean age of the out flowing water pulses. Within each layer the model assumes ideal mixing. This is represented by letting the outflow be composed of an equal portion of each pulse in the layer.

The SOIL model (Jansson and Halldin, 1979; Jansson and Halldin, 1980, Jansson, 1987) describes water and heat transfer in a vertical soil profile using two partial differential equations solved by an explicit forward finite difference scheme. The flow equation for water describes the change in water content over time and depth. The unsaturated water flow is given by Darcy's law in combination with the continuity equation (Richards, 1931).

The water retention characteristic is treated according to the analytical form derived by Brooks and Corey (1964) not accounting for any hysteresis effects. Soil properties and state variables are calculated linearly between midpoints of consecutive model compartments.

Appropriate upper boundary conditions of the model are given by sub-models for precipitation, snow and frost dynamics, interception storage and the evapotranspiration. Daily amounts of snow melt are calculated from a heat sum, a factor accounting for the influence of solar radiation and the surface heat flow (Jansson and Halldin, 1980). The lower boundary condition in the water flow equation can either be considered as horizontal groundwater flow or be represented by a free drainage to an infinite groundwater body. Initial values of tensions, and the location of the groundwater table are used to calculate initial storage of water. An initial equilibrium tension profile above the groundwater table is assumed (i.e. no vertical flow). From each one of the model compartments, free water exceeding a given retention threshold is lost to infiltration either vertically or horizontally if the groundwater table is located in the compartment immediately below the compartment with excess water.

DATA BASE

The soil moisture routine of the modified PULSE model was tested at three catchments in Sweden (Figure 2). The Masbyn catchment, where extensive investigations of soil, soil water and groundwater were made between 1973 and 1977 (Lundin, 1982). Fifty percent of the area were clear-cut during the winter season 1975/76 and was thereafter reforested. Podzolic sandy silty till soils dominate the area. The water holding capacity relationships at different horizons were taken from Lundin (1982). Neutron probe measurements at 10 different depths in the upper meter for the periods 1973-76 were used.

Figure 2. Geographical location of research sites.

The Risfallet catchment is dominated by podzol on sandy loam and gravely till with a significant element of boulder and bare rock. Neutron probe soil moisture measurements were carried out at 8 different depths in the soil profile and at 15 occasions during the period 1987-89. The water retention characteristics is taken from Lundin *et al.* (1992).

The Velen catchment is mainly sandy till, underlain by gneiss and granite. A detailed description of the catchment is given by Hedin (1971). Measurements of soil moisture content at the site Sjöängen 7 were used in this study. Neutron-probe field measurements were carried out weekly during the period 1967 to 1974. The present study is based on measurements at 10 different depths in the upper meter of the soil. The thickness of the different horizons and the water holding capacity were mainly determined from limited soil analysis (Andersson and Harding, 1991). The water retention was determined at three pF values (0.7, 2.0, and 4.2) at three depths in the soil profile (0 - 10 cm, 30 - 40 cm, and 60 - 70 cm).

PARAMETER ESTIMATION

Table I summaries the parameters used in the simulations. The precipitation and snow routine parameters CPREC, CSF, CMELT, TTPREC, and TTMELT were calibrated against runoff measurements for the entire catchments. The parameters CWH and CFR are in the model fixed at 10 % and 5 % respectively. CMELT was calibrated to a value of 2.8 mm °C^{-1} day^{-1} in all simulations.

Table 1. *Input data and parameter values for the PULSE model.*

	Velen[1]	Masbyn[2]	Risfallet[3]
Precipitation station	Sjöängen[4]	Grängesberg[5]	Folkärna[6]/ Hedemora[7]
Temperature station	Sjöängen[4]	Ställdalen[8]	Folkärna[6]
Potential evapotranspiration	Örebro[9] (Wallén 1966)	Ställdalen[8] (Eriksson 1981)	Folkärna[6] (Eriksson 1981)
Depth to groundwater table (mm)	1000	1000	2500
Parameter CPREC	0.76	0.95	0.80
Parameter CSF	0.85	0.75	0.85
Parameter TTPREC	0.3	0	0
Parameter TTMELT	0.7	0	0.5
Horizons	O/E/B/C	O/E/B/C	O/E/B/C
Thickness (mm)	60/240/300/400	120/210/220/450	80/80/600/240
Parameter FC (mm)	27/87/108/100	50/84/68/107	22/21/165/52
Parameter WP (mm)	4/17/21/14	7/4/8/22	2/1/33/18

[1] 58°46'N 14°18'E [2] 59°54'N 15°15'E [3] 60°21'N 16°13'E [4] 58°46'N 14°18'E [5] 60° 4'N 14°59'E
[6] 60°10'N 16°19'E [7] 60°17'N 15°58'E [8] 59°56'N 14°56'E [9] 59°16'N 15°9'E

In the soil moisture accounting routine the parameter FC was determined from measured soil moisture retention curves for each soil layer. A constant groundwater level was then assumed in the model, corresponding to the measured average groundwater level for the simulation period. The parameter WP, representing water held below wilting point, was determined for each soil layer from water retention curves at a suction of 150 m (pF-value 4.2).

The application of the model to vertical point simulations and not mainly to basin simulations resulted in a simplification of the soil moisture routine. The number of empirical parameter combinations was reduced by setting β and LP equal to 1. None of the parameters in the soil moisture routine was thus calibrated against measurements of runoff or soil moisture.

The empirical coefficient α, affecting the distribution of the evapotranspiration between the soil layers, was determined by fitting the exponential equation to literature data on the depth profile of root density (Marshall and Holmes, 1979; Jansson and Halldin, 1980; and Lundmark, 1988). This lead to the value 0.03, which then was used in all applications.

The comparison between the PULSE and the SOIL models was done using data from the Velen research catchment. Additional parameters and input data to the SOIL model were taken from various sources. Transpiration parameters, leaf area index etc have been determined according to the measurements performed in the Velen catchment (Bringfeldt, 1982, Bringfeldt and Lindroth, 1987). The draining gradient was given a value close to the slope gradient at the Sjöängen station, i.e. approximately 1.6° slope (Andersson, 1988).

The three soil layers, for which data were available, were for the SOIL model simulation complemented with two horizons to account for surface and deeper soil characteristics, one organic surface horizon (0-6 cm) and one denser till horizon (100-200 cm). The shapes of the retention curves for these two horizons are based on comparisons with other soil profiles of similar conditions found in a data base (Jansson, 1989). The saturated hydraulic conductivity had to be estimated from the literature (Cozzarelli *et al.*, 1987; Espeby, 1990) taking into account the relationship between drainable porosity and saturated hydraulic conductivity (Ahuja, *et al.*, 1984; Espeby, 1990).

The model soil profile was divided into ten compartments to account for the morphological structure and the numerical requirements of the finite difference technique. Air temperature and precipitation where the same as for PULSE model simulation. Estimated values of relative air humidity, wind speed, and cloudiness were also used.

The model was calibrated for the period 1967-1968. The groundwater level was used to balance the model at the lower boundary and several root distributions were tested to find the best fit. The chosen compartments, root distribution and saturated hydraulic conductivity are given in Table 2.

Table 2. The SOIL model profile (figures within brackets are estimated values)

Soil depth (cm)	Soil designation	Model compartment (cm)	Roots (%)	pF=0.00 (porosity)	pF=0.07	pF=2.00 (FC)	pF=4.50 (WP)	K_s(tot) ($x10^{-6}$ m s^{-1})
0-6	Organic (O)	0-6	20	(90)	(-)	(-)	(7)	416.7
6-30	Eluvium (E)	6-18	20	48.0	43.9	33.7	7.0	120.0
		18-30	20	48.0	43.9	33.7	7.0	120.0
30-60	Illuvium (B)	30-45	15	49.6	39.4	31.8	6.9	41.7
		45-60	10	49.6	39.4	31.8	6.9	41.7
60-200	Parent (C)	60-80	10	34.6	27.6	22.5	3.4	0.85
		80-100	5	34.6	27.6	22.5	3.4	0.85
		100-125		(20)	(-)	(-)	(5)	0.16
		125-150		(20)	(-)	(-)	(5)	0.16
		150-200		(20)	(-)	(-)	(5)	0.16

RESULT

Figure 3 shows the soil moisture simulation with the PULSE model at Masbyn for the period 1973-76. In this simulation no change in the parameter set was made at the time of the clear-cutting during the winter 1975/76. The depth to the groundwater level in the model was assumed to be constant during the entire simulation. The effect of the clear-cutting on the water balance can clearly be observed during 1976. The actual soil moisture content increased significantly due to diminishing water uptake, while the model simulation is similar to that of the previous growth season of 1975.

The values of the simulated soil moisture content in the upper most soil layer are underestimated compared to the observed values. In the three deeper soil layers the level of the soil moisture content as well as the dynamic of the soil moisture variations are well described by the model.

This study emphasis simulations of the soil moisture dynamics at different depths. Runoff data has also been used, primarily for calibration of the snow routine in the PULSE model. The presented runoff simulation has, however, to be regarded only as qualitative information. There is a great difference between the groundwater recharge to an aquifer, which is being modelled, and discharge from the basin, which is being measured.

Figure 4 shows the soil moisture simulation for Risfallet. In this simulation there are no measurements representing the upper soil layer. Good agreement between the simulation and the measurements was obtained in the E-horizon. In soil layer B the level of soil moisture at saturation was correct, but the observed variations of soil moisture content were much smaller than the simulated variations. In soil layer C the simulated values were consistently too high compared with the measurements.

The soil moisture as simulated by SOIL and PULSE for Sjöängen 7 in the Velen catchment is presented in Figure 5. Calibration of the SOIL model is mainly done by varying the root distribution and other evapotranspiration effective parameters, i.e. surface resistance. The soil moisture routine in the PULSE model is not calibrated.

From the winter 1970/1971 the wrong scaler was used with the neutron probe at Sjöängen, which resulted in too high readings (T. Milanov, pers. comm.). This is clearly seen in the presentation of the 80 cm level. The general dynamics should, however, be reasonable. Overall, both models capture the soil moisture dynamics, although some errors are substantial. The SOIL model gives a higher variation and show high peaks during snow melt, especially at the 45 cm level, which are not found in the observations. The PULSE model, on the other hand, does not reach the high values observed for the winter period at the 20 cm level.

DISCUSSION AND CONCLUSIONS

The ability of the PULSE model to capture the dynamic and level of soil moisture at three different sites is surprisingly good. This especially as the soil moisture routine is run without

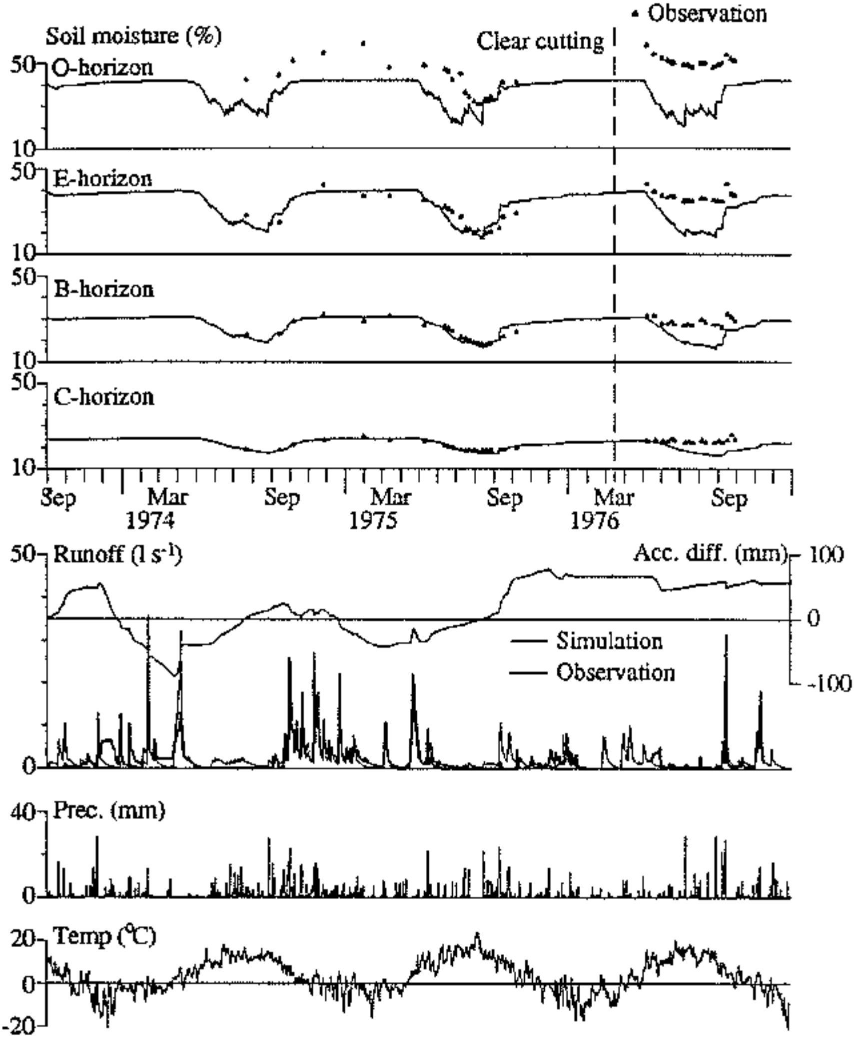


Figure 3. *Simulation of soil moisture at Masbyn for the period 1973-09-01 - 1976-12-31. Dots represents mean values of the soil moisture measurments within each horizon. Simulated and observed runoff, accululated difference between observed and simulated runoff, temperature and precipitation are also presented.*

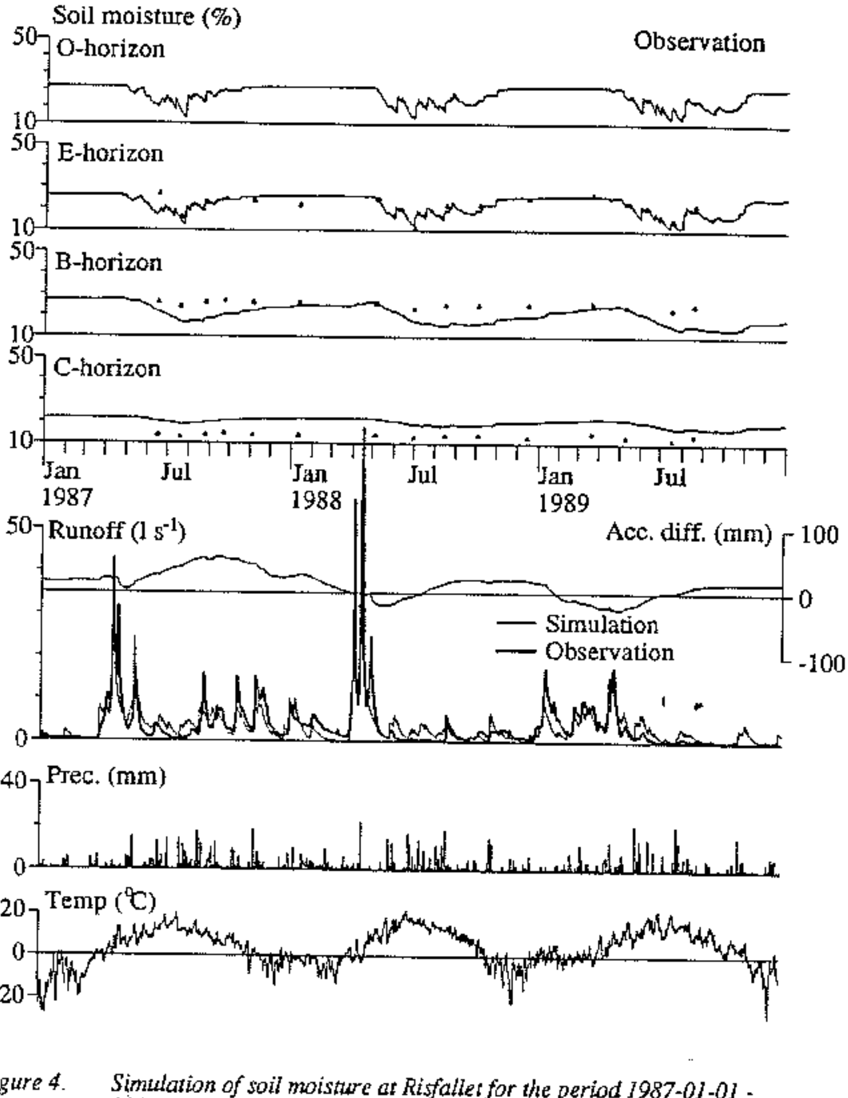


Figure 4. *Simulation of soil moisture at Risfallet for the period 1987-01-01 - 1989-12-31. Dots represents mean values of the soil moisture measurments within each horizon. Simulated and observed runoff, acculated difference between observed and simulated runoff, temperature and precipitation are also presented.*

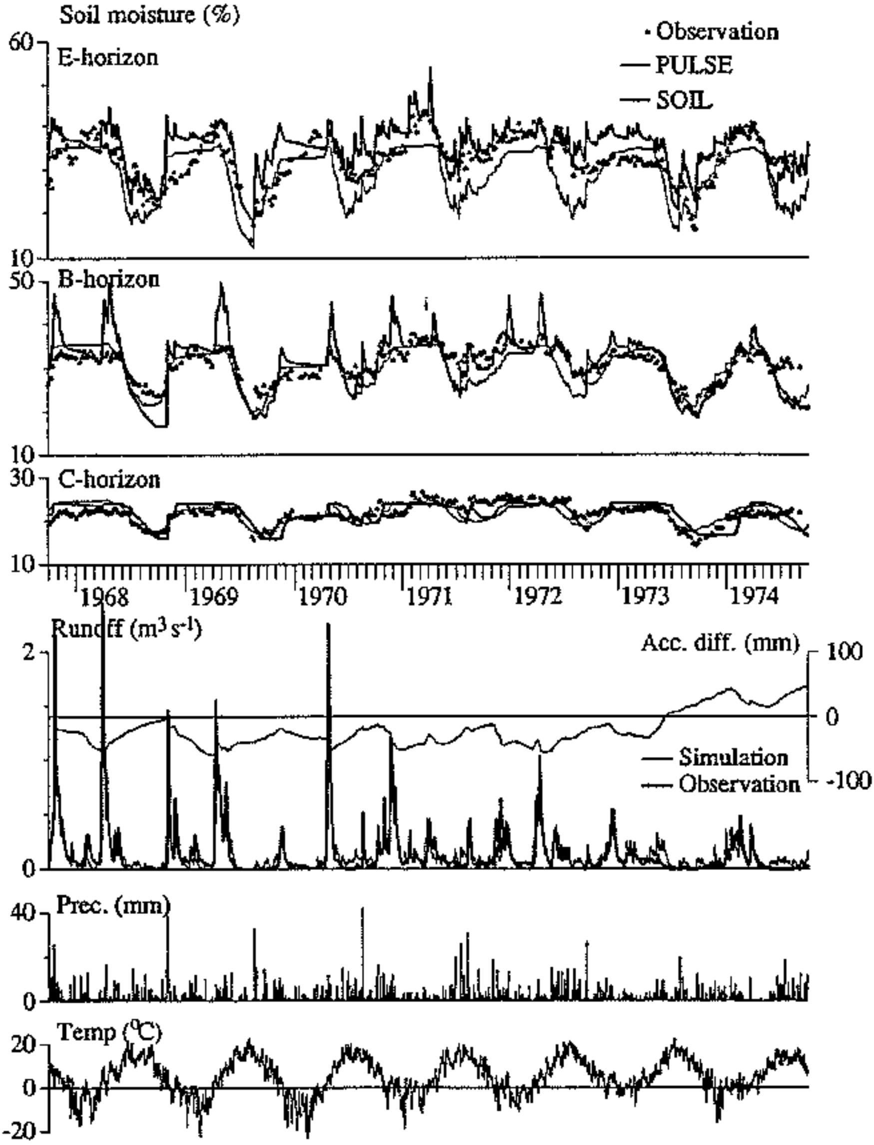


Figure 5. Simulation of soil moisture at Velen for the period 1967-10-01 - 1974-09-31, with PULSE and SOIL models. See figure 3 for detail.

any calibration. The result does, therefore, suggest that the model can be a valuable tool for simulation of soil moisture as input to hydrochemical models.

The difference between observed and simulated soil moisture of the O-horizon at Masbyn could be due to the model formulation. The observations are considered correct despite the problems of neutron probe measurements close to the surface. The high values have been controlled by soil analysis (Lundin, pers comm.). The model formulation does not allow the soil moisture to increase above the specified pF-value, which is determined by the fixed groundwater level.

The weak modelling result representing horizons B and C at Risfallet could be explained by large elements of rock and boulder in the upper meter of the soil and by the fact that the water retention curves were determined only from analysis of material smaller than 20 millimeters. In the upper meter of this soil only 22 percent of the total soil volume is material smaller than 20 millimeters. The neutron probe measurements are also sensitive to rocks and stones in the vicinity of the probe. Although the model formulation might be too simplistic, the problem with estimating the field capacity and measuring soil moisture has to be considered in this soil type.

Both PULSE and SOIL capture the main dynamics of the soil moisture variation, although some errors are considerable. The SOIL model has larger short term variations and gives sharp peaks in soil moisture during periods with high soil moisture, especially during snow melt. This is due to the fact that the groundwater table reaches up to the 45 cm level at these events. The result is in accordance with groundwater measurements from a well at the site, but can not be observed in the soil moisture observations.

The most important limitation of the simulation at Velen is clearly the restricted soil analysis. It is also important to note that the SOIL model simulations are based on several uncertainties. Firstly, there is an uncertainty concerning the root distribution and the actual time when the roots in different parts of the profile are active. These uncertainties strongly affects the computed soil moisture conditions in the upper part of the profile. Secondly, the saturated hydraulic conductivities are based on other soil profiles from similar geological conditions, since no analyses of saturated hydraulic conductivity have been made at Sjöängen. Thirdly, water retention properties for the surface layer and the bottom layer of the soil profile were also transferred from other similar geological conditions. In till it has been shown that the soil physical properties of the bottom layer influence much of storage and flow of water in the upper part of the profile (Espeby, 1992). These facts may explain some of the deviations from observed levels.

The SOIL model is a good tool for basic research on soil water processes. The data demand in form of parameters and forcing functions is, however, a problem for basin-wide or regional applications of the model.

The weakest point in this application of the PULSE model is that the variation in groundwater level is not considered in the soil moisture routine. A dynamic groundwater level could increase the soil moisture during spring in the upper soil horizons. This would clearly improve the simulation for both the Masbyn and the Velen catchments. A natural step in future development of the model is therefore to link a dynamic groundwater level to the soil moisture routine to allow variation in the field capacity according to a reasonable groundwater table.

When judging the results of the present study it is important to bear in mind the objective of the research project. For regional applications we have to accept that no data normally is available for model calibration and that little is known about soil characteristics. It is therefore encouraging that the model performs relatively well without calibration and that this seems to be a general conclusion for a number of sites. The model is not site specific, nor over-parameterized. Some results may look questionable, this reveals, however, the uncertainty that we have to face in later uncontrolled applications. In addition, the simulation of ^{18}O in lysimeters with the modified PULSE model produced reasonable transit times and distributions (Lindström and Rodhe, 1992).

The general conclusion is that the PULSE model, with its limited data demand and ease of handling, is well suited for basin-wide and regionalized long term simulations for acidification forecasts.

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APPLICATIONS OF GEOSTATISTICS TO GROUNDWATER FLOW AND SOLUTE TRANSPORT MODELLING

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ABSTRACT

The application of geostatistical approach to the groundwater flow and solute transport simulation is demonstrated by using a hypothetical field problem. The study shows that the geostatistical approach is suitable to evaluate the predictive uncertainty of flow and transport in heterogeneous aquifer due to the partial sampling of conductivity field. The predictive capability of contaminant transport using stochastic approach, however, is limited if only limited conductivity data are sampled.

1. INTRODUCTION

Traditional approach of modelling groundwater flow regards hydraulic properties of aquifers as uniform over the entire area of interest, or in part of it which are separated by well defined boundaries, i.e. the aquifers are assumed to be homogeneous. The large scale dispersion of a solute in aquifer is described as a diffusion process with regular dispersions in space and time governed by the advection-dispersion equation using a scaling-uped dispersivity value (e.g. Bear, 1972).

However, the assumption of spatial homogeneity of aquifer properties is generally not supported by field findings. Field measurements indicate consistently that hydraulic properties vary throughout the space in an irregular manner (e.g. .Dagan, 1986). Groundwater flow and contaminant transport are uneven distributed temporally and spatially enhanced by the spatial heterogeneity of aquifer properties. There is increasing evidence to show that homogeneous assumption is an inappropriate basis for describing groundwater flow and solute transport in geological systems (Smith and Schwartz, 1981a). Accounting for the spatial variability of aquifer properties is essential for understanding of groundwater flow and contaminant transport phenomena in the field situation.

In practice, it is not possible to have entire information of spatial variation of aquifer properties to specify the actual complex heterogeneity of aquifer. Only limited measured hydraulic properties are available, the hydraulic properties at unmeasured positions are remained to be uncertain. During the past decade, stochastic approaches have been widely used to describe the spatial heterogeneity of aquifer properties and evaluate the uncertainty on groundwater flow and solute transport due to limited sampling of hydraulic properties (e.g. Smith and Schwartz, 1981a,b; Varljen and Shafer, 1991).

In this study, only hydraulic conductivity, K, is considered to be variable in space. Groundwater travel time is also influenced by effective porosity. However, the effect of uncertainty in porosity is not as significant as uncertainty in hydraulic conductivity. Smith and Schwartz (1981) have shown that solute transport is insensitive to the spatial variation in porosity.

Using stochastic approach, K is regarded as a Space Random Function (SRF) determined by its statistical features (moments) and spatial correlation structures. As a result, the groundwater flow and solute transport are also Random Functions. The statistical features and spatial correlation structures of conductivity field are essentially estimated (inferred) from the available sampling data of K (the field measures by pumping tests, slug tests or single hole packer tests) using geostatistical techniques (Journel and Huijbregs, 1978). The whole conductivity field is simulated based on the inferred statistical features. The uncertainty in flow and transport due to the uncertainty of K at unsampled points is evaluated by using Monte-Carlo method.

In this paper, the application of stochastic conditional simulation method to groundwater flow and solute transport is illustrated using a hypothetical field problem. Based on the limited conductivity sampling data, the uncertainty of flow and contaminant transport in a heterogeneous aquifer is evaluated.

2. STOCHASTIC SIMULATION OF GROUNDWATER FLOW AND SOLUTE TRANSPORT

2.1 The reference field and basic sampling conductivity data

In order to demonstrate the implementation of geostatistical technique and stochastic approach to the groundwater flow and solute transport simulation, a 2-D hypothetical confined aquifer is used as a reference field. The aquifer has the size of 3600m x 3600m and is discretized into a 60x60 mesh giving the block size of 60m x 60m. The considered aquifer is assumed to have uniform thickness of 10 m and constant porosity of 0.2. The conductivity values at all 3600 blocks are assumed to have been exhaustively tested and thus the field is considered to be a "known reality". Fig. 1 shows the image of the reference conductivity field. The histogram, statistic moments (mean and variance) and experimental variogram calculated from 3600 data in natural logarithm (Ln) are shown in Fig. 2. The reference conductivity field is found to have statistical isotropic correlation structure which can be fitted by an exponential model with correlation length of 240m.

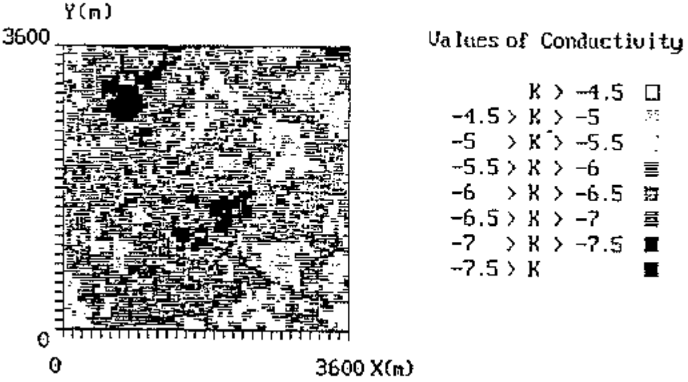


Fig. 1 Spatial image of reference conductivity field

The upper and bottom boundaries in the reference field are assumed to be no-flow, whereas left and right boundaries are constant heads resulting in a mean gradient of 2/1000 parallel to the X-axis (Fig. 3). A single water supply well (constant pumping rate, Q, equals 500 m³/d) is located in the field. In addition, a waste disposal site having the size of 60m x 960m is located on the upper-stream of the pumping well (Fig. 3).

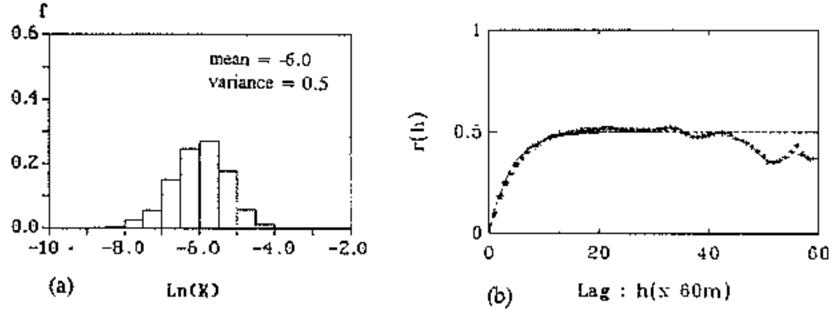


Fig. 2 Histogram (a) and variogram (b) of reference field

The steady-state 2-D groundwater flow equation is solved using 5-point standard block centred finite difference scheme. Fig. 4 shows the resulted head distribution in the reference field. Contaminant accidently released from the disposal site will carried by the groundwater flow. The released contaminant is regarded as made up from a set of conservative particles. The movement of particle is followed by using particle tracking technique. The arrivals of particle at the pumping well are recorded. Fig. 5 shows the particle breakthrough curve at the well indicating that the pumped groundwater would be polluted if contaminant is released at the waste disposal site. Two distinct peaks with different travel times are revealed from the breakthrough curve.

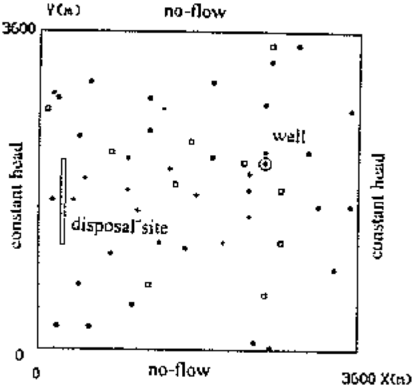


Fig. 3 Boundary conditions and sampling data locations

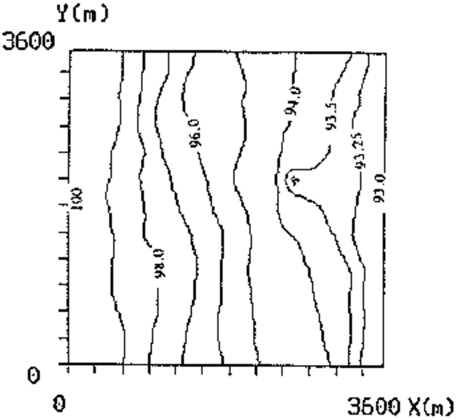


Fig. 4. Head distribution in reference field

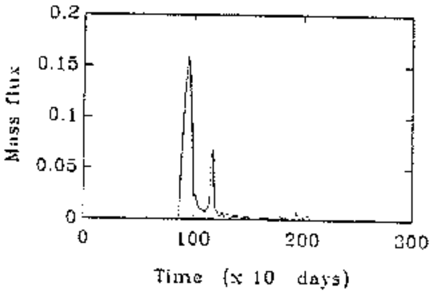


Fig. 5 Particle breakthrough curve in reference field

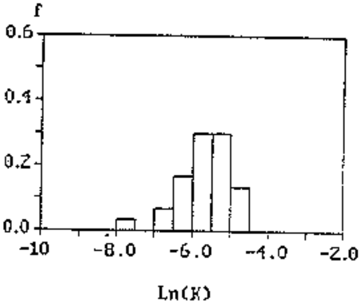


Fig. 6. Histogram of 30 sampling data

It should be note that the exhaustive conductivity data set in the reference field would never be available in practice. The purpose of using a reference field, where all conditions and results are known, is to verify the effectiveness and relevance of the technique used. The same methodology was used by e.g. Varljen and Shafer (1991); Journel and Alabert (1989). The above flow and transport results are considered as "true" results occurring in the "known reality" which are usually needed to be predicted based on limited sampling conductivity data in practice. The predictive results and uncertainty will be compared to the "true" results to judge the relevance of simulation approach.

A practical problem can be formulated as the following: we assumed that the conductivity field has been measured at 30 locations. Fig. 3 (dots) shows the positions of the 30 sampling data which are selected from the field. The conductivity values at sampled locations are extracted from the reference field. Based on the 30 available conductivity data, we need to predict the possible pollution of pumped water in case of an uncontrolled release of contaminant from the waste disposal.

The histogram of the 30 available conductivity data is shown in Fig. 6 giving the mean and variance of Ln(K) to be -5.703 and 0.422 respectively. This indicates that the conductivity values in this area are spatially varied. Due to the lacking of knowledge on conductivity values at unsampled locations, the prediction of groundwater flow and contaminant transport is subjected to uncertainties. To quantify the predictive uncertainty, a stochastic approach is required.

2.2 Procedure of stochastic simulation

The standard procedure of stochastic conditional simulation includes four steps which are: (1) geostatistical analysis of available data, (2) conditional simulation of conductivity fields, (3) Monte-Carlo calculation of groundwater flow and solute transport, and (4) statistical analysis of the results to obtain the predictive uncertainty of flow and transport.

For the geostatistical analysis, the mean, variance, and correlation structure (or variogram) of the conductivity field are inferred from the available sampling data. The procedure to estimate above parameters from sampling data is referred as "statistical inference" (Journel and Huijbregts, 1978). For the conditional simulation of conductivity fields, the mean, variance and variogram inferred from the sampling data obtained by step (1) are used to generate equally likely realizations of the conductivity, all possessing the same statistical properties as the inferred ones, and conforming to observed values at sampled locations (Delhomme, 1979).

In the third step, Monte-Carlo calculation is conducted by solving groundwater flow and solute transport equations for each of the conditional conductivity fields generated in the previous step. Finally, the ensemble of head distribution and breakthrough curve of contaminant at pumping well together with their uncertainties are obtained by statistical analysis of flow and transport results from all realizations.

2.3 Results of stochastic simulation

Following the above procedure, the groundwater flow and contaminant transport are simulated based on the 30 sampling data. Fig. 7 shows the inferred experimental variogram of 30 data (star) and the fitted exponential model (dash line) with correlation length of 300m. 100 realizations of conditional simulation of conductivity fields are generated using the Turning Bands method (TUBA, Mantoglou and Wilson, 1982). Groundwater flow and particle transport in all realizations are calculated using the same flow and transport conditions as the reference field.

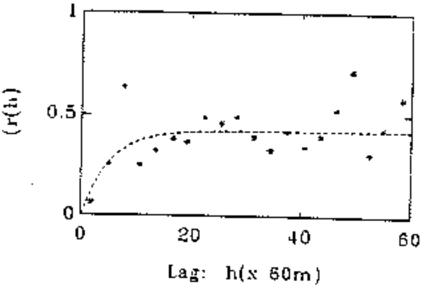


Fig. 7 Experimential variogram and fitted model from 30 sampling data

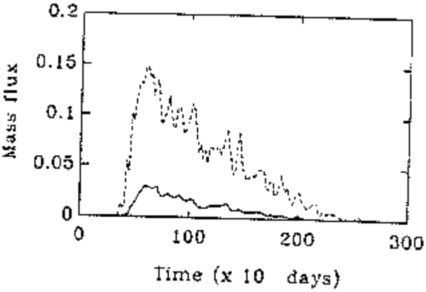


Fig. 9 Ensemble breakthrough curve based on 30 sampling data

Fig. 8 shows the contour maps of expected head distribution and uncertainty of head quantified by standard deviation of head. The expected breakthrough curve of mass arrival at the pumping well (solid line) and its 3 standard deviation envelope (99.5% confident interval for a normal distribution, dash line) are shown in Fig. 9 together with the breakthrough curve in the reference field (point line).

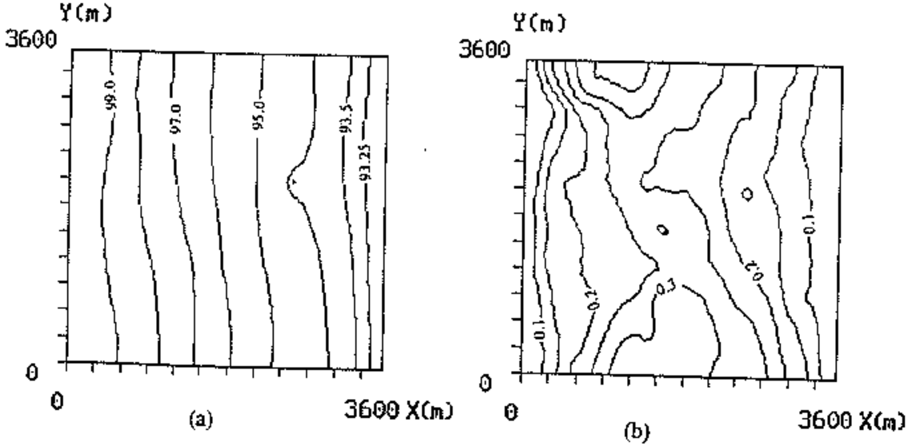


Fig. 8 Expected head distribution (a) and head uncertainty (b) based on 30 sampling data

The results show that the head uncertainties around the sampled points are smaller than that at unsampled areas (Fig. 8b). The expected breakthrough curve of particle arrival yields a faster arrival than the reference field, which is caused by the fact that the inferred Ln(K) mean from the 30 sampled data is larger than the reference field (Table 1). The features of particle arrival at the pumping well in the reference field are not adequately reflected. Large predictive uncertainty on the particle arrival is obtained. For the further reduction of the uncertainty, more sampling conductivity data are needed.

3. THE EFFECT OF DIFFERENT DATA SAMPLING PROCEDURES

We assume that 10 more measurements of conductivity are to be carried out. Two different sampling procedures are used. The locations of additional 10 sampled data from different sampling procedure are also shown in Fig. 3. In case A, 10 additional sampled data (+ in Fig. 3) are mainly located in the area where the contaminate transport is expected to be preformed. In case B, 10 additional data are randomly selected (□ in Fig. 3).

Table 1. The inferred statistics of Ln(K) from different data sets

	mean of Ln(K)	variance of Ln(K)	correlation length
reference field	-6.0	0.5	240m
30 sampling data	-5.703	0.422	300m
Case A	-5.910	0.513	300m
Case B	-5.730	0.379	300m

The inferred statistics from different sampled data sets are listed in Table 1. The inferred mean and variance of Ln(K) in Case A are close to those in the reference field. However, in Case B, the inferred mean is larger than the reference field and variance is smaller than the reference field. The experimental variograms and fitted exponential models are shown in Fig.10.

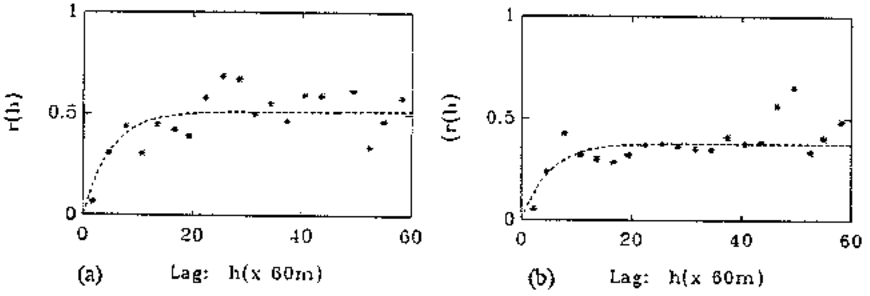
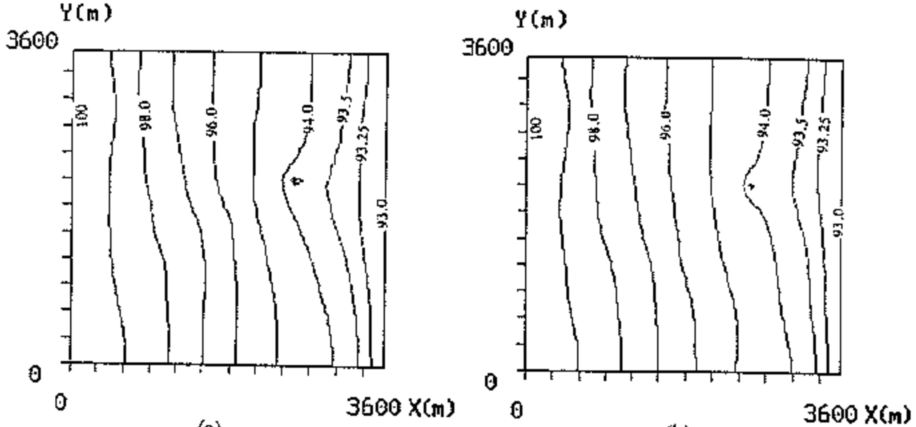


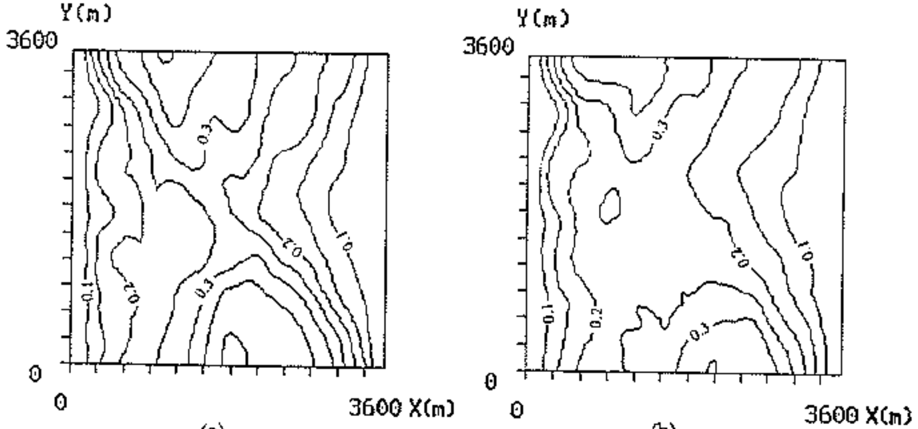
Fig. 10 Experimential variogram and fitted model from Case A (a) and Case B (b)

Using above inferred statistics,the same precedure mentioned in previous section are used. Fig. 11 shows expected head distributions obtained from two cases and the uncertainty of head distributions are shown in Fig. 12. Ensemble particle breakthrough curves are shown in Fig. 13.



(a) (b)

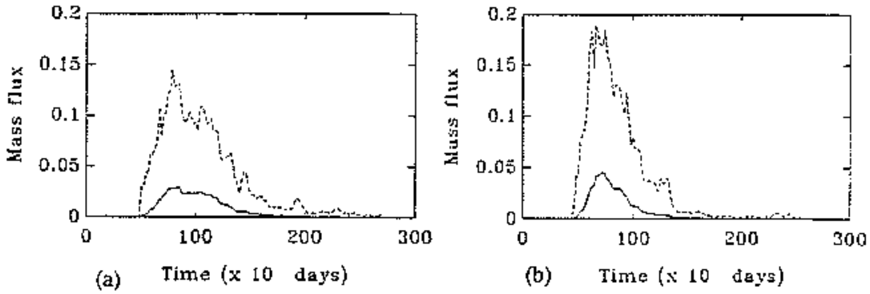
Fig. 11 Expected head distribution obtained from Case A (a) and Case B (b)



(a) (b)

Fig. 12 Head uncertainty obtained from Case A (a) and Case B (b)

The expected head distribution in Case A is closer to the reference field compared to Case B. The head variances in both cases are reduced compared to Fig. 8b where only 30 data are used. The ensemble breakthrough curves are also improved by adding the 10 data in both cases. However, it can be clearly seen from Fig. 13 that the improvement of transport results in Case A is better than in Case B. This indicates the effect of sampling data locations on the solute transport simulation. On the other hand, the predictive uncertainties on particle arrival in both cases are remained to be relatively large. This implies that the predictive capability of solute transport in a heterogeneous aquifer is limited due to limited sampling conductivity data.



(a) (b)

Fig. 13 Ensemble particle breakthrough curves from Case A (a) and Case B (b)

4. DISCUSSIONS AND CONCLUSIONS

The application of geostatistical approach to the groundwater flow and solute transport was demonstrated by using a assumed field problem. Study shows that geostatistical approach is suitable to evaluate the uncertainty of groundwater flow and solute transport in heterogeneous aquifer due to the partial sampling of conductivity data.

In practice, any available sampling data sets are limited due to the high expense of sampling. When only limited sampling data are available, the distribution of sampled data locations can have distinct effect on the simulation results. The study by Kung and Wen (1992) has also shown that solute transport results may be notably improved by adding limited sampling data which are selected appropriately. On the other hand, one should be aware that the predictive capability of contaminant transport using stochastic approach is limited if only limited sampling data are available (only about 1% of the whole field data is in this study), which is the usually situation encountered in practice.

In addition, in many cases, besides the direct measurement of K with no uncertainty, referred to as "hard data", different kinds of indirect information of K with more or less uncertainty is available, referred to as "soft data" (Journel and Alabert, 1989); such as the geological (e.g. rock type), geophysical information (e.g. seismic data), If soft data is Incorporated into the conditional simulation of conductivity field, the available information is expanded. This might provide the possibility to better account for the heterogeneity of K and to obtain better prediction of groundwater flow and transport.

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THE VARIATION OF BASEFLOW FROM A DANISH CHALK AQUIFER

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ABSTRACT

The variation of baseflow from a regional chalk aquifer to a Danish river system is analysed on the basis of synchronous streamflow measurements and numerical calculations of the interaction between groundwater and streamflow. The results show that the baseflow strongly depends on the local hydrogeology along the stream: High contributions occur in central areas with no clay deposits. Fairly constant contributions come from subcatchments where the potential surface is flat and the aquiclude between the stream and the groundwater thin. Greater variation is found in areas where the hydraulic gradient is high. The results are used to discuss a widely used low-flow estimation procedure.

INTRODUCTION

In Denmark, as well as other regions with pronounced seasonal variations in precipitation and evapotranspiration, the main contribution to streamflow during low-flow periods comes from groundwater sources. In recent years conflicts of interest between different uses of stream water during low-flow periods (recreation, irrigation, fishing etc.) have increased the need for insight into the interaction between groundwater and stramflow, and operational tools for making rational decisions about the groundwater exploitation. Setting up a full-scale coupled groundwater/streamflow model usually exceeds available resources of time and data. Therefore in practice the decision is often based on measures of low-flow characteristics (e.g. Danish Environment Protection Agency, 1979).

The primary objective of the present paper is to obtain some insight into the coupling between streamflow and groundwater by fully exploiting ordinarily available data, such as well observations, climatic data and streamflow data. This is done by using a numerical groundwater model of a Danish chalk catchment. The model is partly calibrated on results from synchronous streamflow measurements, which were repeated during various dry weather periods (in order to reduce the uncertainty). The measurements are used to estimate the AM50, the median of the annual minima.

The AM50 was introduced into Danish legislation in the early 1970es in connection with new limits on waste water discharge (Jensen, 1973). The AM50 has become the most used low-flow measure in Denmark (e.g. Danish Environment Protection Agency, 1979; County of Aarhus, 1985), whereas in the UK, for example, the key variables are the Q95, the 95 % fractile of the flow duration curve, and the MAM(7), the 7 day mean annual minimum (Gustard and Bullock, 1991).

The present paper falls into four parts. In the first part the hydrogeology of the catchment is outlined. Secondly, the results of the synchronous streamflow measurements are analysed and used to estimate the AM50. Thirdly, the results of the model work are presented, and finally, the results are used to discuss some aspects of the widely used AM50 estimation procedure based on synchronous discharge measurements (Danish Land Development Services, 1990).

HYDROGEOLOGICAL SETTING

The substratum in the catchment of the River Alling in Denmark (Fig.1) is dominated by fractured Danian chalk, which forms the regional aquifer. The chalk surface is domed because of a deep (2-3 km) Permian salt dome (Madirazza, 1986). At the centre of the dome the chalk surface is 30-40 m above sea level and very close to the surface.

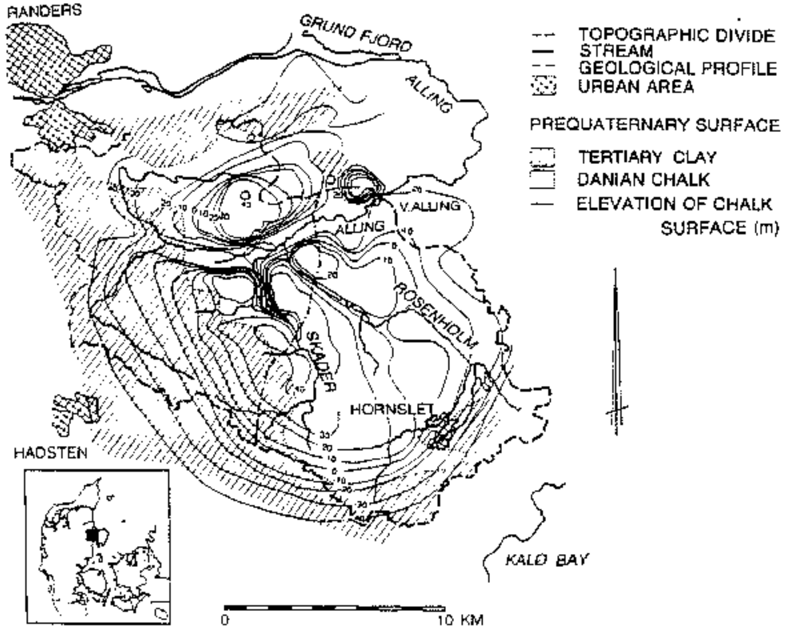

Fig.1 The pre-Quaternary surface in the Alling catchment.

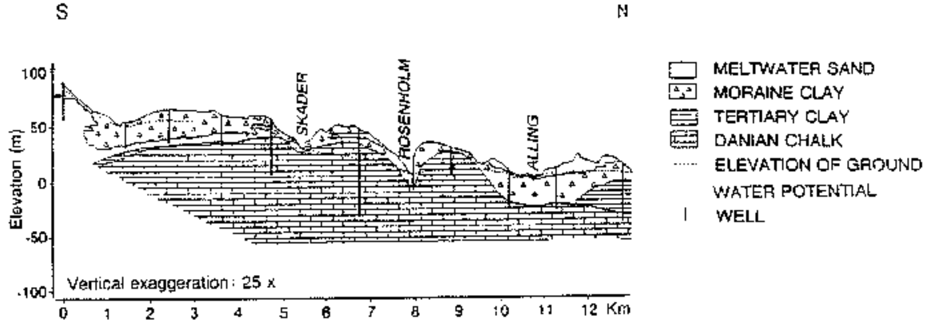

Fig.2 Geological profile across the Alling valley. The location is shown in Fig.1.

In the western and southern areas the Danian chalk is overlain by almost impermeable Tertiary clay (Fig.1) with a thickness of up to 50 m near the watershed (Clausen, 1989). In the remaining area the chalk is overlain by Quaternary deposits of till clay and meltwater sand, the latter often forming secundary aquifers (Fig.2). The deposits are thin in the central areas and even in the shallow Skader and Rosenholm valley. However, in the broad and deep Alling valley the Quaternary deposits reach thicknesses of 50 m.

The Quaternary deposits in the valleys determine the hydraulic contact between the regional aquifer and the streams. Fig.3 shows the valley deposits dominated respectively by clay and by sand. This distribution, defined solely on geologic information, will later be compared with hydraulic parameters estimated from discharge measurements. All geological information in Figs. 1, 2 and 3 has been derived using records from about 200 wells shown in Fig.3.

The hydraulic head ϕ in the regional aquifer (Fig.4) is based on water level records from the 200 wells shown in Fig.3. The head is high (> 60 m) and the hydraulic gradient is great in the south-western area, while in the northern and eastern areas ϕ is low (< 20 m) and the hydraulic gradient small. The contour lines are very much influenced by the Alling and the Rosenholm valleys, while the Skader valley does not seem to affect the head significantly. The groundwater catchment is about 10 % smaller than the topographic catchment.

The recharge R of the aquifer varies within the catchment. In the central areas with unconfined groundwater (Fig.4) only a thin till layer covers the chalk. Here R equals the infiltration I from the root zone. The actual evapotranspiration AE and I during the period 1974-88 were computed by Clausen (1989) using values of precipitation P, potential evapotranspiration PE, and the root zone capacity RZC. The applied estimates of RZC were based on soil type and vegetation according to Madsen and Platou (1983). The average values of P, PE, AE, I, as well as the specific discharge Q for the topographic catchment of the River Alling at Vester Alling, are given in table 1. The difference between I and Q is due to subsurface run off (approx. 4 mm/year) and pumping (approx. 6 mm/year, County of Aarhus, 1985).

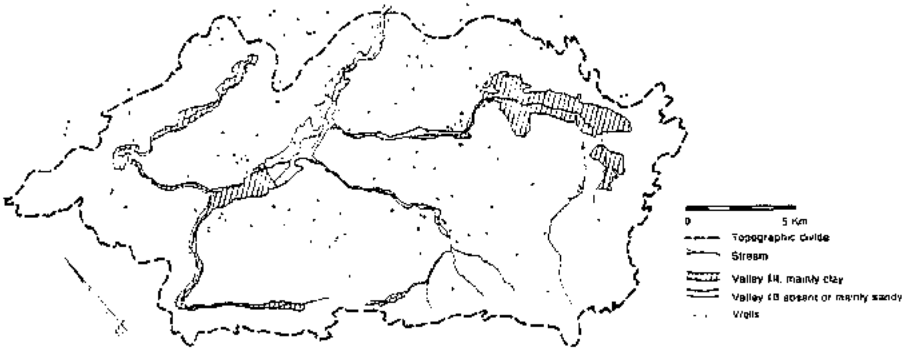

Fig.3 The nature of the Quaternary valley deposits and the location of wells.

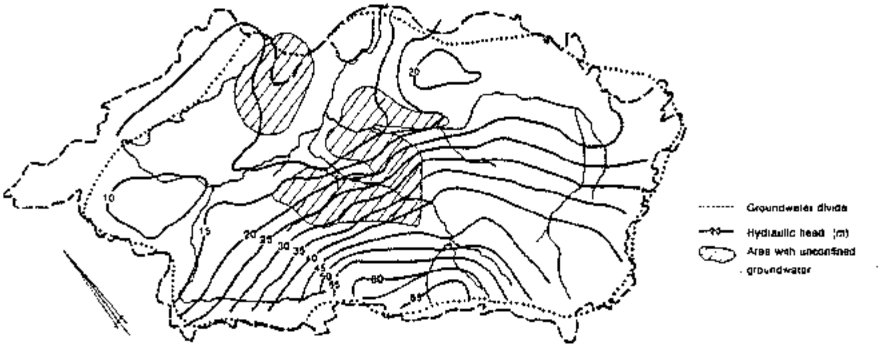

Fig.4 The hydraulic head in the regional aquifer and areas with unconfined groundwater.

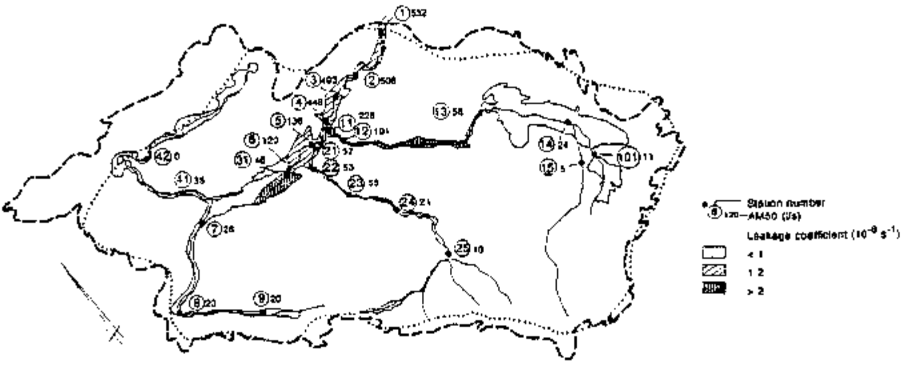

Fig.5 Station numbers, estimated AM50 values, and leakage coefficients λ for the valley reaches (calculated from AM50 and differences in hydraulic head).

Table 1. Average values of precipitation P, potential and actual evapotranspiration, PE and AE, the infiltration from the root zone I, and the discharge Q of the River Alling at Vester Alling during the period 1974-88. The precipitation is corrected for errors, see Clausen (1989).

Area km2	Period -	P	PE	AE mm/year	I	Q
242	1974-88	713	565	467	243	233

In areas where the groundwater is confined only part of the infiltrated water from the root zone reaches the primary aquifer, while the remainder is routed through secondary aquifers direct to the stream. This explains the great annual water level variation in three wells in the unconfined areas (between 1 and 3 m), compared with a variation of less than 0.8 m in 11 wells in the confined areas. (During 1988 the water level was monitored by N & R Consult A/S and during 1990 by the authors).

The transmissivity T in the aquifer was estimated from pumping tests in 19 wells. In three of the wells long-term (months) pumping tests were performed (N&R Consult A/S, 1990; I.Krüger A/S, 1981). In the remaining wells T was estimated from recovery data from short-term pumping tests. The estimateted values range from $1.1 \cdot 10^{-3}$ m^2/s to $50 \cdot 10^{-3}$ m^2/s.

The storativity S in the unconfined part of the aquifer was estimated to be 3.5 % using hydraulic head recession and surface water drainage rates during periods of zero recharge (Clausen, 1989).

RESULTS OF THE SYNCHRONOUS DISCHARGE MEASUREMENTS

In the Alling system synchronous streamflow measurements were carried out once in 1975 by the Danish Land Development Services (1975a) and ten times during the period 1987-90 by the authors. Fig.5 shows the locations of stations at which the streamflow was measured at least once. Station 1 and 41 are gauging stations with continuous recordings over about 15 years.

Fig.6 shows the relative discharge at stations 6, 12 and 22 expressed as a percentage of Q_1, the discharge at the gauging station 1. The values are plottet against Q_1. Fluctuations of the measured values can, in most cases, be explained in terms of the accuracy of the current meter measurement (∼ 5 %).

However, some of the 1975 results deviate significantly from all the other results. This is particularly so at station 12 on the Rosenholm (Fig.6). These values were omitted because diurnal fluctuations dominate the data (Danish Land Development Services, 1975b). These diurnal fluctuations are possibly due to backwater effects induced by the light-related rise and fall of aquatic weeds (Ovesen, 1991).

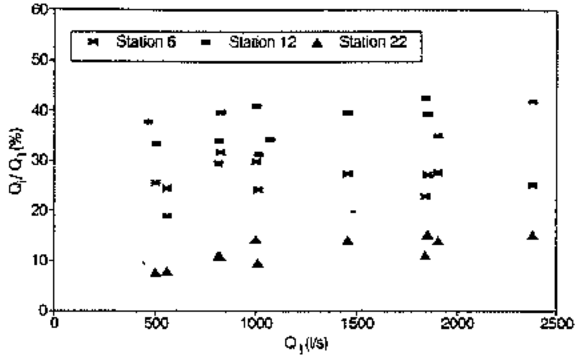

Fig.6 The measured disharge at station i (Q_i) as a percentage of the discharge at the gauging station 1 (Q_1) plottet against Q_1.

The discharge measurements were used to estimate the AM50 at the ungauged stations. Because of the large number of measurements representing the whole range of low-flow situations, the AM50 was estimated simply as the mean of the relative discharges (as shown in Fig.6) multiplied by the AM50 at station 1.

The AM50 discharges are shown in Fig.5, and the AM50 of the specific discharges for subcatchments are shown in table 2. The results show that the specific low-flow is particularly high near the confluences and in the lower part of the Rosenholm. It is also high in one reach in the Skader. In all the upper catchments the AM50 is low, as was to be expected. The values are reflected in the "pseudo leakage coefficient" λ for the valley reaches defined by the equation

$$\Delta AM50 = \lambda \cdot A \cdot (\phi - h) \ . \qquad (1)$$

where ΔAM50 is the difference between AM50 at two nearby stations, A is the area of the valley reach, and h the elevation of the stream surface.

The λ is a "pseudo" leakage coefficient because in (1) we have ignored flow from the secondary aquifers. This is because of the assumption that in the low-flow situation the flow from the regional aquifer dominates over flow from the secondary aquifers.

Table 2. The area of subcatchments in km^2 and estimated AM50 in $l \cdot s^{-1} \cdot km^{-2}$ for reaches in the Alling system defined by the number of the station at the downstream end.

Reach	1	2	3	4	5	6	7	8	9	11	12
Area	12,0	12,5	2,5	0,2	4,0	15,8	11,0	7,0	11,0	0,8	18,0
AM50	2,4	1,2	14,6	160	4,0	1,1	0,55	0	1,8	53,2	6,8
Reach	13	14	15	101	21	22	23	24	31	41	42
Area	18,0	9,0	18,0	15,0	1,2	10,0	5,0	10,0	4,9	20,0	19,0
AM50	1,9	1,2	0,51	0,97	3,4	0,18	4,3	1,7	9,8	1,8	0

The calculated values of λ for the valley reaches are shown in Fig.5. These values agree with Fig.3 since small values of λ occur in reaches with thick clayey valley deposits, whereas high values are found in reaches where thick clay deposits are absent.

MODELLED BASEFLOW VARIATION

The regional groundwater flow was modelled using a one-layer two dimensional finite difference numerical model (Aquifer Simulation Model) developed by Kinzelbach & Rausch (1989). The solution of the basic differential equation is based on the Iterative Alternating Direction Implicit (IADI) method.

The model skeleton is a grid net composed of 60 x 40 elements (Fig.7). The length in each direction is either 250 m or 500 m. The grid density is highest near the streams so that these may be simulated as realistically as possible. The model area is bounded by the groundwater divide (impermeable boundary).

The modelling is based on the assumption that in the low-flow situation the stream is fed solely by the regional aquifer. Thus, to calculate the contribution to each stream cell we can apply the leakage coefficients as shown in Fig.5. However, the assumption does not hold in the western part of the catchment, where impermeable clays cover the chalk and the ϕ in the regional aquifer is far below the stream surface. Here we assume that the contribution from the regional aquifer is zero.

The T and R values were calibrated by a steady-state simulation of the groundwater flow when the discharge at station 1 is at AM50. With the calibrated R and T values the difference between the true value and the observed value of ϕ in each element was less than 1 m on average. As an approximation to the true value of ϕ in the low flow situation we applied the potential map shown in Fig.4, contoured from the lowest observed value of ϕ in each well.

Fig.7 shows the calibrated values of R. The value is constant within each of the four areas: Valleys, areas with Tertiary clay above the chalk, areas with no secondary aquifers above the chalk, and the remaining area. The average value of R for the entire catchment equals AM50.

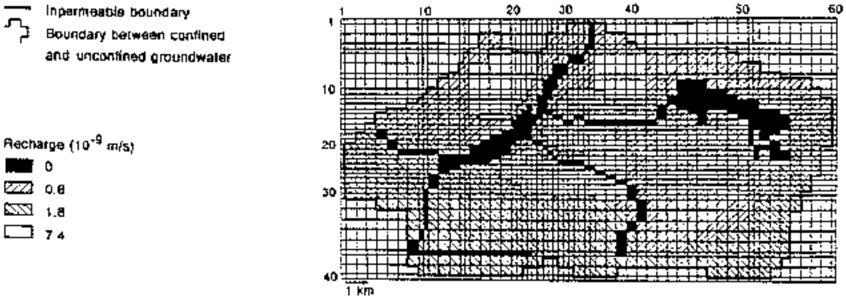

Fig.7 Grid net applied in the numerical model, and estimated values of the recharge, R.

The calibrated values of T range from $0.2\cdot10^{-3}$ m^2/s to $5.0\cdot10^{-3}$ m^2/s. The lowest values are found close to the water divide in the South-Western area. Here, presumably, the Tertiary clay has protected the chalk against glacial erosion.

After completion of the steady-state calibration the baseflow from the regional aquifer to the stream was calculated from a non-steady-state simulation of the groundwater flow during the period 1974-88. R was assumed to vary synchronously within the catchment. The monthly R was calculated as the value shown in Fig.7 multiplied by the R-factor shown at the bottom of Fig.8. The R-factor was calculated as the ratio between the monthly values of I, calculated by Clausen (1989), and the mean value of I (Table 1). The time step in the calculations was one week.

The values of S in the confined areas should ideally be calibrated in the model. However, this was not possible, partly because of the lack of long time series of ϕ, and partly because the observed streamflow includes flow from the secondary aquifers. It was therefore assumed that S is uniform throughout the confined areas, and the simulations were repeated with different values of S. It was found that, though the absolute value of the baseflow variation varied, the rank order for the different reaches remained the same.

Fig.8 shows the observed hydrograph and the modelled baseflow at station 1, derived by applying a value of S at 3.5 % for the unconfined area and 0.5 % for the confined area. With these values the coefficient of variation, CV, of the modelled baseflow for each individual reach (numbered by the station number at the downstream end) was calculated and is plotted as a function of AM50 on a logarithmic scale in Fig.9.

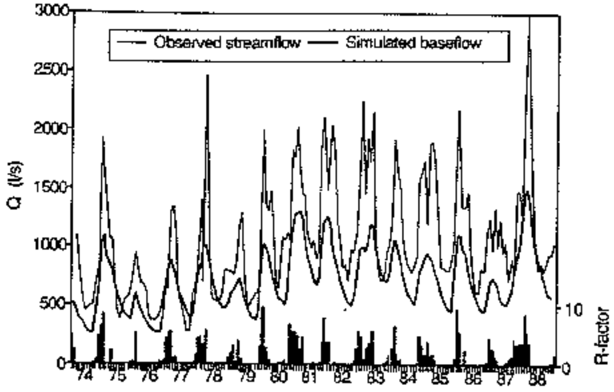

Fig.8 Observed streamflow and simulated baseflow at station 1 for the period 1974-88. The bars at the bottom depict the monthly R-factor with which the recharge values in Fig.7 were multiplied.

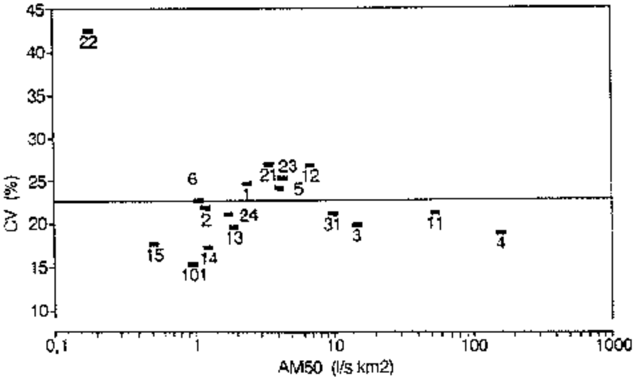

Fig.9 The coefficient of variation (CV) of the modelled baseflow as a function of AM50. The line indicates the mean CV. The reach numbers refer to the station at the downstream end.

Fig.9 shows that the greatest variation is found in the Skader, where the hydraulic gradient is high and almost parallel to the stream. The very high CV for the reach upstream of station 22 is due to frequent changes between effluent and influent flow situations.

The smallest variations are found in the upper Rosenholm, where the hydraulic gradient is low. Fairly constant contributions are also found in the reaches upstream the stations 3, 4, 11 and 31, which are characterised by high leakage coefficients and high AM50 values.

DISCUSSING THE RESULTS

The baseflow variation has been investigated by numerical modelling of the groundwater flow. In this way the influence of geology and topography on baseflow variation has been examined, whereas climatic influences have not been considered in this study.

The modelling was based on the results of numerous synchronous discharge measurements performed during dry weather periods, and the assumption that the flow from the secondary aquifers is negligible in low flow situations. On the one hand, this assumption allowed the flow to be simulated by a one layer model, but, on the other hand, it permitted the model to be calibrated only in the steady-state simulation.

The results showed that the baseflow variation depends primarily on the distribution of the hydraulic head, which, in turn, reflects the local geology. This information could perhaps be incorporated in the existing AM50 estimation procedure, which in most cases is based on a hypothetical relationship between the measured specific discharge q and the AM50 of subcatchments (Fig.10).

The graph in Fig.10 shows that in subcatchments with a small AM50, q varies more than in subcatchments with a large AM50. This assumption is reasonable in that the head often varies more in the upper catchment, where the specific discharge is small, than in the lower catchment. However, we have found that the hydraulic head in the Rosenholm varies very little and the baseflow variation is small. The assumed relationship between q and AM50 could therefore be evaluated by means of a potential map.

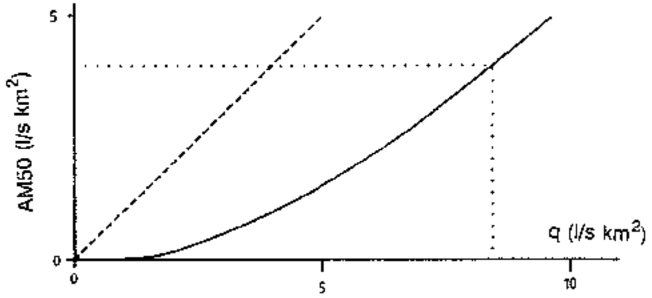

Fig.10 Hypothetical relationship between the measured specific dicharge, q, and the mean of the annual minima, AM50, (after The Danish Land Development Services 1990).

CONCLUSION

The results of the synchronous streamflow measurements showed that the greatest contribution from the chalk aquifer to the stream occurs around the confluences where clay deposits are absent in the valley. Because of the good hydraulic contact in these areas the streamflow will respond very rapidly to any changes in the groundwater abstraction pattern.

The results from the model work showed that the greatest baseflow variation occured in the Skader, while the smallest variation was found in the Rosenholm. In this case the baseflow variation does not depend on the AM50, but rather on the local distribution of the hydraulic head.

ACKNOWLEDGEMENTS

The authors are grateful to the Danish Land Development Services for supplying the discharge data and to the County of Aarhus, who maintain the gauging station on the River Alling at Vester Alling. We are also thankful to the Danish Meteorological Institute and the Department of Agrometeorology of the Danish Research Service for Plant and Soil Science for supplying the precipitation and evapotranspiration data. The authors would like to thank C. Aub-Robinson, Alan Gustard and Andy Young for useful discussions and for improving the English text.

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FIELD SCALE SOLUTE FLUX THROUGH MACROPOROUS SOILS

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ABSTRACT

Spatial variability in the soil matrix and in the macropores is incorporated in a transport model for investigating the effect of various properties of the macroporous flow region on the field scale solute flux through the unsaturated zone. Advection takes place in both the macropores and the soil matrix, and first-order mass transfer between the two flow regions is incorporated by use of the results of Destouni and Cvetkovic (1991). The existence of macropores in the field is reflected in an early peak in the field scale breakthrough curve. This early peak is attenuated due to mass exchange with the soil matrix. The rate coefficient for mass transfer from the macropores to the soil matrix and the relative extent of the soil matrix have similar effects on the field scale breakthrough curve, but the latter has a greater effect on solute breakthrough through the soil matrix. The mean advection rate in the macropores strongly affects the arrival time, the magnitude of, and the mass contained in the early peak of the field scale breakthrough curve. In comparison, the influence of advection variance in the macropores is smaller because it affects only the magnitude and width of the early peak.

1. INTRODUCTION

In general, natural soils exhibit a spatial heterogeneity that may be important for the field scale spreading of solute. One manifestation of spatial heterogeneity that is typical for the unsaturated zone is the existence of relatively large and more or less continuous voids. These voids are commonly referred to as macropores and may, for instance, be interaggregate pores, earthworm holes, drying cracks in clay soils, and decayed root channels. Such macropores are generally characterized by distinctly different soil hydraulic properties than the soil matrix and may result in rapid solute movement through the unsaturated zone.

In addition to the heterogeneity that is reflected in the existence of two distinctly different flow regions in the same field, it is concievable that each region will also exhibit spatial heterogeneity within itself. The need for accounting for spatial variability in the macropore flow and geometry characteristics has been recognized in several studies of water flow problems (Beven and Germann, 1981; Germann and Beven, 1986; Beven and Clark, 1986).

The objective of this paper is to incorporate spatial variability in the soil matrix and in the macropores in a transport model for investigating the effect of various properties of the macroporous flow region on the field scale solute flux through the unsaturated zone. The focus is on solute transport from areally distributed sources at the soil surface. Advection in both the macropores and the soil matrix, and first-order mass transfer between the two flow regions will be considered.

2. TRANSPORT MODEL

For advection dominated transport in statistically homogeneous fields, the expected field scale mass flux of nonreactive solute is defined from the probability density function (pdf) for solute travel time, p_T, as (Shapiro and Cvetkovic, 1988; Dagan et al., 1992; Destouni, 1992a)

$$\langle s \rangle = M_0 \; p_T(t;Z) \tag{1}$$

in which M_0 is the total, instantaneously injected solute mass and $p_T(t;Z)$ quantifies the probability that an indivisible parcel of water and solute crosses a horizontal control plane at the depth Z at time t. For areally distributed sources that are sufficiently large relative to the horizontal integral scale, the transport problem may be considered as ergodic and (1) can be used for quantifying the actual field scale breakthrough curve at the depth Z (Destouni, 1992a). For simplicity, the ergodic assumption is assumed to be valid in the following. The problem of statistical homogeneity in macroporous soils will be handled by use of a bimodal distribution of the soil hydraulic properties, which in turn leads to a bimodal travel time pdf p_T (Destouni, 1991a).

Solute spreading at the field scale may often be regarded as being primarily an effect of advection variability, as expressed by (1). Transverse local dispersion may, however, play an important role in macroporous soils by transferring solute between regions with distinctly different hydraulic characteristics. The resistances that are associated with mass transfer into relatively immobile flow regions may often be significant and are manifested at the field scale as sorption-desorption reactions, commonly referred to as physical nonequilibrium (Brusseau and Rao, 1989).

Cvetkovic and Shapiro (1990) provided a general result for an instantaneous injection of solute that undergoes linear nonequilibrium sorption-desorption in a semi-infinite domain with a steady-state, spatially variable, three-dimensional velocity field. This result, in which the travel time pdf is uncoupled from the mass transfer reactions, can be used for describing transport in the macroporous region. For steady, vertical flow in vertically homogeneous soil, the general result simplifies to (Destouni and Cvetkovic, 1991)

$$\langle s \rangle = M_0 \left[\exp(-k_1 t) \; p_T(t) + \int_0^\infty s_2(t,T) \; p_T(T) \; dT \right]$$

$$s_2 = k_1 k_2 T \exp(-k_1 T - k_2 t + k_2 T) \; \hat{I}_1[k_1 k_2 T(t-T)] \tag{2}$$

$$T = Z/v$$

in which $\hat{I}_1(W) \equiv I_1(2\sqrt{W})/\sqrt{W}$, with I_1 being a modified Bessel function of the first kind of order one, k_1 and k_2 are the constant mass transfer rate coefficients into and out of the relatively immobile flow region, respectively, T is the travel time to Z of an indivisible parcel of water and solute, and v is the local mean pore water velocity.

The travel time pdf p_T in (2) represents in this case only the macroporous region. To be able to handle the entire field as statistically homogeneous through a bimodal p_T, a condition has to be introduced in (2), such that the mass transfer is only active for the macroporous flow region. Such a condition may, for instance, be expressed as

$$\langle s\rangle = M_0\left[\exp[-k_1 t]\ p_T(t) + \int_{T_c}^{\infty} s_2(t,T)\ p_T(T)\ dT\right] \qquad t<T_c \qquad (3a)$$

$$\langle s\rangle = M_0\left[p_T(t) + \int_{T_c}^{\infty} s_2(t,T)\ p_T(T)\ dT\right] \qquad t\geq T_c \qquad (3b)$$

in which T_c is the travel time associated with the fastest solute pathway in the soil matrix. Solute travel times $T<T_c$ are thus associated with pathways in the macroporous flow region. The condition (3b) implies that there is no attenuation of the solute front in the soil matrix. The lower limits in the integrals (3) imply that the mass exchange term $s_2 \neq 0$ only after the the solute front in the macroporous flow region has passed Z, i.e., for $T \geq T_c$.

Although the flow conditions that underlie (2)-(3) will generally not prevail in the field, such simplifying assumptions may still be useful for approximating flow and solute advection in the field (Protopapas and Bras, 1991, Destouni, 1991b, 1992b). Moreover, analyses of relatively simple systems are often useful for gaining insight into the effect of various model parameters; such insight may, in turn, aid in interpreting field data and in focusing future theoretical and experimental efforts more effectively. Thus, for the comparative and illustrative purposes of the following discussion, Equation (3) will be assumed to be valid.

3. TRAVEL TIME PDF

The main problem with evaluating p_T in (3) is how to relate the statistical description of the soil hydraulic properties to the advection statistics. For the flow conditions that are relevant for (3), the solute travel time $T=Z/v$ can be related to the soil hydraulic properties along an individual streamline by the model of Dagan and Bresler (1979), Bresler and Dagan (1981) yielding

$$T = Z\,\frac{(\mathcal{R}/K_s)^{\beta}\,(\theta_s-\theta_{ir}) + \theta_{ir}}{\mathcal{R}} \qquad \mathcal{R}/K_s<1 \qquad (4a)$$

$$T = Z\,\frac{\theta_s}{K_s} \qquad \mathcal{R}/K_s\geq 1 \qquad (4b)$$

in which $\mathcal{R}$ is the constant rate of recharge, K_s and θ_s is the hydraulic conductivity and volumetric water content at saturation, respectively, θ_{ir} is the irreducible volumetric water content, and β is a soil coefficient related to the pore size distribution. To account for spatial heterogeneity, the parameters K_s and β will in the following be regarded as random space functions, bimodally distributed according to

$$p_W(W) = \frac{\nu}{\sigma_1\sqrt{2\pi}}\exp\left[-\frac{(W-\mu_1)^2}{2\sigma_1^2}\right] + \frac{1-\nu}{\sigma_2\sqrt{2\pi}}\exp\left[-\frac{(W-\mu_2)^2}{2\sigma_2^2}\right]$$

$$K_s = \exp(W); \qquad \beta = \gamma + \delta W \qquad (5)$$

In (5), the pdf of W, p_W, is a combination between two normal pdfs, and ν is a weighting parameter that quantifies the fraction of the field that is occupied by the soil matrix. Moreover, μ_1 and σ_1^2 are the mean and variance of W in the soil matrix, and μ_2 and σ_2^2 are the corresponding parameters in the macropores.

Furthermore, a linear relation between K_s and β is assumed in (5). Although indications of such a relation have been found from field data (Destouni, 1991a), field studies that are focused on cross-correlations between various soil hydraulic properties are limited; the relation suggested in (5) should therefore only be considered as one particular example that is used here for illustrative purposes.

A combination of (4) and (5) yields

$$T = \frac{\mathcal{R}^{\gamma+\delta W}}{r}\exp(-(\gamma+\delta W)W) \qquad Tr < 1 \qquad (6a)$$

$$T = \frac{\mathcal{R}}{r}\exp(-W) \qquad Tr \geq 1 \qquad (6b)$$

in which $r\equiv\mathcal{R}/(Z\theta_s)$ and, for simplicity, θ_{ir} has been assumed zero. From (6), W(T;Z) can be expressed as

$$W = \frac{\delta \ln\mathcal{R}-\gamma}{2\delta} \pm \left[\frac{(\delta \ln\mathcal{R}-\gamma)^2}{4\delta^2} - \frac{\ln(\mathrm{Tr}\mathcal{R}^{-\gamma})}{\delta}\right]^{1/2} \qquad \mathrm{Tr} < 1 \qquad (7a)$$

$$W = - \ln[\mathrm{Tr}\mathcal{R}^{-1}] \qquad \mathrm{Tr} \geq 1 \qquad (7b)$$

For realistic parameter values the negative root (7a) leads to negative values of W only and can therefore be disregarded. From (7), the travel time pdf $p_T(t;Z)$ can be evaluated as $p_T=|\partial W/\partial T|p_W$ yielding the expressions

$$p_T(t;Z) = \frac{1}{2\delta t}\left\{\frac{(\delta \ln\mathcal{R}-\gamma)^2}{4\delta^2} - \frac{\ln(\mathrm{tr}\mathcal{R}^{-\gamma})}{\delta}\right\}^{-1/2} p_W(W(t;Z)) \qquad \mathrm{tr} < 1 \qquad (8a)$$

$$p_T(t;Z) = \frac{1}{t}\, p_W(W(t;Z)) \qquad \mathrm{tr} \geq 1 \qquad (8b)$$

The relation W(t;Z) quantifies the required W value for a solute particle to reach the depth Z at the time t, and is evaluated from (7). The travel time pdf p_T is independent of β for saturated flow conditions (8b). Furthermore, if the spatial variability in β is neglected, the expression for unsaturated flow conditions (8a) simplifies to

$$p_T(t;Z) = \frac{1}{\beta t}\, p_W\left[\frac{1}{\beta}\ln(\mathrm{tr}\mathcal{R}^{-\beta})\right] \qquad \mathrm{tr} < 1 \qquad (9)$$

4. ILLUSTRATION OF RESULTS

The parameter set that has been used for illustrating the results is given in Table 1. The parameter T_c in (3) was chosen as the travel time that corresponds to $W_c \approx (\mu_1+\mu_2)/2$, as given by (6). The parameter γ was calculated from $\gamma=\mu_\beta-\delta\mu_W$, in which $\mu_W=\nu\mu_1+(1-\nu)\mu_2$.

The effect of the weighting parameter ν in (5) on the field scale solute flux is illustrated in Figure 1. The existence of macropores (for illustrative purposes chosen here as 20% of the field, i.e., ν=0.8) is reflected in an early peak in the field scale breakthrough curve. This early peak has been attenuated due to the mass exchange with the soil matrix. The delayed contribution due to this exchange is reflected in the small peak between the early peak and the main peak. The main peak is primarily associated with transport in the soil matrix. The discontinuity at tr≈0.5 is due to the conditions (3). The second discontinuity at tr=1 is due to the conditions (8).

Figure 2 illustrates that a decrease in the values of k_1 and k_2 has a similar effect on the field scale breakthrough curve as that of decreasing ν. The reason for this is that a decrease in k_1 decreases the attenuation from the solute front in the macropores and therefore increases the early peak in the breakthrough curve. Furthermore, a corresponding decrease in the rate coefficient for the mass transfer back into the macropores, k_2, implies that the ratio k_1/k_2 remains constant, whereby the arrival of the second, small peak is unaffected of the decrease in k_1 and k_2. The main difference between the influence of ν and that of k_1 and k_2 is that ν has a greater effect on the main peak of the breakthrough curve.

Figure 3 illustrates that a decrease in k_2, without a corresponding decrease in k_1, will result in later arrival and more spreading of the solute that has been subject to exchange between the macropores and the soil matrix. This is reflected in the field scale breakthrough curve by the fact that the second, small peak has vanished; the mass contained in that peak for $k_1/k_2=1$ does for the higher ratio, $k_1/k_2=10$, instead give rise to increased tailing.

Due to the mass exchange with the soil matrix, an increase in the mean of W in the macropores, μ_2, does not only affect the arrival time of the first peak in the breakthrough curve, but also the magnitude of and the mass contained in this peak. This effect is illustrated in Figure 4 and the reason for it is that the faster transport in the macropores (through the increase in μ_2) results in decreased attenuation of the solute front because the rate of mass transfer relative to the advection rate has decreased.

Figure 5 illustrates the effect of the variance of W in the macropores, σ_2^2, on the field scale breakthrough curve. In comparison to the effect of μ_2 (Figure 4), the effect of σ_2^2 is smaller. Although σ_2^2 affects the magnitude and width of the early peak, it has only a small effect on the mass that is contained in that peak, or on its arrival time.

5. DISCUSSION AND CONCLUSIONS

The existence of macropores in the field will generally be reflected in an early peak in the field scale breakthrough curve. However, this early peak is attenuated due to mass exchange with the soil matrix. The relative extent of the soil matrix (i.e., ν) and the rate coefficient for mass transfer from the macropores to the soil matrix (i.e., k_1) have similar effects on the field scale breakthrough curve. Decreasing ν or k_1 results in inreased early solute arrival through the macropores, the difference being that ν also affects the main solute arrival through the soil matrix.

The mean advection rate in the macropores (given by μ_2) strongly affects the arrival time, the magnitude of, and the mass contained in the early peak of the field scale breakthrough curve. In comparison, the influence of the advection variance in the macropores (given by σ_2^2) is smaller because it affects only the magnitude and width of the early peak. However, the results of Destouni and Cvetkovic (1991) indicate that for fields with spatially variable mass transfer rate coefficients, and for reactive solute with spatially variable reaction parameters, advection variability within the macroporous flow region will have a more significant effect on the field scale breakthrough curve.

Double- or multiple-peaked solute plumes or solute breakthrough curves have been observed in several experimental studies in field soils (Jury et al., 1986; Butters et al., 1989; Roth et al., 1991). However, the interpretation of these experiments has commonly been restricted to modelling the main peak behaviour only. The early peak(s) have been neglected, partly because the rapid solute movement was unexpected and the measured data were insufficient, and partly because the models used for interpretation of the data could not account for this complex solute behaviour. The methodology presented in this paper, and the results of Destouni and Cvetkovic (1991) may be useful for predicting early solute breakthrough in field scale tracer experiments, and for interpreting field data where such behaviour occurs.

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TABLE 1 Parameter values for illustration of results.

	Standard value	Varies in Figure
$\mathcal{R}$ (m/yr)	0.3	——
ν	0.8	1
$\exp(\mu_1)$ (m/yr)	3.0	——
$\exp(\mu_2)$ (m/yr)	300.0	4
σ_1	1.0	——
σ_2	1.0	5
k_1/r	5.0	2
k_2/r	5.0	2,3
μ_β	0.14	——
δ	0.03	——

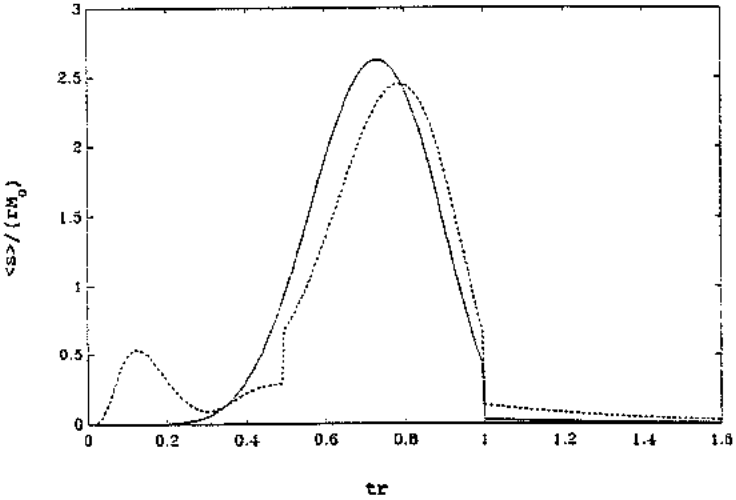

Figure 1. Field scale solute flux for: (solid line) $\nu=1$ and (dashed line) $\nu=0.8$.

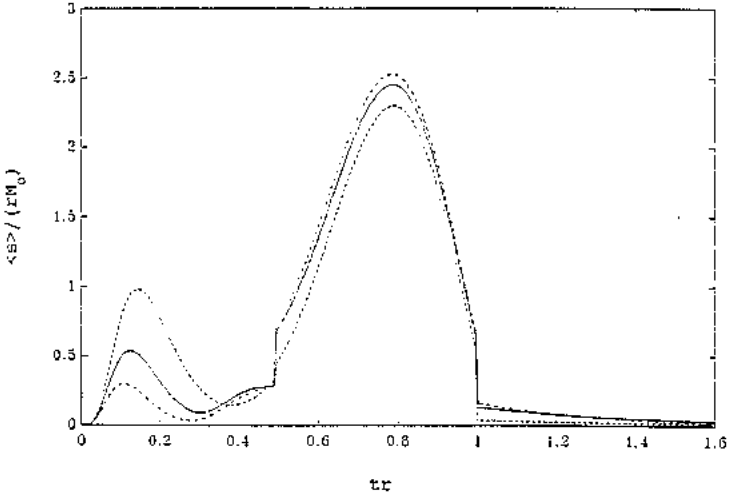

Figure 2. Field scale solute flux for: (dashed line) $k_1=k_2=0.5$, (solid line) $k_1=k_2=5.0$, and (dashed-dotted line) $k_1=k_2=10.0$.

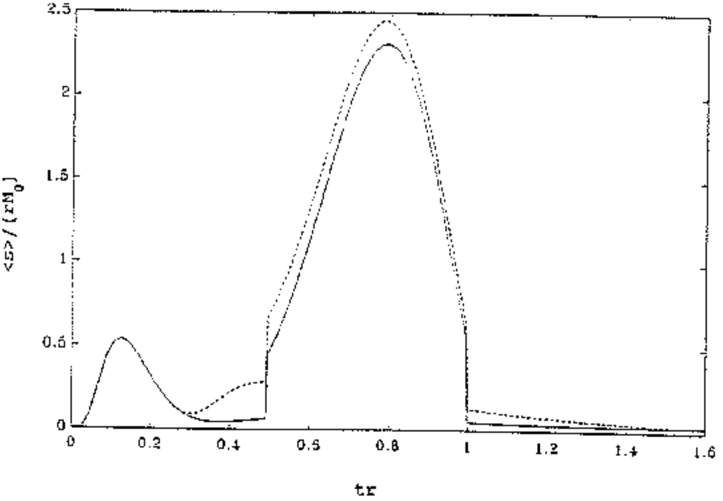

Figure 3. Field scale solute flux for: (solid line) $k_2=0.5$ and (dashed line) $k_2=5.0$.

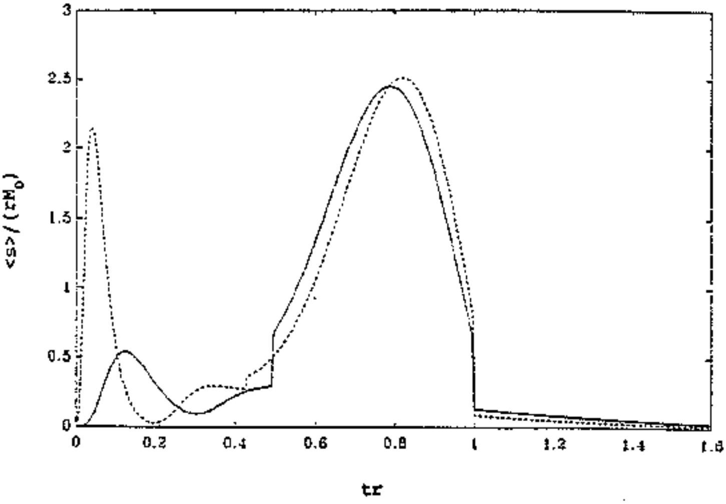

Figure 4. Field scale solute flux for: (solid line) $\exp(\mu_2)$=300 m/yr and (dashed line) $\exp(\mu_2)$=3000 m/yr.

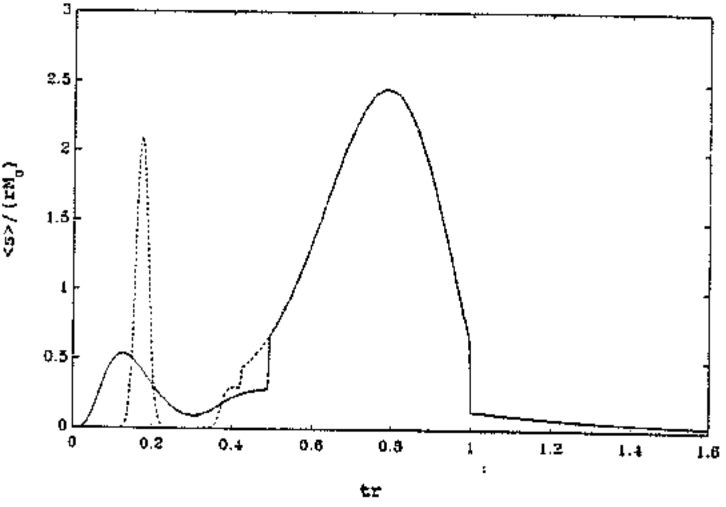

Figure 5. Field scale solute flux for: (solid line) σ_2=1.0 and (dashed line) σ_2=0.2.

A SIMPLE SOIL TEMPERATURE MODEL

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ABSTRACT

Hydrochemical models which incorporate reaction kinetics must have knowledge of temperature. In dynamic models the temperature must be given with time resolution comparable with the time step used in the model. Yearly averages will give large errors for time scales shorter than a year.

This paper presents a simple model for soil temperature, which could be used for dynamic hydrochemical models of the soil profile. The model is essentially based on a moving average of the air temperature, which gives a damping and time lag of the temperature wave. An additional damping of temperature with depth without any time lag is also used. The model has only one calibration parameter which determines the damping and time lag with depth.

The model satisfactory predicts temperature down to 1 m depth in the soil. The low requirement of input data and the use of only one calibration parameter makes it suitable for incorporation in dynamic hydrochemical models of a soil profile.

INTRODUCTION

The Swedish Integrated Groundwater Acidification Project had as the main objective to develop a dynamic hydrochemical model of groundwater acidification. The model should be used for simulations of different acid deposition scenarios. The model consist of two different models, a hydrological (PULSE, Sandén et al, 1992) and a hydrochemical (SAFE, Warfvinge and Sverdrup, 1992). Hydrochemical models that take the reaction rate (kinetics) into account rely on temperature as an important driving variable. The SAFE- model is of this type. It is a dynamic model, which needs dynamic input of soil temperatures for the different soil layers.

The simplest way to address the problem of soil temperature, is to use the long-term average air temperature. This does not take the seasonal variability into account. As the main variation in soil temperatures, at high latitudes, is between summer and winter. A sinuous function could describe a significant portion of this variation. The most complete way to assess soil temperature, is to use a physically based dynamic model. In this type of model the heat flow is explicitly modelled, as well as freezing and thawing. An example of this type of model is SOIL (Jansson and Halldin, 1979). This type of model needs many driving variables and physical parameters, which can either be measured or calibrated.

For the present study it was important to use a dynamic model with a limited number of driving variables and parameters. The reason for this is, that the hydrochemical model should be used to asses long-term acidification of soil and groundwater on a regional scale. The heterogeneity of variables and parameters is considered a major problem in this respect. The chosen model structure is therefore in essence based on moving averages. It has one calibrated parameter, and rely upon air temperature as the driving variable. It also uses the snow pack, if available, to reduce the influence of air temperature during winter. The model is run with a daily time step. More than 95% of the temperature variation in the different soil layers is explained by the model. The results also show a reasonable damping and time-lag of the temperature wave. This soil temperature model is developed to be a subroutine to the PULSE-model (Sandén et al., 1992).

MODEL STRUCTURE

The model had to fulfill a number of requirements. As the hydrological and hydrochemical models are fairly complex and time consuming in the long-term simulations. The temperature model should increase the computation time as little as possible. To be able to run the model on a regional scale measured parameters had to be avoided. Input data also had to be limited and easily attainable. The number of calibrated parameters should be kept at a minimum.

The physical properties of the soil will smooth and time-shift the air temperature variations. This can in the simplest way be modelled by moving averages. This will produce a smoothing and lag of the soil temperatures. The model can be written as:

$$T_{zt} = \frac{1}{n_z} T_t^{atm} + \frac{1}{n_z} T_{t-1}^{atm} + \ldots + \frac{1}{n_z} T_{t-n_z}^{atm} \tag{1}$$

where T_t^{atm} = air temperature day t,
z = depth below soil surface.

The parameter n_z must be estimated for each soil depth of interest. This parameter is a function of depth and is calculated as:

$$n_z = \frac{D\,z}{\alpha - z} \tag{2}$$

where D = number of days in a year (365),
α = empirical coefficient.

When z is equal to α the moving average is calculated with temperature data from a whole year. The value of n_z is rounded to the nearest integer. With this formulation we are left with one parameter that needs calibration. This model structure proved to be insufficient when tested against field measurements. The model could not produce reasonable time lag and damping with the same value of α. To handle this, the air temperature was damped by a function which does not give any lag. The air temperature T_t^{atm} in the moving average equations (1) is thus substituted by:

$$T_{zt}^{atm} = T_t^{atm} + \left(\overline{T} - T_t^{atm}\right) \frac{n_z}{D} \tag{3}$$

where $\bar{T}$ = long-term average annual air temperature. By this formulation no extra calibration parameters are needed.

To handle the isolating effect of snow cover the air temperature were corrected according to:

$$\begin{aligned} T^{cor} &= 0 & SP &> 5mm \\ T^{cor} &= T^{atm} \cdot 0.1 & SP &< 5mm,\ T^{atm} < 0 \\ T^{cor} &= T^{atm} & SP &< 5mm,\ T^{atm} > 0 \end{aligned} \tag{4}$$

where SP = snow pack in mm water as calculated by the PULSE-model.

RESULTS

Soil temperature measurements from an unforested area in the Velen research catchment were used to test the model. The site is located in south central Sweden. The soil is mainly sandy till. A detailed site description can be found in Hedin (1971).

Figure 1 shows the results from the chosen model, using equation (3). The resemblance between observed and simulated soil temperature is satisfactory. The model explains more than 95% of the observed variation at all three soil depths. The same figure also presents an alternative model using a physically based equation were the input is given as a sinuous function which takes the amplitude and average annual temperature of the air into account. The damping is then a function of depth in the soil and thermal diffusivity. The following equation is used (from Marshall and Holms, 1979):

$$T_{z,t} = \overline{T} + A_0 \exp-\left\{\sqrt{\frac{\omega}{2\kappa}}\, z\right\} \sin\left\{\omega t - \sqrt{\frac{\omega}{2\kappa}}\, z\right\} \tag{5}$$

where A_0 = amplitude of the temperature wave,
$\omega = 2\pi/\tau$,
τ = period of the temperature cycle,
κ = thermal diffusivity.

This model gives the same wave every year. In the presentation negative values are replaced by zero.

Figure 2 presents a sensitivity analysis regarding the parameter α. The model is rather insensitive to reasonable changes of this parameter.

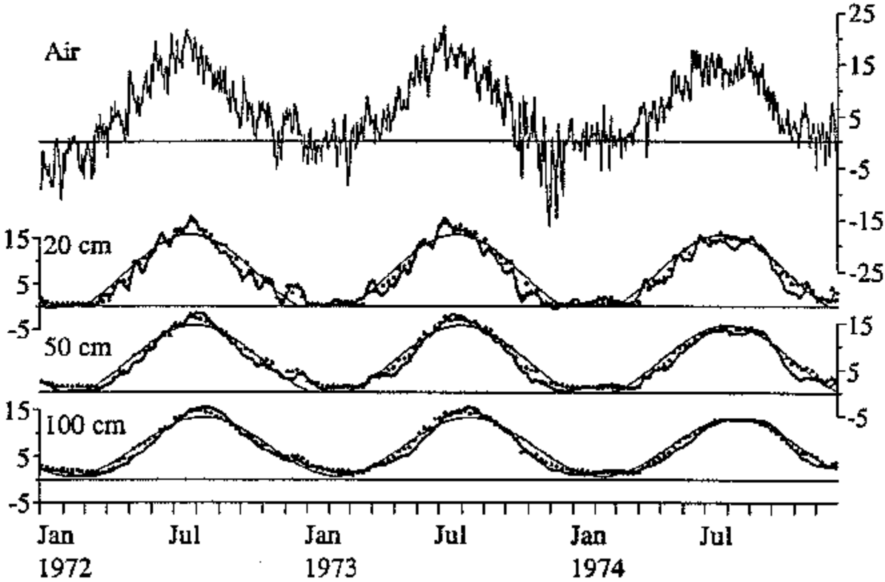

Figure 1. *Observed (dots), moving average model (thick line) and sinuous model (thin line) soil temperatures at three depths at Velen. The value used for is 6 m.*

The model was run at one additional site to test that the model is not site specific. A soil temperature record were used from the Swedish Agricultural University at Ultuna, outside Uppsala in the wester part of central Sweden. The soil is here a heavy clay. The results of this application are presented in Figure 3. The value of α is in this application considerably lower (2.5 m), which indicates a much lower thermal diffusivity in this soil.

DISCUSSION AND CONCLUSIONS

The relatively simple problem of soil temperature simulation is the main reason for the surprisingly good results obtain with this crude model. To further improve the model performance, the complexity would have to be increased largely. That could not be justified by the purpose of this modelling exercise. The model results should, however, only be trusted in the calibration range (the first 100 cm of the soil). There is no information, so far, on how the model behave compared with observations outside this range.

The simple physically based model does also give reasonable soil temperatures. The variation between years and the problem around freezing does, however, limited the usefulness of this model formulation.

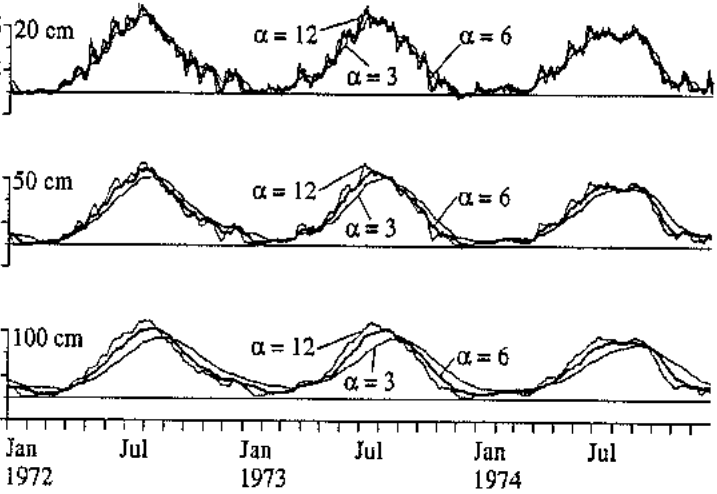

Figure 2. *Sensitivity analysis for the parameter α. Three different values are presented. The simulation is valid for the Velen catchment.*

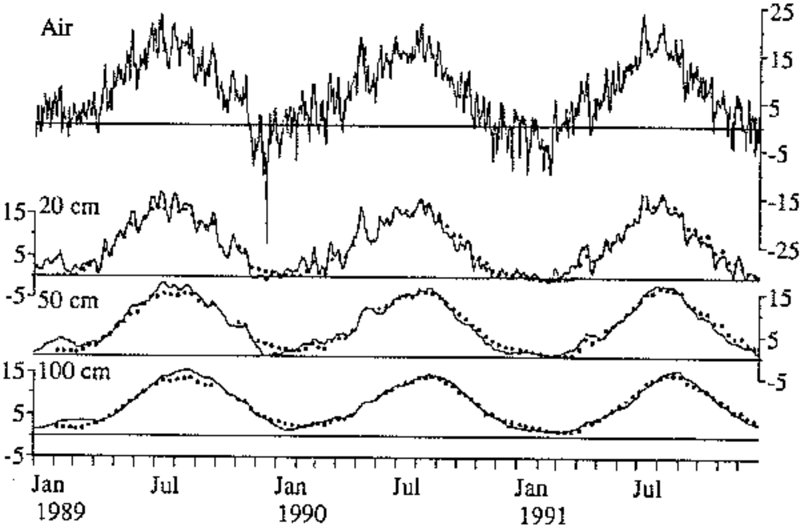

Figure 3. *Observed (dots) and simulated (line) soil temperature at three different depth for the Ultuna site. The value for α is 2.5 m.*

The model is fairly insensitive to reasonable errors in the calibration parameter. An analysis of the hydrochemical models sensitivity to the soil temperature simulations (Warfvinge and Sandén, 1992) showed that SAFE is insensitive to large errors in the α parameter. The problem of temperature damping by the forest is not considered here. The low sensibility of the model, both to damping and time lag errors, suggests that this could be overlooked.

The result from applying the model to the clay soil at Ultuna was also promising. The difference in soil properties between the two sites should cover a large part of the range in soil thermal diffusivity. The model is therefore considered to have a general applicability.

For hydrochemical models, that need soil temperature data, the present model is sufficient in most cases. It is simple, with low demands on input data and parameters. The model also takes little amount of computational resources.

ACKNOWLEDGEMENT

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EXPERIMENTAL STUDY OF MACROPORE FLOW AND TRANSPORT BEHAVIOUR IN CLAYEY MORAINE

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ABSTRACT

Large undisturbed soil monoliths (30 cm in diameter) were removed from the unsaturated zone at an agricultural field consisting of clayey moraine and placed in the laboratory for flow and transport experiments. The spatial distribution of monolith outflow was determined in constant rate water application experiments. The outflow varied significantly across the bottom and despite the time invariant input of water the outflow distribution varied rapidly over time. Solute tracer (Cl^-) pulse applications were performed to investigate the influence of macropores on the solute transport. Besides the early breakthrough and extensive tailing which is commonly associated with macropore flow, a phenomenon of multiple peaks was observed which can be attributed to differences in size, connectivity and tortuosity of the macropore networks within the individual monoliths or air entrapment. Finally, dye tracer applications with subsequent dissection were carried out to establish visual evidence of macropore flow and to quantify the macroporosity.

INTRODUCTION

Water is the primary medium for transport of dissolved matter in subsurface soil environments. In recent years, more attention and concern have been given to the problems associated with water transporting contaminants to surface water and groundwater systems. Of particular concern is the leaching of nitrate to groundwater, because high nitrate concentrations make the groundwater unsuitable for water supply. Thus, an understanding of the mechanisms which control the transport and residence time in the unsaturated zone of surface-applied nutrients is required.

A number of models based on Darcy's law and the convection-dispersion equation have been developed for describing solute transport in the unsaturated zone, and reliable results have been obtained for unstructured soils. However, these models fail when structured soils are considered. In these types of soil, the transport is mainly confined to the more or less continuous networks of wormholes, root channels, cracks and fissures, termed macropores in the following. At high precipitation rates, the presence of macropores causes the majority of the dissolved matter to by-pass the soil matrix, and instead transport takes place in a comparatively small part of the porous medium: the macropores. The by-passing results in very fast transport of solutes through the vadose zone, and several field and laboratory experiments (see e.g. Beven and Germann (1982) and White (1985)) have shown that the residence time is far too short to be accounted for by a simple displacement theory.

Tyler and Thomas (1981) conducted laboratory experiments on undisturbed soil columns and found that the maximum effluent concentration of the chloride tracer appeared far ahead of one pore volume. They interpreted this as an effect of channeling flow in structured soils. Similar results were found by Kissel et. al. (1973), Wild and Babiker (1976) and White et. al. (1984). McMahon and Thomas (1974) compared undisturbed and disturbed columns, and showed that both chloride and tritiated water appeared to have moved much further in the undisturbed columns than in the disturbed ones, indicating a considerable by-passing of the soil by both water and chloride. Similar results were recently found by Khan and Jury (1990).

Fluorescent dyes have been used by Omoti and Wild (1979), who concluded that there may be preferential movement through pores much smaller than would normally be considered macropores. Andreini and Steenhuis (1990) also performed dye experiments, but with conventional tillage and conservation tillage columns. They observed that in the conservation tillage column nearly the entire depth of the profile was short-circuited by preferential flow, while in the conventional tillage column the solute passed through the mixed, unstructured plow layer before the profile below the plow pan was short-circuited. Andreini and Steenhuis conducted the experiments on grid lysimeters, and observed that the dyed flow paths led to the areas where water and solute exited the column.

The previous work has shown that macropore behaviour is very much site specific and the numerical models proposed are based on various interpretations of the physical processes governing macropore flow and transport. The objective of the present study is to develop a laboratory experimental procedure for conducting flow, transport and dye experiments on large undisturbed, structured soil monoliths in order to obtain a better understanding of the physical processes associated with macropore flow and transport.

Contrary to most previous investigations we have used large undisturbed soil monoliths (30 cm in diameter, 48 cm in length) to preserve the soil structure present in the field. The technique for collecting the monoliths in the field, the laboratory set-up and monitoring system are described and the results of the investigations are presented and discussed for two of the three monoliths.

EXPERIMENTAL PROCEDURES

Three soil monoliths (A, B and C) were excavated near Viby on Sjælland, Denmark. The area is part of a flat moraine country with a glacial series consisting of 10-25 meters of clayey moraine with local horizons of coarser composition. The soil is built on fairly heavy clay till (app. 20 % clay fraction). A wide variety of wormholes and channels from burrowing animals was observed throughout the 1 meter collection depth prior to the removal of the samples. The channels are mainly vertical and continuous over relatively large distances, in certain cases up to 130 cm. The horizontal channels are usually restricted to the top layer where the plant roots are present. The channels vary in size with a maximum of approximately 10 mm in diameter. The monoliths were excavated from a location subject to a field-scale tracer experiment, Villholth et. al. (1991), and the laboratory experiments were designed to provide complementary information to the ongoing field investigations.

A hand-carving technique used previously by Reeves and Beven (1990) and Andreini and Steenhuis (1990) was chosen to isolate and collect the samples in the field. The method consists of isolating an undisturbed block of soil by hand, and then coating it with a sealant material to maintain the integrety of the sample. Once the sealant is dry, the undisturbed sample can be transported to the laboratory. We believe that this sampling technique is subject to least disturbances during excavation and transport to the laboratory.

The monoliths were carved out by hand to a depth of 70 cm, initially as squares of 50 x 50 cm and later trimmed to the final shape of approximately 35 cm in diameter. In order to create an impermeable boundary around the edges of the monoliths, they were wrapped in a plaster of Paris bandage, sealed with waterproof lacquer and wrapped in plastic film. Finally, a PVC-casing, 42 cm in diameter and 53 cm high, was placed around the monoliths, and the resulting gap filled with plaster of Paris. When the plaster was dry, the monoliths were loosened at the base and carefully transported to the laboratory.

The experimental set-up, see figure 1, consisted of a base, providing the support for the monolith, which was constructed as a grid cell pattern to diverge water and solute into a distributed collecting system. A rain simulator consisting of a disperser and a peristaltic pump was designed to provide a controlled, constant intensity water supply uniformly distributed over the monolith surface. A system of collecting hoses and bottles were placed beneath the monolith for collecting distributed amounts of water and solute during the experiments. The base was designed to facilitate measurements of the outflow distribution in a grid constructed around a 45 x 45 cm stainless steel grid of approximately 2 cm height. The grid consisted of a 9 by 9 array of 5 cm square cells, see figure 2 and Wildenschild (1991) for details. When the monolith and base were attached to each other, the whole system was lifted to the

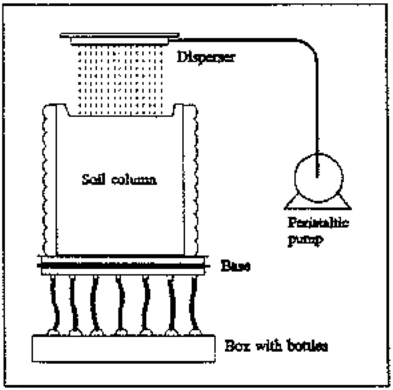

figure 1
Column laboratory setup

setup which is shown in figure 1. To prevent water and solute from running across the soil surface and down along the sidewalls during ponding, a hollow was dug out in the top of the monoliths to a depth of 5 cm. The area to which water was supplied was hereby reduced to 30 cm diameter.

The monoliths, which had dried for more than a month prior to water application, were exposed to intensities of 5, 10 and 20 mm/h in increasing order and the distribution of outflow at the base of the sample was measured. The time elapsed from the rainfall initiation to the appearance of outflow at the bottom of the monolith was used for evaluating the response time of the monoliths. After the outflow response time and distribution were determined the solute tracer experiments were carried out to obtain solute breakthrough curves for the different application rates.

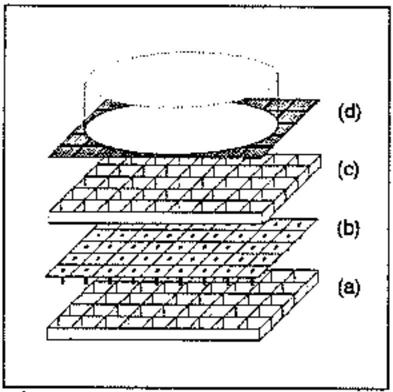

figure 2
Base setup for the monoliths. (a) and (c) stainless steel grid, (b) zinc plate with cubes, (d) fine mesh with silicone strings.

The solute was applied as a slug directly on the soil surface when the monolith outflow rate had reached a steady state. The solute concentration was subsequently measured continously with a specific electrode at the outlet following this pulse injection. The chloride ion was assumed to move as a conservative tracer, similar to the nitrate ion, Reeves and Beven (1990). A mixture of 8.24 g NaCl in 200 ml of tap water (25000 mg Cl$^-$/l) was used in the experiments.

		(3,1)	(4,1)	(5,1)	(6,1)	(7,1)		
	(2,2)	(3,2)	(4,2)	(5,2)	(6,2)	(7,2)	(8,2)	
(1,3)	(2,3)	(3,3)	(4,3)	(5,3)	(6,3)	(7,3)	(8,3)	(9,3)
(1,4)	(2,4)	(3,4)	(4,4)	(5,4)	(6,4)	(7,4)	(8,4)	(9,4)
(1,5)	(2,5)	(3,5)	(4,5)	(5,5)	(6,5)	(7,5)	(8,5)	(9,5)
(1,6)	(2,6)	(3,6)	(4,6)	(5,6)	(6,6)	(7,6)	(8,6)	(9,6)
(1,7)	(2,7)	(3,7)	(4,7)	(5,7)	(6,7)	(7,7)	(8,7)	(9,7)
	(2,8)	(3,8)	(4,8)	(5,8)	(6,8)	(7,8)	(8,8)	
		(3,9)	(4,9)	(5,9)	(6,9)	(7,9)		

figure 3
Plan of the 69 cells monitored in the experiments.

The dye tracer experiments were performed in an attempt to mark the preferential pathways of water and solute. An adsorbing dye (Rhodamine B) was used to make sure that the high flow regions would be stained and the colour not washed off during the experiment. A solution of 0.5 g Rhodamine B per liter was used in the experiments. Three liters of dye tracer solution were applied to monolith B through the rainfall simulator at an intensity of 10 mm/h and 23 liters were added to monolith A when the outflow from the monoliths had ceased. The monoliths were sliced either horizontally at 8 cm intervals (monolith B) or vertically (monolith A) and examined for dye tracer. To quantify the macroporosity at each horizontal slicing level a handdrawn image was made on transparent paper (overlay) on which all visual pores and dye stains were marked. A special grid mesh was placed over the monolith surface in order to indicate the position of the original grid system. In this way the different cells could be followed all the way through the monolith. An image-processing facility, PIPPIN, developed by Anakron Consult, Denmark, was used for computing digitized grey scale pictures from a video image of the handdrawn images. With this facility the macroporosity was estimated as the area of all marked (visible) pores relative to the total cross sectional area at a given dissection level. The facility is also capable of estimating the pore size distribution for the different layers in the monoliths.

RESULTS AND DISCUSSION

The three different types of experiments are reported for monoliths A and B. The flow distribution at the bottom of the monoliths varied significantly across the outflow area, which is interpreted as a result of macropore flow. Furthermore, rapid temporal changes in flow pattern were observed for both monoliths, see figure 4 (and figure 3 for the location of the cells in the experimental grid). We interpret this flow phenomenon to be caused by air entrapment. Linden and Dixon (1976) have reported direct evidence that low soil air pressures block the water entry into macropores and thereby impede macropore flow.

The initiation of flow for the two monoliths at an intensity of 5 mm/h is shown in figure 5. Initiation of monolith outflow can be observed far ahead in time of what would correspond to one pore volume (app. 2 days), indicating extensive by-passing in the form of macropore flow.

When the flow rate had reached a steady state the solute tracer experiments were carried out and the resulting BTCs are shown in figures 6-8 together with the relevant outflow curves (see figure 3 for location of individual cells). Note that the concentration is plotted with different scaling (y-axis) and that the application time of the solute coincides with the start of the solute outflow curve. The points on the solute outflow curves marked as calibration points refer to the times at which outflow samples were collected for Cl^- analysis by titration in order to establish the calibration curve. The observed solute outflow con-

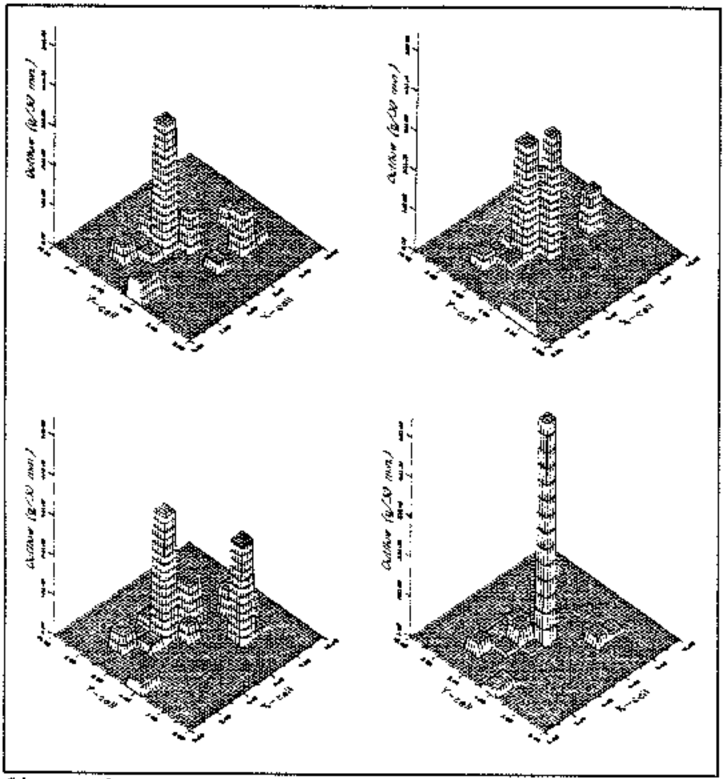

figure 4

Typical changes in outflow pattern at 30 min. intervals for one of the monoliths (B).

centration curves for both monoliths features fairly early breakthrough with considerable variations in peak concentration depending on which cells are monitored. Some of the curves show quite extensive tailing, which together with the early breakthrough, is a usual phenomenon related to macropore flow. Most of the curves have multiple peaks, although the number of peaks and the peak concentration are less for monolith A than for monolith B.

The multiple peaks of the observed BTCs and the tailing can be attributed to different phenomena. Tailing is interpreted as a result of the process of diffusion where the matrix is considered as a source or sink with respect to the macropores depending on the direction of the concentration gradient, Tyler and Thomas (1981). The result of this process will be a fast breakthrough (through the macropores) followed by extensive tailing as a result of the slow diffusion process from matrix to macropores.

The multiple peaks are interpreted as a result of differences in size, tortuosity, and connectivity of the macropore system as well as the earlier mentioned air entrapment.

Large, well-connected macropores will transmit water and solute fast as opposed to small, tortuous and less well-connected macropores which results in different breakthrough peaks. Assuming that the soil consists of a multitude of individual macropores which in some cases are connected to whole macropore networks, we may explain the observed phenomena. Air entrapment will also be the cause of multiple peaks because water and solute is suddenly released when the pressure of the water building up on top of an air bubble is sufficiently large for the water to break through it. The result is another individual solute breakthrough peak.

Obviously, these effects will be more predominant on a relatively small scale as in these experiments where the influence of individual macropores on the total outflow is distinct. Similar findings are reported by Andreini and Steenhuis (1990), who also carried out flow and tracer experiments on monoliths. Hence, our interpretation of the system is that flow in macropore networks, air entrapment and diffusion processes are the mechanisms responsible for the characteristics of the BTCs.

This conclusion is particularly supported by the following observations: Comparing the 5 mm/h and 10 mm/h runs for monolith B, see figure 6(b) and 7(b), a fast response can be observed in

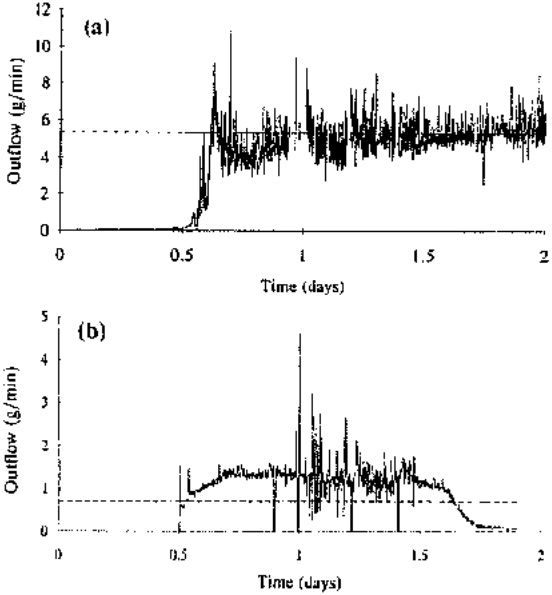

Figure 5
Initiation of flow at 5 mm/h. ***(a)*** *monolith B, ——— represents total outflow and - - - - - represents the precipitation.* ***(b)*** *monolith A, ——— represents the outflow from 9 center cells and – – – – represents the precipitation corresponding to the area of 9 cells. One pore volume corresponds to a time lapse of app. 2 days.*

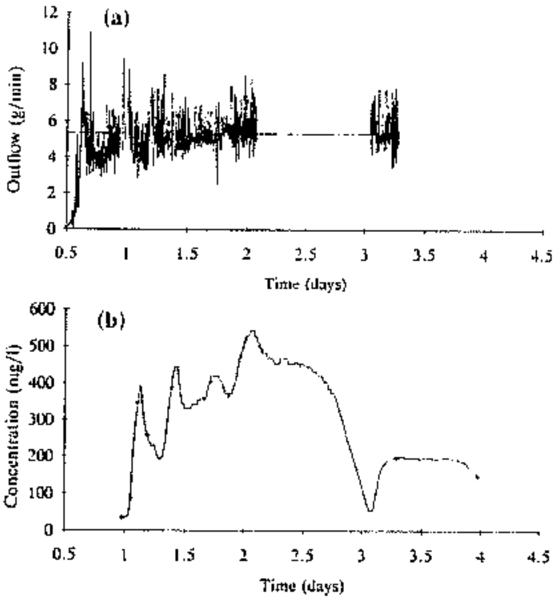

Figure 6
Results of the solute tracer experiments, monolith B, 5 mm/h. (a) Monolith outflow, ——— represents total outflow and - - - - represents the precipitation. The curve is broken because of discontinous flow measurements. (b) Solute outflow from 9 center cells, ◆ are calibration points.

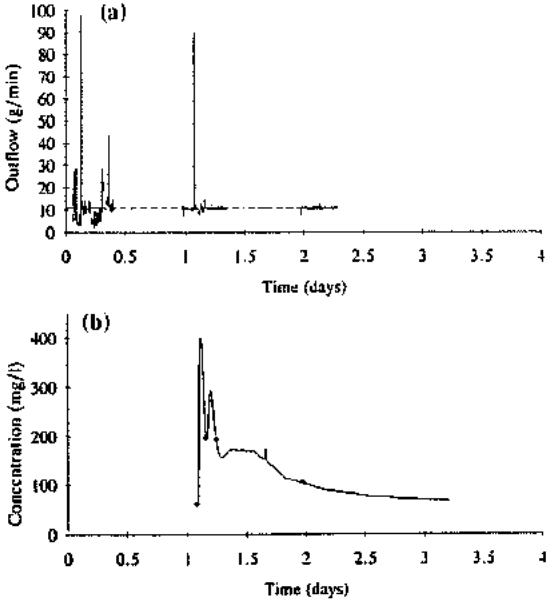

Figure 7
Results of the solute tracer experiments, monolith B, 10 mm/h. ***(a)*** *Monolith outflow,* ——— *represents total outflow and* -·-·- *represents the precipitation. The curve is broken because of discontinuous flow measurements.* ***(b)*** *Solute outflow from 9 center cells,* ◆ *are calibration points.*

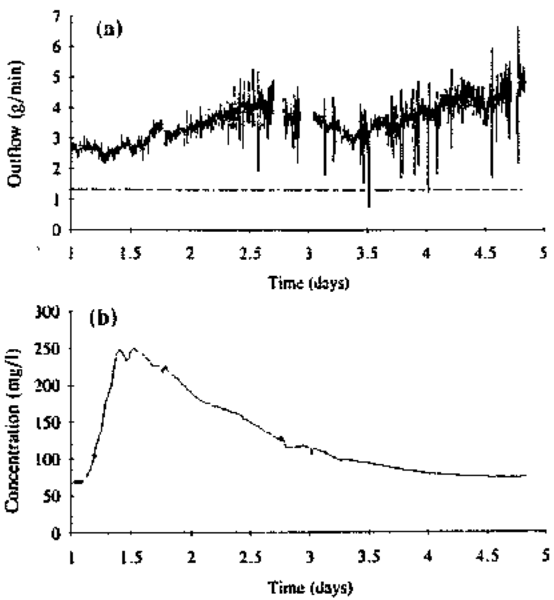

Figure 8
Results of the solute tracer experiments, monolith A, 10 mm/h. ***(a)*** *Monolith outflow,* ——— *represents outflow from 9 center cells and* -·-·- *represents the amount of outflow corresponding to 9 cells in case of uniform flow distribution. The curve is broken because of discontinuous flow measurements.* ***(b)*** *Solute outflow from 9 center cells,* ◆ *are calibration points.*

the 10 mm/h case (fast rise and decline). The fast response is probably caused by the higher flow rate, causing earlier breakthrough at the bottom, and faster dilution and out-washing of the solute, resulting in a faster decline at this flow rate. Comparing the solute outflow concentration for the two different monoliths at 10 mm/h, see figure 7(b) and 8(b), it is seen that the response of monolith A is much slower than that of monolith B. If this is to be explained by the proposed macropore flow theory, the slower response should be the effect of a generally less well-connected and more tortuous macropore network. This would account for the slower rise and decline in monolith A, and the differences in connectivity and tortuosity within monolith A would still generate the multiple peaks which can be observed. The lower peak concentration in monolith A is then caused by the large degree of mixing with "clean" water which takes place in a more tortuous flow path. Regarding the response time of the monoliths this interpretation is well supported by the observations made during the dye experiments.

The results of the dye tracer experiments and the subsequent dissection of the monoliths have shown that the use of Rhodamine B as a dye tracer is quite successful. The dye has clearly marked the pathways of flow and demonstrated the flow patterns in a macroporous soil.

A significant difference in response time of the two monoliths was observed. The dye tracer appeared much later and more diluted at the bottom of monolith A than of monolith B, and the subsequent dissection showed that the dye had moved further and was more distributed in monolith B than in monolith A.

The horizontal slicings have shown that it is almost impossible to follow a single, stained macropore all the way through a monolith. Instead, staining in certain areas can be followed over large distances. Both vertical and horizontal slicings have shown that not all macropores transmit both dye and water. Having two macropores situated next to each other, one may transmit dye tracer while the other does not. This must be a result of the latter macropore being less well-connected to the soil surface and perhaps also more tortuous, causing some of the dye to be delayed in the upper layers of the monolith, and this part of the dye will not reach the bottom of the monolith untill much later. Another fact supporting this theory is the larger number of stained macropores which were observed in the top layers of the

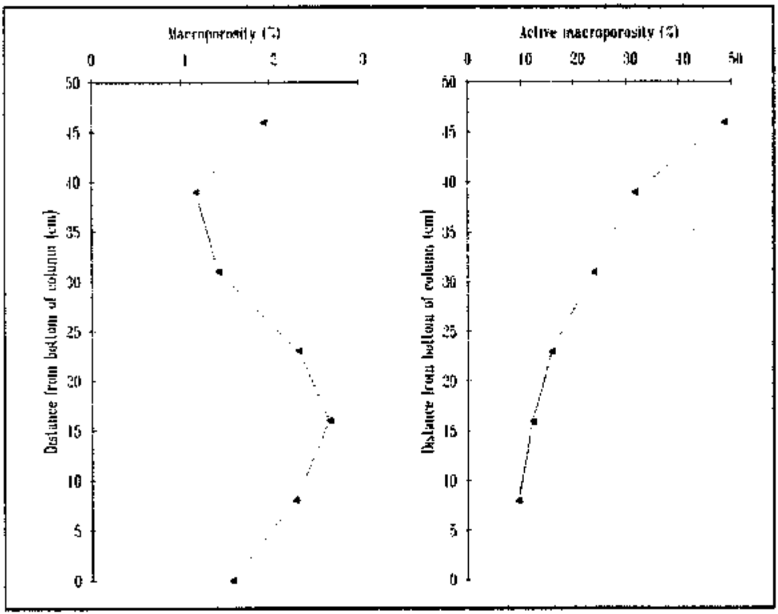

figure 9
Estimated macroporosity for monolith B: (a) macroporosity (total), (b) active macroporosity (percentage of total macroporosity)

monolith in comparison to the bottom layers. The possible retardation and accompanying dilution of the dye tracer due to adsorption to the soil particles may to some degree have been responsible for this, but still, some dye (following the well-connected macropores) reached the bottom of the monolith very fast indicating a significant difference in the flow ability of the pores. In an attempt to document this, an active (stained) macroporosity has been estimated in association with the image-processing. The macroporosity of monolith B is shown in figure 9(a), it varies between 1.2 and 2.7 %. In addition to the total macroporosity an active macroporosity was estimated, see figure 9(b), as the percentage of the macroporosity which was stained in the dye experiment. There is a distinct decrease in the estimated active macroporosity with increasing depth.

To estimate the size distribution at the different levels the macropores were placed in different area size classes. The majority of the macropores were found in the smaller size classes between 0.038 and 0.170 cm^2 corresponding to a pore diameter between 2.2 mm and 4.7 mm. The size distribution graphs further indicated that the largest pores are situated in the bottom layer of the monoliths, which is in good agreement with the observations made during the monolith sectioning and the findings of Edwards et. al. (1988).

CONCLUSIONS

Water flow and solute transport in macroporous soil have been investigated in different laboratory experiments. The experiments have shown that both water and solute transport is dominated by the presence of macropores. The flow distribution was non-uniform across the outflow area and it changed rapidly with time, due to air entrapment.

Initiation of outflow from the initially dry monoliths was observed far ahead of what in time would correspond to one pore volume, indicating extensive by-passing in the form of macropore flow. The solute outflow concentration curves featured early breakthrough and in some cases extensive tailing. This type of outflow pattern is typical for macropore flow, but, in addition, most of the curves obtained in the experiments had multiple peaks. The dye tracer experiments and successive sectioning showed that a larger number of macropores was active at the top of the monolith than at the bottom. The macroporosity ranged between 1.2 and 2.7 % with no systematic changes with depth, while the percentage of the macroporosity which was active (stained) varied significantly from top (48.7 %) to bottom (9.5 %).

The solute BTCs and the dye tracer experiments demonstrated that the variable number of peaks are caused by air entrapment as well as differences in size, connectivity, and tortuosity of the individual macropores in the macropore system. Water and solute moving in different macropores of varying structure will have different residence time and result in individual peaks at the monolith bottom.

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SIGNIFICANCE OF GROUNDWATER LEVELS FOR DISCHARGE PEAK FLOWS

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ABSTRACT

Inundations occur almost every year in the vicinity of Swedish rivers. Occasionally these floodings may be severe. Relevant hydrological prerequisites have not yet been fully clarified. Precipitation, amount and distribution, together with soil water conditions and groundwater levels are the main factors governing discharge response.

However, land use also affects hydrological conditions. In forest land the distribution of clear-felled and young forest areas, together with drainage, influences the discharge and the occurrence of high flows. Clear-felling results in elevated groundwater levels while drainage acts in the opposite way with lowered groundwater levels. Clear-felling results in reinforced peak flows. Drainage will lead to channelling of water pathways which facilitate runoff but drainage also extends the possibilities to store water in the unsaturated soil moisture layers above the groundwater which mitigates high and rapid runoff.

Investigations have been performed in a number of basins. At normal and low groundwater levels part of the precipitation was stored in the soil, resulting in low runoff. On the other hand, at high groundwater levels discharge peaks became high, i.e. precipitation at events with high soil water content could be hazardous in the context of inundation. These conditions were observed in virgin basins as well as in clear-felled and drained basins.

INTRODUCTION

In Sweden, extreme climatic conditions are not matters of common occurrance. But, more or less severe floodings occasionally occur at spring snowmelt and during periods of considerable rainfall. Of particular note, among other events during recent years, were high flows in Bergslagen region in 1977 and those in the counties of Dalarna and Hälsingland in September 1985. The latter flooding caused a dam rupture which led to a disentanglement of dam security (SOU 1987:64).

In the Nordic countries hazardous floodings are rare and often appear unexpectedly. Natural conditions that provide prerequisites for high flows are high groundwater levels in combination with intense and heavy precipitation or rapid snowmelt together with rainfall. Also pre-event large contents of surface water provide conditions for high water flows.

Not only these natural and hydrological conditions have influences on high flows. Also land-use affects runoff. In forested areas, such as the major part of the Nordic countries, forest management is important. The main forest incisions made, in this respect, are clear-felling and drainage. Both these activities have been argued to contribute to high flows.

LAND-USE OPERATIONS

Effects of forest management have been investigated in small catchments. Effects of clear-felling are elevated groundwater levels and increased soil moisture content (Fig 1) (Lundin, 1979). Elevated groundwater levels provide high lateral groundwater flow because of the often high hydraulic conductivities in the upper soil layers as compared with deeper layers (Lundin, 1982). This may provide an opportunity for precipitation on clear-cut areas to easily and rapidly discharge to surface stream waters. The amount of precipitation that reaches the soil also increases due to the absence of interception.

Clear-felling was found to increase annual runoff by up to 100% (Grip, 1982; Rosén, 1984; Brandt et al., 1986). Discharge peaks were found to increase after clear-felling and then more at rainfall when groundwater level was low than when the groundwater level was found close to the soil surface (Grip, 1987).

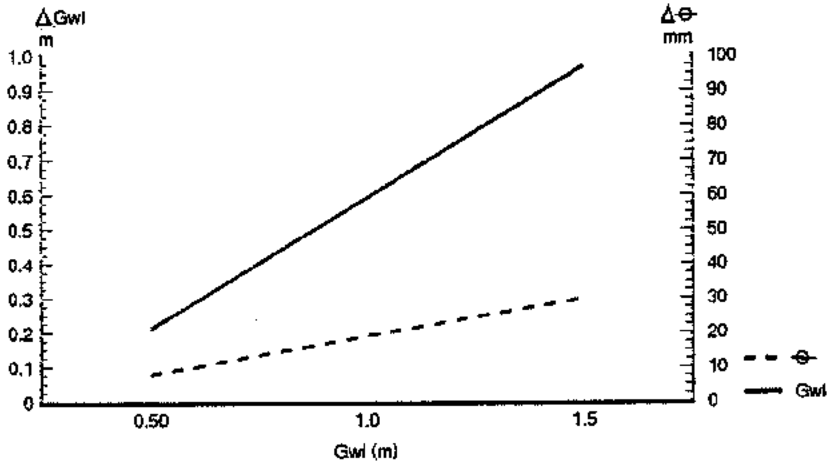

Figure 1. Change in soil moisture content in the upper 0.55 m soil layer (Θ) and change in groundwater level (Gwl) after clear-felling, as compared to the groundwater level at the site when forested (Gwl), at the Masby catchment, 1973-1977.

A high water content and elevated groundwater levels also causes problems during forest regeneration of the clear-cut areas. To provide suitable conditions for young forest plants, a water adjustment is needed during the thicket stage. Groundwater level should not be found closer to ground surface than 0.3-0.5 m (Holmen, 1980). On moist and wet soil types this is achieved by drainage, designed to regulate the water level below the critical depths. Drainage then attempts to change the hydrological conditions in the opposite way to clear-cutting. But, at the same time, drainage facilitates streamwater discharge by the channels made (Fig 2).

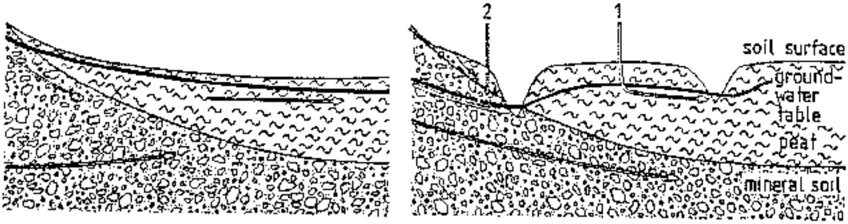

Figure 2. Water pathways and groundwater levels in a wet soil type before and after drainage. Note the unsaturated zone established by drainage and which has to be passed before reaching the groundwater to achieve lateral discharge.

The lowered groundwater level after drainage provides an extended unsaturated soil layer (Table 1). The size of this storage deficiency is comparable with ordinary large precipitations. If precipitation water is stored in this layer, drainage would mitigate high discharges.

Table 1. Water deficit to saturation (mm) in the upper 0.5 m soil layer in undrained and drained conditions in peatlands and in clear-cut areas on mineral till soils.

	Undrained	Drained
Peatland	30	100
Mineral soil	20	80

A general picture of effects on runoff of peatland drainage shows increased total runoff by 24% (Braekke, 1970). Drainage clearly increased the potential for greater runoff. However, the effects achieved depend upon rainfall and snowmelt intensities, groundwater levels, drain shape and tree stand (Starr & Päivänen, 1981). Mostly lowered discharge peaks were found after drainage and increases mainly occurred in summer and autumn (Multamäki, 1962). At spring snowmelt and after considerable rainfall periods with additional precipitation, discharge peaks increased but the changes vary considerably, i.e. by 6 to 130% (Seuna, 1978; Bergquist et al., 1984; Lundin, 1984).

WETLAND TYPES

Most of the results mentioned concerned peatland drainage and only a few deal with drainage on clear-cut mineral soil areas. Different effects would be expected due to the object drained. Wetlands comprise a wide range of types. The main groups are marine, limnic and terrestrial. Terrestrial wetlands include wet meadows, bogs, fens and wetland forests. Hydrological conditions vary differently both spatially and temporally at the different types.

The total forest wetland area in Sweden comprises 10.1 Mha, which is about 35% of the total forest land including mires (Hånell, 1990). About half of this area consists of more or less treeless wetlands, designated mires, while the other half has a forest cover.

Total forest drainage in 1988 concerned about 45000 ha and two thirds of this, 30000 ha, was drainage on clear-cut mineral soils, which clearly illustrates the interest in these types.

INVESTIGATIONS

The investigations that were performed to elucidate effects of clear-felling and drainage on runoff were conducted as comparisons between similar catchments in pairs. During a first period, runoff from the catchments was compared with both wetland catchments virginally intact. After this period, one of the areas was clear-cut and/or drained and the other kept unchanged as control. Differences in interconnected relationships between the catchments during the two periods were considered to be impacts of the incisions.

Groundwater levels were measured within the catchments and discharge determined by water level recorders at V-notch weirs.

A major difficulty when measuring extremely high discharges was their rare occurrence. Extreme flows did not occur every year and during the short investigation periods there were rarely more than one or two extremes and then at different hydrological conditions at undrained and drained situations. Mainly results had to be gained from studies made of ordinary high flows occurring at a number of events during the periods.

EFFECTS OF PEATLAND DRAINAGE

At a large sedge fen in the central part of Northern Sweden very obvious differences in effect of drainage were seen at two spring snowmelt periods with prevailing different hydrological conditions. At the first snowmelt period there was mostly sunny weather and low precipitation. This resulted in a 40% smaller spring runoff as calculated for undrained conditions. In the second snowmelt period there was a precipitation of 138 mm which could be compared to a long-term mean precipitation of 70 mm. Runoff then increased by 28% (Lundin, 1984). In the first period the peak discharge reached only 57% of the expected undrained peak while the peak in the latter period exceeded the expected undrained peak by 62%. At a later snowmelt period (1985) there was also a very high spring peak discharge which reached 1.5 m^3/s, to be compared with a calculated undrained peak of 0.9 m^3/s, i.e. an increase of 70%.

In 1988 the fen was opened up for peat-winning. For this purpose, a fairly deep drainage was used with short distances, 20 m, between the ditches. After this drainage, most high discharges decreased and the highest peak discharge was lowered by 32%. But in May 1991 the peak reached twice the expected undrained discharge peak (Lundin, 1992).

At drainage of a bog surrounded by relatively high mountains, discharge peaks were lowered by a mean of about 22% after bog drainage.

In central Sweden, in the Bergslagen region, some small sedge fens in moraine terrain were investigated in connection with drainage (Bergquist et al., 1984). During the first four years after drainage most high discharges decreased, and then by 17-34%, and only a few small increases were observed, reaching about 6%.

Several discharge peaks at the undrained control and the drained impact catchment were compared during each of the two periods before and after drainage. The average relationship between the two catchments changed from the undrained calibration period to the period after drainage, showing decreased peak flows at the drained catchment (Table 2 and Fig 3).

Impact of drainage showed a variation with depth to pre-event groundwater levels, i.e. there were larger decreases at deeper groundwater levels. With the pre-peak level in layer 0-5 cm below ground surface there was a mean decrease of 14%. With the level in layers 6-10 cm and 11-22 cm the decreases were 16% and 24%, respectively. However, the influences of groundwater levels were often small and difficult to discern (Fig 4).

Table 3. Quotient of peak discharges at the impact (drained) catchment and the control before and after drainage.

	Number of peaks	Quotient	95% confidence interval
Undrained	9	1.09	0.93 - 1.25
Drained	13	0.93	0.89 - 0.97

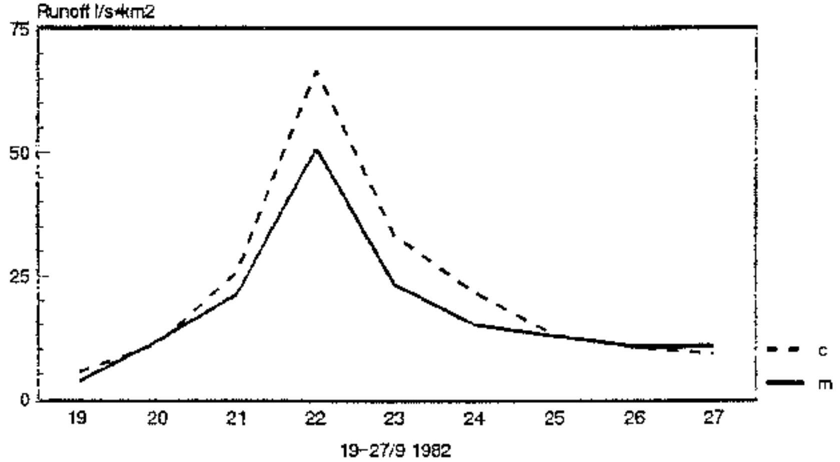

Figure 3. An example of a typical discharge peak calculated as undrained (c) and measured after drainage (m). From Siksjöbäcken basin, central Sweden.

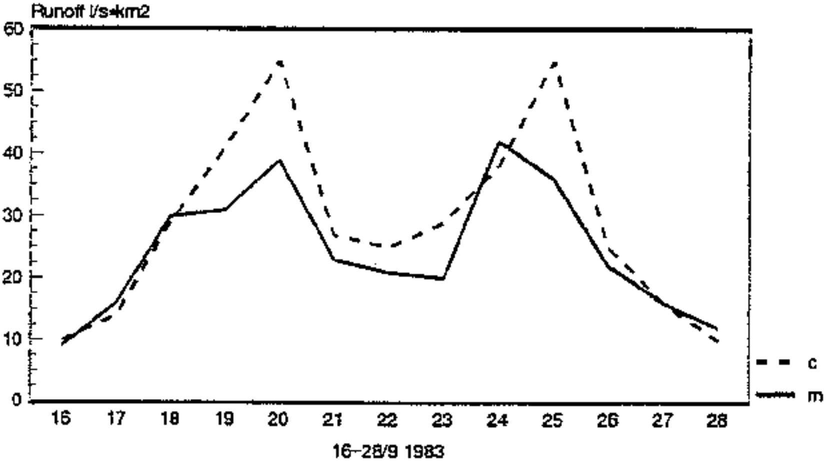

Figure 4. Two discharge peaks caused by about the same amount of precipitation but at different pre-rainfall groundwater levels. In the lagg the water level before the first peak was 0.2 m below ground surface but before the second peak it was only at a depth of 0.03 m. Discharge was calculated, from the control, for undrained conditions at the impact catchment (c) and measured after drainage (m). Precipitation at the first peak was 60 mm and at the second 50 mm. Note the almost equal peak sizes at undrained conditions.

FOREST CUTTING AND MINERAL SOIL DRAINAGE

Two adjacent catchments in central Sweden were studied during different phases of forest operations. One was kept mainly intact as comparison control and the other was, during the first period, totally forested with a stand volume of 148 m^3sk/ha in the central 50% of the catchment. This stand was clear-cut in 1976 and the catchment was then studied as a clear-cut area during the years 1976-1981. In September 1981, mainly the central elongated part of the catchment was fairly lightly drained with about two km of ditches, i.e. 108 m/ha. After this drainage the hydrological conditions were studied during a four-year period.

Peak discharges were compared between the two catchments during the three periods. The quotient impact/control showed increased peaks after cutting and still larger increases after drainage of the clear-cut area (Table 4).

Effects of rainfall on peak discharges varied with pre-rainfall groundwater levels. With the water level in the uppermost 0.3 m of the soil in discharge areas there was an average increase in peak discharges after drainage of 50% as compared to undrained but clear-cut conditions. At pre-rainfall groundwater levels deeper than 0.3 m, peak discharges decreased by 10%. High peak discharges often occurred at rainfall with high groundwater levels. Then a conclusion would be

Table 4. The quotient between discharge peaks at the impact catchment and the control during three periods. The first period, 4 years, with both catchments forested; the second after clear-cutting, 6 years; and the third after drainage of the clear-cut area, 4 years.

Phase	Number of peaks	Mean quotient	95% confidence interval
Forested	15	0.95	0.89 - 1.01
Clear-cut	17	1.00	0.88 - 1.12
Clear-cut and drained	21	1.19	1.01 - 1.37

that at extreme events there were increases in peak flows after drainage of the clear-cut area. In a special study of the three and four highest peak discharges, > 200 $l/s*km^2$ as daily mean, all indicated increased peak discharges, both after clear-cutting and further strengthened after drainage. The very highest measured runoff coefficient reached 472 $l/s*km^2$ after clear-cutting and drainage, while the coefficient at the control only was 295 $l/s*km^2$. This event was caused by a precipitation of about 70 mm in two days and a groundwater level before precipitation at about 0.15 m below ground surface in the discharge area. Runoff during the four-day runoff event at the control was about 40 mm and at the impact area 58 mm.

These results elucidate an extended view of peak discharges. Increased peaks are, of cause, important but the duration of this increase is probably even more relevant. If there are only peaks of very short duration caused by, for example, improved watercourses then effects are limited. But if total volume during a high flow period ranges over four to ten days, which often occurs, then the total water load downstream could be hazardous.

Calculations of high flow volumes at the two studied catchments resulted in volumes increasing by 15% after clear-cutting and 50% after both clear-cutting and drainage, as compared with the forested situation.

CONCLUSIONS

Extreme discharge situations rarely occurred and were not often measured in investigations specially designed to provide information on this phenomenon. Experience had to be derived from investigations concerning connected issues. However, since natural conditions such as intensities and amount of precipitation, together with existing hydrological conditions, seemed to be the most relevant factors, influence of land-use and man-made management was often difficult to discern.

However, the investigations performed showed that forest management influenced peak discharges. Clear-felling elevated groundwater levels which made the peaks higher and mineral soil drainage at clear-cut areas further strengthened the peaks and also the total water volume leached from treated areas. This was especially evident at high groundwater levels and at the very highest discharges.

Peatland drainage, on the other hand, did not show the same obvious increase in peak discharges. Increases were observed only on a few occations. The average effect on high discharges was lowered peaks after drainage and then larger decreases with deeper groundwater levels. An obvious difference between peatlands and clear-cut areas was the waterlogged condition that often existed at the peatland in natural conditions but that seldom occurred over a total clear-cut area. Peatlands studied were mainly treeless.

These investigations were performed in fairly small catchments and the effects must not uncritically be adapted to larger watercourses without a total survey of land-use in the larger basins.

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GEOCHEMICAL TRANSPORT MODELLING OF ION EXCHANGING SOLUTES IN A SOIL COLUMN

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ABSTRACT

The mathematical formulation and numerical solution strategy behind a geochemical transport model are reviewed. The model is used to simulate transport of ion exchanging solutes in a soil column experiment. The simulated breakthrough curves for several components show very good agreement with observations and thus indicates that these types of models can be a very useful tool for interpreting geochemical processes at least at the laboratory scale.

INTRODUCTION

Reactive contaminants that infiltrate to the subsurface will be transported with the groundwater and at the same time participate in geochemical/biochemical processes. Typically, transport of contaminants in groundwater is of a multi-component nature, where it is the non-linear behaviour of solute transport and geochemistry/biochemistry that decides the mobility of contaminating species. Species mobility is one of the primary concerns in groundwater environmental pollution studies. Because of this, there is a need for developing predictive mathematical models that can take into account coupled transport and geochemistry/biochemistry in groundwater.

An important element in the development of geochemical transport models is the validation step. This paper will briefly review the formulation and solution strategy behind the MST1D model (Engesgaard and Kipp, 1992; Engesgaard, 1991) and present an attempt of validating the model by simulating transport of ion-exchanging solutes in a soil column experiment.

THE GEOCHEMICAL TRANSPORT MODEL (MST1D)

The geochemical transport model is based on the Local Equilibrium Assumption (LEA) which assumes that changes in species concentrations due to physical processes (advection and dispersion) are much slower than changes in species concentrations caused by geochemical processes.

Multi-component solute transport and chemical reactions are simultaneous processes. The governing equations for a solute transport model with equilibrium chemical reactions are a set of partial differential transport equations and a set of algebraic chemical equations.

The numerical geochemical transport model is based on the reactive transport equations in the following form (see e.g. Engesgaard and Kipp (1992) and Engesgaard (1991) for a derivation of the reactive transport equations)

$$\frac{\partial u_j}{\partial t} - D\frac{\partial^2 u_j}{\partial x^2} + v\frac{\partial u_j}{\partial x} = -\frac{\rho}{\theta}\left(\frac{\partial s_j}{\partial t} + \sum_{k=1}^{N_p} B_{kj}\frac{\partial p_k}{\partial t}\right) \quad j=1,\ldots,N_c \tag{1}$$

where u_j is the total aqueous concentration of component j (moles/L), N_c is the number of components, s_j is the sorbed concentration of component j (moles/kg soil), p_k is the concentration of mineral k (moles/kg soil), B_{kj} is the stoichiometric coefficient of component j in mineral k, N_p is the number of minerals, v is the interstitial flow velocity (m/s), D is the dispersion coefficient (m^2/s), ρ is the soil dry bulk density (kg soil/L medium), and θ is the saturated porosity (L fluid/L medium).

The geochemical equilibrium reactions that can be solved by MST1D include aqueous complexation, ion exchange, mineral precipitation/dissolution, and redox processes. This paper will not address the problems of simulating redox-controlled transport (see instead e.g. Engesgaard and Kipp (1992)).

The solution of the coupled set of equations is carried out by the Sequential Iteration Approach (SIA) (Yeh and Tripathi, 1989). The solution algorithm comprises solving the transport equations one at a time with the explicit source-sink term (right hand side of equation (1)) set initially to zero at the beginning of the simulation and subsequently to that of the previous time step, then solving the chemical equilibrium equations with the total aqueous component concentrations, u_j, from the transport solution. The changes in amount of mineral and sorbed concentrations give revised estimates of the source-sink terms, which are passed back to the transport equations for another iteration. The iterative cycle continues until the computed total aqueous component concentrations from the transport equations and those computed from the chemical equilibration calculation agree to a user-set tolerance. Generally, a fractional tolerance of $5 \cdot 10^{-3}$ to $1 \cdot 10^{-4}$ has been found to be adequate for most cases.

The advantage of this solution strategy is the modularized structure of the geochemical transport model. The modularization gives access to a choice between developing a specific geochemical equilibrium code or choose among the vast number of already existing codes. The MST1D model uses the PHREEQE code (Parkhurst et al., 1980) as its geochemical module. PHREEQE calculates the equilibrium speciation and mass transfer due to mineral precipitation/dissolution but does not include a direct procedure for including ion exchange reactions. Appelo et al. (1990) have shown how to trick the code to simulate ion exchange by considering the negative soil surface charge as an additional component and writing the ion exchange reactions as half-cell reactions. By manipulating the half-cell equilibrium constants it is possible to specify the correct selectivity coefficient for the reactions.

SIMULATION OF SOIL COLUMN EXPERIMENT

This example simulation deals with modelling the transport of ion-exchanging solutes in a soil column experiment. A series of experiments has been carried out at the Dept. of Environmental Engineering, Technical University of Denmark of which only a few was reported by Kjeldsen et al. (1984). The experiments were originally designed to identify relevant parameters for groundwater quality monitoring at waste incinerator residue disposal sites.

Leachate collected at the site was percolated through the soil column at a saturated Darcy-velocity of 0.052 m/day. One pore volume is equivalent to a hydraulic retention time of 1.79 days. The soil was sampled at groundwater level in the vicinity of the site. The composition of the leachate and initial column water is shown in Table 1.

Table 1 Composition of leachate and background solutions in moles/L of total aqueous component concentrations. Sorbed concentrations are also given in units of moles/L.

	inlet	**background**
pH	9.47	7.56
Ca^{2+}	$1.02\ 10^{-4}$	$4.03\ 10^{-2}$
Mg^{2+}	$6.58\ 10^{-5}$	$1.24\ 10^{-3}$
Na^+	$9.13\ 10^{-2}$	$7.34\ 10^{-3}$
K^+	$2.92\ 10^{-2}$	$3.69\ 10^{-5}$
NH_4^+	$1.17\ 10^{-2}$	$5.28\ 10^{-11}$
SO_4^{2-}	$1.15\ 10^{-2}$	$1.28\ 10^{-3}$
CO_3^{2-}	$1.79\ 10^{-2}$	$7.56\ 10^{-3}$
Cl^-	$1.00\ 10^{-1}$	$1.50\ 10^{-3}$
X^- (=CEC)	-	$6.19\ 10^{-2}$
$Ca\text{-}X_2$	-	$2.41\ 10^{-2}$
$Mg\text{-}X_2$	-	$6.69\ 10^{-3}$
Na-X	-	$2.66\ 10^{-4}$
K-X	-	$6.31\ 10^{-5}$
$NH_4\text{-}X$	-	$5.72\ 10^{-11}$

The parameters characterizing the physical-chemical soil column system are shown in Table 2. Interstitial velocity and dispersivity were found by the CXTFIT program (Parker and van Genuchten, 1984) from the chloride breakthrough curve. The porosity was found from estimating the pore volume (area under the chloride breakthrough curve) and the volume of the soil column itself. The CEC was found from a mass balance on the amounts of Ca^{2+} and Mg^{2+} released from the soil assuming that these two cations are the only ions on the soil at the beginning of the experiment. This is a good assumption because the initial pH is above 7 and the amounts of sorbed H^+ can therefore be neglected. The CEC calculated in this manner was approximately 25% less than that estimated from a mass balance on the amounts of Na^+, K^+, and NH_4^+ sorbed onto the soil

Table 2 Physical and chemical parameters for the soil column experiments.

Column length	0.29 m
Pore velocity	0.158 m/d
Porosity	0.33
Bulk density	1600 kg/m^3
Dispersivity	0.0097 m
CEC	1.28 meq/100 g

during displacement.

The geochemical system consist of eight components of which five can participate in ion-exchange reactions, 18 complexes, and one mineral. The ion exchange reactions along with their selectivity coefficients are shown in Table 3. The initial amounts of sorbed Ca^{2+} and Mg^{2+} (Table 1) have been found from the CEC and the mass action equations based on the reactions in Table 3.

Three different model runs will be presented here; one run where there are no minerals precipitating, and two runs where either a pure calcite or a magnesian calcite is precipitating. Table 4 shows the two minerals for the last two runs. The magnesian calcite represents a 20% substitution of $MgCO_3$ into calcite. The solubility for calcite was set at $\log K_s = -7.65$. This value is close to one log unit higher than the value suggested in the PHREEQE database (-8.46). However, it was necessary to increase the solubility of calcite in order for the soil to be initially free of calcite. If a lower solubility was used, calcite would precipitate causing pH to be much higher than observed in the starting solution. The solubility of the magnesian calcite was set at the same value as for calcite.

Table 3 Ion exchange reactions and selectivity coefficients

Ion exchange reaction	**K**
$2Ca^{2+} + 2Mg\text{-}X_2 = 2Ca\text{-}X_2 + 2Mg^{2+}$	1.30
$Ca^{2+} + 2Na\text{-}X = Ca\text{-}X_2 + 2Na^+$	8.00
$Ca^{2+} + 2K\text{-}X = Ca\text{-}X_2 + 2K^+$	0.36
$Ca^{2+} + 2NH_4\text{-}X = Ca\text{-}X_2 + NH_4^+$	0.90

Table 4 Calcite and magnesian calcite minerals

Mineral reaction	**log K**
$CaCO_3 = Ca^{2+} + CO_3^{2-}$	-7.65
$Ca_{0.8}Mg_{0.2}CO_3 = 0.8Ca^{2+} + 0.2Mg^{2+} + CO_3^{2-}$	-7.65

The chloride breakthrough curve (BTC) is shown in Figure 1. The velocity and dispersivity found by CXTFIT give a fairly good simulation of solute transport in the soil column. The simulated BTC breaks a little too early and is not steep enough. The cause

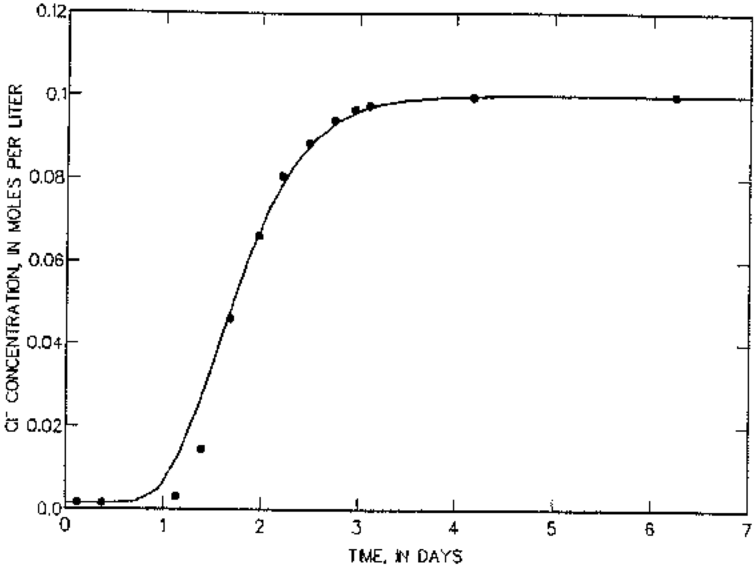


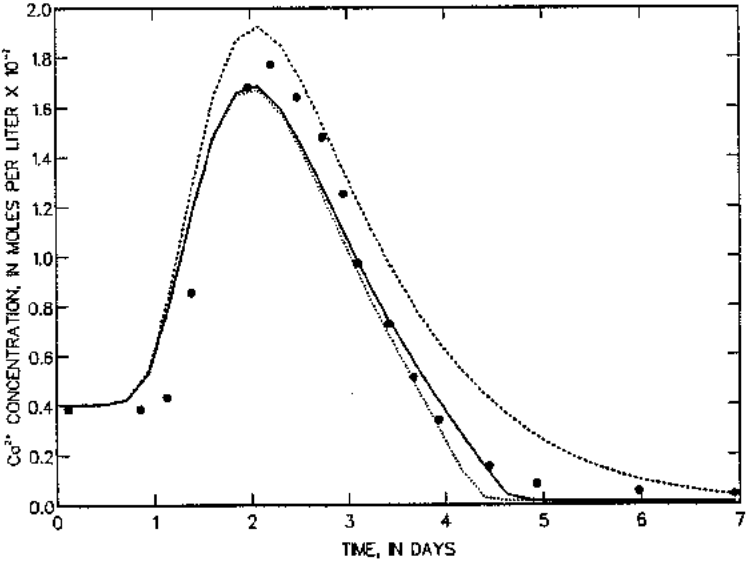
Figure 1 Observed (dots) and simulated chloride BTC.

of the discrepancy is probably numerical dispersion.

The Ca^{2+} and Mg^{2+} BTC's are shown in Figure 2, the Na^+ and K^+ BTC's in Figure 3, the NH_4^+ BTC in Figure 4, and the pH BTC in Figure 5. All figures include three model runs; with no precipitation, with calcite precipitation, and with magnesian calcite precipitation.

The observed BTC's for Ca^{2+} and Mg^{2+} show significant release of the components from the soil of up to a factor of five relative to initial concentrations. If no carbonate mineral is allowed to precipitate, MST1D simulates too much Ca^{2+} and Mg^{2+} in solution, Figure 2 (and especially at the first front of the peak BTC's) and a too early pH-front breakthrough, Figure 5. If precipitation of a pure calcite is allowed, Ca^{2+} is removed from the solution (especially on the front of the BTC). This will remove an equal amount of CO_3^{2-} causing bicarbonate to dissociate which produces H^+ and lowers pH. This process is a buffer against a pH increase until precipitation ceases. A good match of the pH BTC is achieved by allowing precipitation of a carbonate mineral. Kjeldsen (1991) observed a slight decrease in flow velocity which can be explained by carbonate mineral precipitation. Precipitation of calcite is seldom instantaneous and the use of a LEA-model can be questioned. The observed pH BTC has a much more dispersed front breakthrough than the simulated. This is an indication that the precipitation process is governed by kinetics. The simulation results thus indicate that precipitation "at some rate" of a carbonate mineral has been a likely process in the soil column and that the LEA-based simulation gives a satisfactory description of the processes in the soil column.

The Mg^{2+} BTC is affected by precipitation of calcite because the Ca^{2+} ions



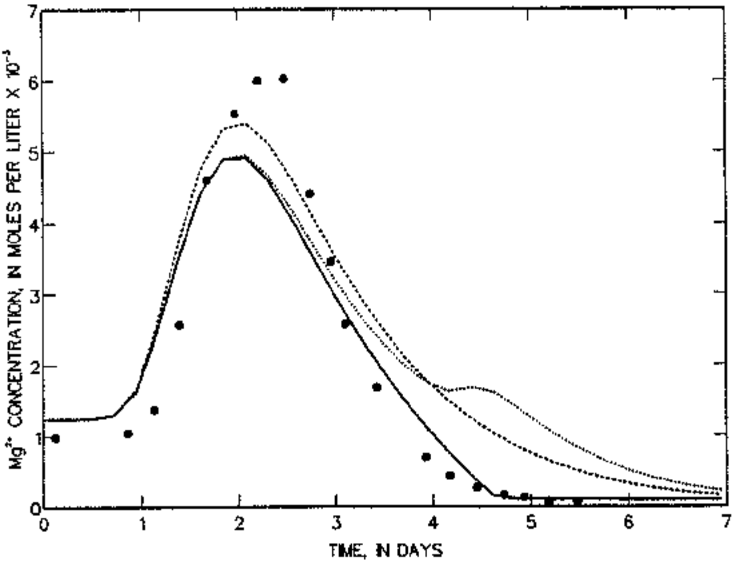


Figure 2 Observed (dots) and simulated Ca^{2+} (top) and Mg^{2+} (bottom) BTC's for the cases with no mineral (stippled line), calcite (dotted line), and magnesian calcite (solid line).

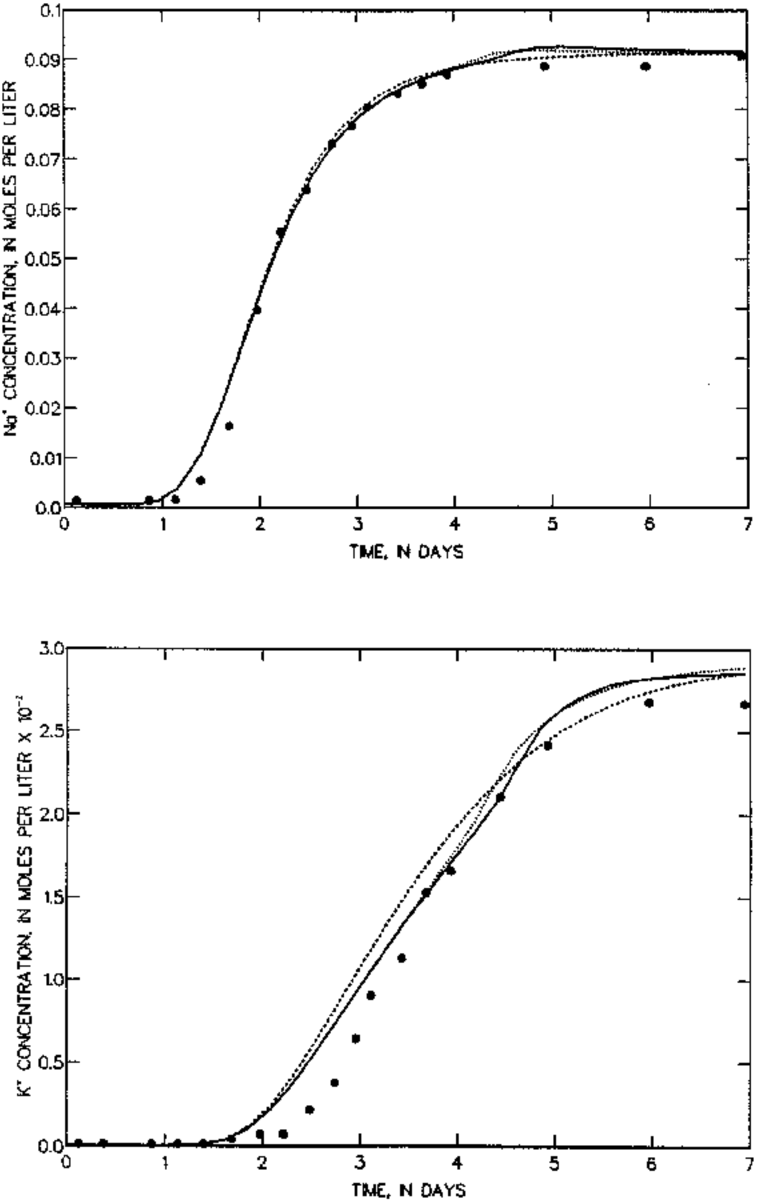


Figure 3 Observed (dots) and simulated Na$^+$ (top) and K$^+$ (bottom) BTC's for the cases of no mineral (stippled line), calcite (dotted line), and magnesian calcite (solid line).

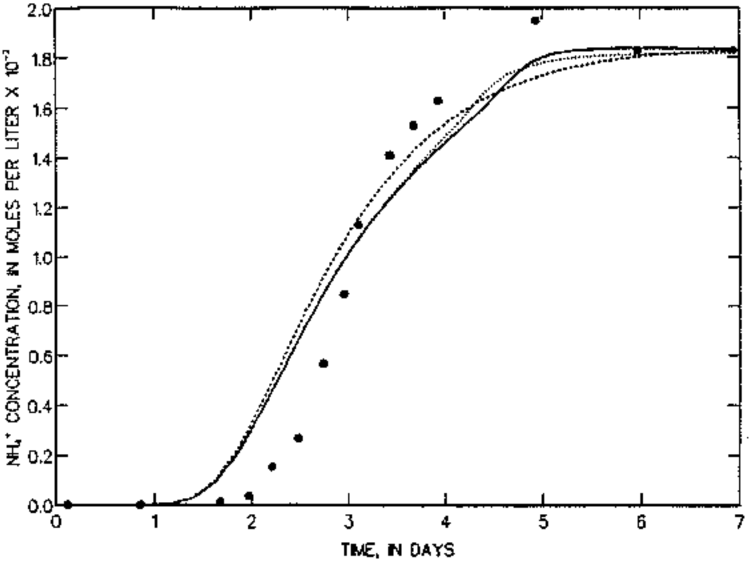


Figure 4 Observed (dots) and simulated NH$_4^+$ BTC's for the cases of no mineral (stippled line), calcite (dotted line), and magnesian calcite (solid line).

precipitated as calcite now can not compete with Mg^{2+} and the rest of the cations for the sorptive sites. On the front of the Mg^{2+} BTC there is still too much Mg^{2+} in solution. Furthermore, a chromatographic effect of a sudden increase in the Mg^{2+} concentration after four days is seen. The same effect can be seen in the Na$^+$ BTC. The observed Ca^{2+} and Mg^{2+} BTC's are remarkably similar. It was therefore hypothesized that the precipitating carbonate mineral was not a pure calcite but a magnesian calcite. A 20% mole fraction of Mg^{2+} has been used in the magnesian calcite. Clearly the results are much better for the Mg^{2+} BTC. The precipitation of a carbonate mineral decreases the simulated peak Mg^{2+} concentration somewhat below the observed peak concentration.

The Na$^+$, K$^+$, and NH$_4^+$ BTC's are practically unaffected by the precipitation of a carbonate mineral. Generally, the BTC's are simulated quite well although the K$^+$ and NH$_4^+$ BTC's are not steep enough. It is believed that numerical dispersion can not explain this discrepancy. Both the K$^+$ and NH$_4^+$ BTC's show significant retardation while the Na$^+$ BTC is only slightly retarded.

DISCUSSION AND CONCLUSIONS

The successful application of MST1D to the soil column experiment is an incentive for continuing with field-scale applications, the ultimate goal for developing these predictive tools. However, the reasonable good fit between simulations and observations is perhaps due the dimensionality of the system, the steady-state transport,

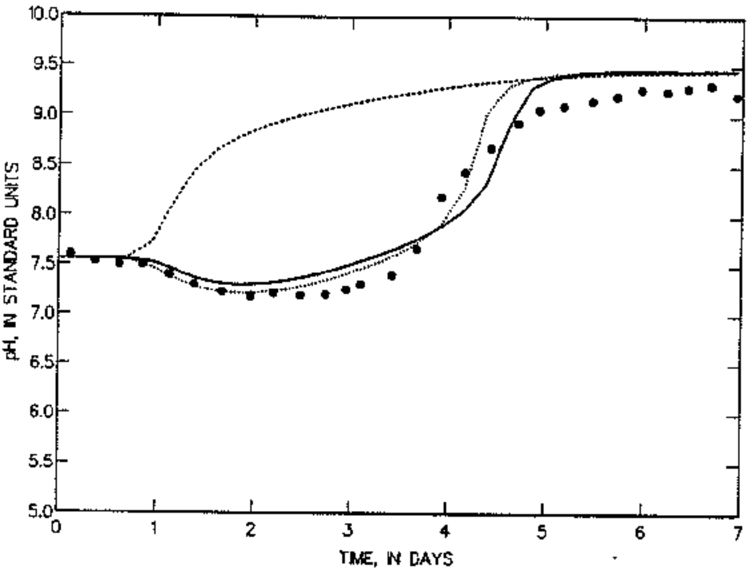


Figure 5 Observed (dots) and simulated pH BTC's for the cases of no mineral (stippled line), calcite (dotted line), and magnesian calcite (solid line).

the control on LEA, the homogeneous conditions with respect to the chemical parameters, and the few species in the geochemical system. At the field-scale, it is impossible to be certain that all of these conditions are fulfilled. More likely, the temporal and spatial variability in fluid flow and boundary conditions along with the heterogenous nature of most aquifers will provide a system where the geochemical transport models will have more difficulty in predicting observed species behaviour. On top on that, it is a fundamental question whether the micro-scale processes used in MST1D are valid for typical numerical grids sizes that would be used in field-scale applications. Another costly problem is that of getting data to validate the model for field-scale application. These data are not only aquifer data but should also, principally, include a determination of all equilibrium constants in the thermodynamic data base. Typically, the number of species and thus equilibrium constants may be over 100.

At present it therefore seems that the geochemical transport models are most suited for interpretation of soil column experiments. At the field-scale geochemical transport models may still be useful in testing hypothesis and carrying out sensitivity analysis. This could, hopefully, be a supplement to other investigations, and add to the base of understanding the transport behaviour of contaminants in groundwater.

ACKNOWLEDGEMENT

The development of the MST1D model was carried in cooperation with research hydrologist Kenneth L. Kipp, U.S. Geological Survey, Denver, USA. Peter Kjeldsen, Dept. of Environmental Engineering, Tech. University of Denmark, is acknowledged for letting me use the experimental data.

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TRANSPORT MODELLING OF BIODEGRADABLE ORGANIC MATTER

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ABSTRACT

At Vejen landfill in Denmark an extensive monitoring program has been carried out in order to establish a better understanding of the transport and biodegradation processes in the groundwater zone. The observations show that the aquifer is geo-/biochemically divided into sequential redox zones downstream to the landfill. The hydrogeological properties of the aquifer were found by using wells to determine the extent of different geological formations and by using slugtests to determine the hydraulic conductivity of the identified formations. The aquifer can be characterized as a fairly homogeneous sandy aquifer with a impermeable clay layer at the bottom. In order to evaluate the observations three-dimensional modelling of the flow, the conservative transport and the transport and biodegradation of organics was made. The solute transport modelling was carried out using chloride as a conservative species and organic matter (NVOC) as a biodegradable species. To simulate biodegradation of NVOC biodegradation terms were incorporated into the existing transport model. These terms describe aerobic, nitrate-reducing and methanogenic biodegradation of NVOC. The simulation results showed good agreement concerning head potentials, reasonably good agreement for transport of chloride. The simulation of transport and biodegradation of NVOC shows significant retardation, which is in accordance with field observations. The biochemical submodel is, however, too simplified to simulate the actual processes in the field. In conclusion, a more precise numerical formulation incorporating the redox zone system is outlined.

INTRODUCTION

Since 1987 the groundwater at Vejen landfill in Denmark has been subject to detailed monitoring with the purpose of gaining a better understanding of the fate of organic pollutants migrating from a landfill. In order to understand the biochemical degradation pathways a redox mapping has been carried out. This mapping has shown that the aquifer downstream to the landfill is composed of sequential redox zones ranging from a methanogenic zone near the landfill to sulfate-reducing, iron/manganese-reducing, nitrate-reducing and finally an aerobic zone. These redox zones are created by the organic degradation processes. To understand the simultaneous transport and biodegradation at the Vejen landfill a three-dimensional (3D) groundwater and solute transport model has been extended to include biodegradation terms and subsequently applied to the aquifer in the near-field of Vejen landfill. This paper presents simulation results regarding groundwater flow, transport of chloride as a tracer, and transport and degradation of organic matter given as NVOC. The biodegradation submodel was added to the transport model to describe the biodegradation. Finally, a more realistic formulation of the degradation processes at the Vejen landfill will be outlined.

PRESENTATION OF VEJEN LANDFILL

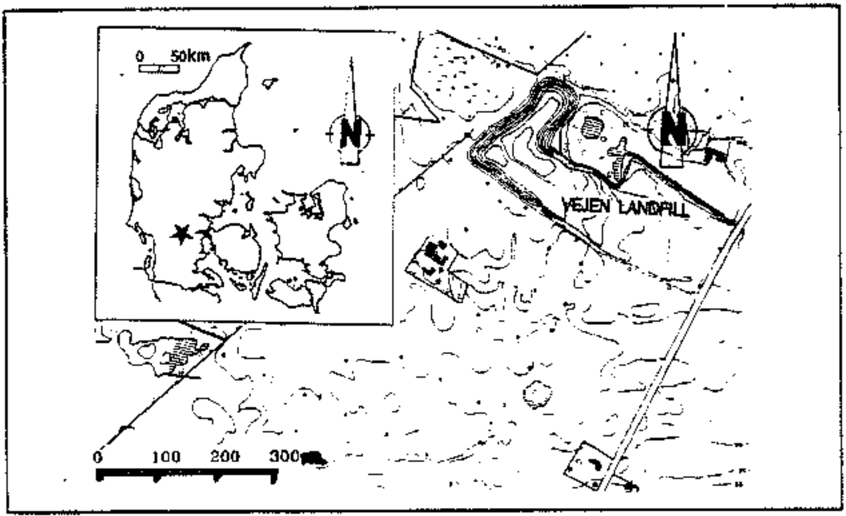
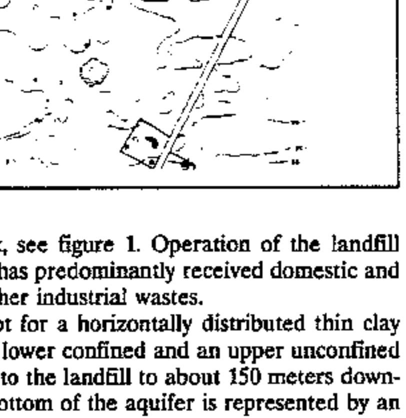


Figure 1: *Vejen landfill in Denmark*

Vejen landfill is located in Jutland, Denmark, see figure 1. Operation of the landfill began in 1962 and ended in 1980. The landfill has predominantly received domestic and construction wastes, but also pesticides and other industrial wastes.

The sand aquifer is fairly homogeneous except for a horizontally distributed thin clay layer, which divides parts of the aquifer into a lower confined and an upper unconfined aquifer. The clay layer extends from upstream to the landfill to about 150 meters downstream to the landfill where it vanishes. The bottom of the aquifer is represented by an impermeable clay layer, located app. 20 meters below the landfill and 10 meters below the soil surface 400 m downgradient to the landfill. The geology is shown in Figure 2.



Figur 2: *Simplified geology in the near-field of Vejen landfill*

Eight vertical hydraulic conductivities profiles with a 0.5 m resolution were measured using slugtest series to obtain data on the horizontal and vertical distribution of hydraulic conductivity. The average hydraulic conductivity of the sand aquifer were calculated to be 40-50 m/d.

At a nearby tracer experiment, dispersivity coefficients were found to be 45 cm in the longitudinal direction and only a few millim-

etres in the transverse direction [Jensen et al., 1990]. The values were found using the same 3D model as used in this paper. Porosity was measured to 0.3 [Bjerg et al., 1991]. The average infiltration is app. 420 mm/year calculated with an unsaturated zone model on the basis of observations at a nearby meteorological station [Kjeldsen, 1991].
The location of the observation wells in the near-field of the landfill is shown on figure 3. The major groundwater flow direction is from north to south.

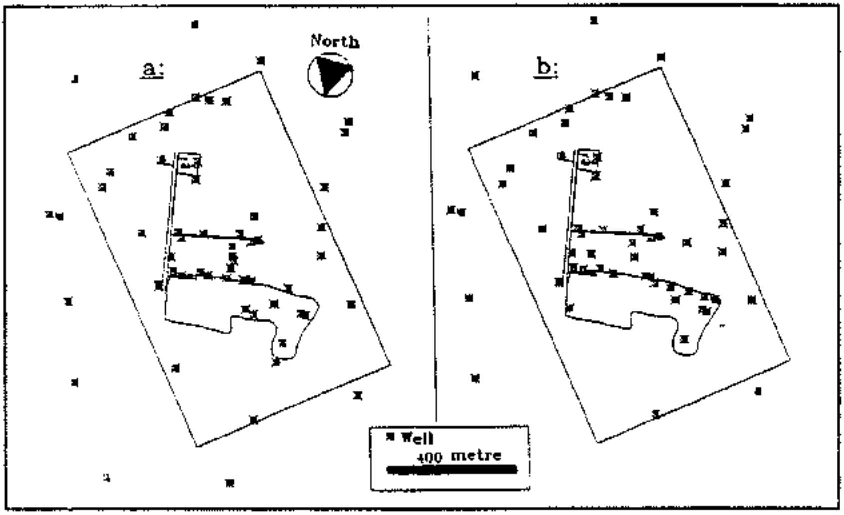


Figure 3: *Observation wells in the near-field of Vejen landfill. a: Upper aquifer, b: lower aquifer.*

Three-dimensional flow and transport model with biodegradation.

The three-dimensional model SHE was used for the flow and transport simulations. Information about SHE can be found in [DHI, 1989] and only the biochemical submodel will be described here.
Biodegradation is here stated as a sequential four-species oxidation of NVOC with oxygen, nitrate, and methanogenic biomass. NVOC is degraded in sequential order by changing electron acceptors. NVOC is degraded first with oxygen followed by nitrate, and, if there is anything left, by methanogenic biomass. The aerobic and nitrate reducing biodegradation is modelled as instantaneous processes according to the following scheme:

$$O_2 = \begin{Bmatrix} 0.0 & \text{if } S \geq O_2/F_O \\ O_2 - SF_O & \text{if } S < O_2/F_O \end{Bmatrix} \tag{1}$$

$$NO_3^- = \begin{cases} 0.0 & \text{if } S \geq NO_3^-/F_{NO} \\ O_2 - SF_O & \text{if } S < NO_3^-/F_{NO} \end{cases} \tag{2}$$

$$\Delta S = \frac{\Delta O_2}{F_O} - \frac{\Delta NO_3^-}{F_{NO}} \tag{3}$$

Where:

S	NVOC	[mg/l]
O_2	oxygen	[mg/l]
NO_3^-	nitrate	[mg/l]
F_O	mg oxygen consumption/ mg degraded NVOC = 2.67	
F_{NO}	mg nitrate consumption / mg degraded NVOC = 4.13	

F_O and F_{NO} are calculated on the basis of the following degradation equations:

$$CH_2O + O_2 \rightarrow CO_2 + H_2O$$

$$5/4\ CH_2O + NO_3^- + H^+ \rightarrow 5/4\ CO_2 + 1/2\ N_2 + 7/4\ H_2O$$

NVOC degradation by the methanogenic biomass was modelled with a Michalies-Menten substrate removal term, dependent on the substrate concentration and the growing biomass, as shown in the terms below:

$$\frac{\Delta S}{\Delta t} = -k_1 X_{Bio} \frac{S}{K_s + S} \tag{4}$$

$$\frac{\Delta X_{Bio}}{\Delta t} = Y k_1 X_{Bio} \frac{S}{K_s + S} - bX_{Bio} \tag{5}$$

Where:

Y	mg biomass growth / mg NVOC degraded	
X_{Bio}	biomass	[mg/l]
b	biomass decay rate	[day^{-1}]
k_1	maximal substrate removal rate	[day^{-1}]

To controll the biomass concentration an upper and lower limit for biomass population was incorporated. The source/sink terms for oxygen, nitrate, NVOC, and biomass were expressed explicitly and added to the existing transport model.

FLOW SIMULATIONS

A hydrogeological model was constructed on the basis of observations from app. 130 wells. The aquifer was idealized as if being composed of three formations: sand, clay, and landfill material. The hydraulic conductivities of the formations found in the slugtest analysis were used directly without calibration. On the basis of 56 and 45 observed head potentials in the upper unconfined and the lower confined part of the aquifer, respectively, the model area and boundary conditions were determined. The model area with boundary conditions is outlined in figure 4. The direction of the model area was chosen parallel to the major flow direction with upper northern and lower southern specified head boundary conditions and lateral no-flow boundary conditions. The spatial discretization was chosen to be 25 and 1 meteres in the horizontal and vertical direction, respectively. The specified head boundaries were determined on the basis of measured values. The southern down-stream specified head boundary was simulated with a stationary hydrostatic head potential distribution. At the northern upstream boundary a stationary head potential boundary with different values in the confined and unconfined aquifer was used. A small stream near the landfill was simulated using constant piezometric head values, based on measured water levels in the stream. The results of the stationary flow simulation will be presented below. [Jensen et al., 1991] have shown that there is little variation in groundwater velocity and flow direction over the years.

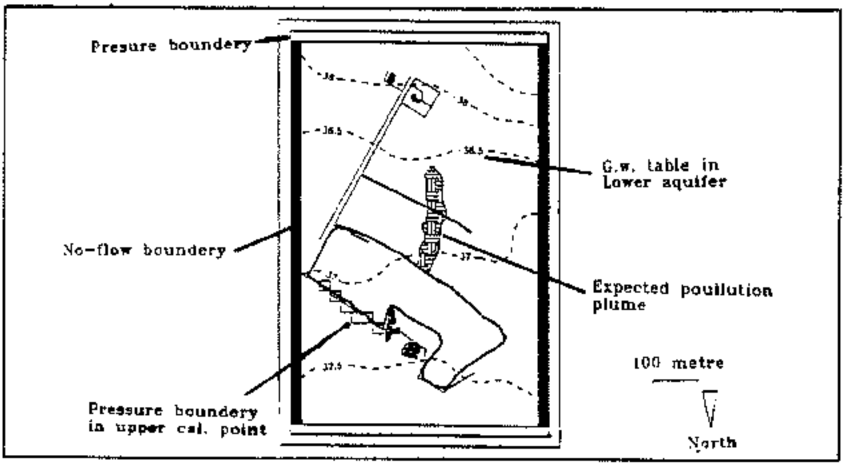


Figure 4: *Model area with boundery conditions.*

Flow simulation was carried out only fitting on the hydraulic conductivity of the landfill material. The best fit was obtained with the landfill represented as a hydrogeological formation with a low permeability. Figure 5 shows the simulated and observed piezometric head distributions for both the upper unconfined and the lower confined aquifer. In the northwestern part of the model area, there is some discrepancy between

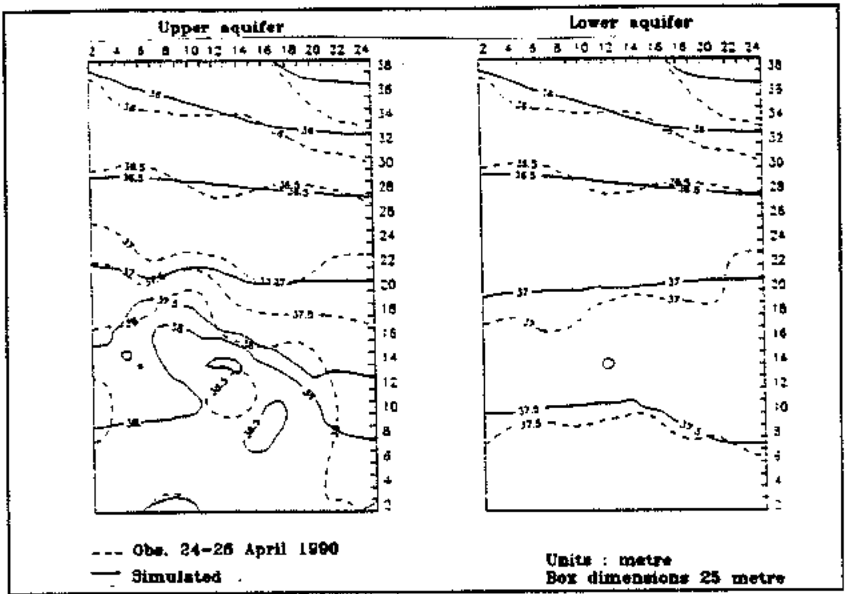


Figure 5: *Simulated versus observed head potentials in the upper and the lower aquifer*

the observed and simulated head potentials. In this area there are few observations wells, so the observed isopotential curves are poorly documented. Generally, there is a good agreement between the observed and simulated head potentials in the upper and lower aquifer. The simulated flow field and the hydraulic conductivity distribution are shown in a transect in figure 6. The slope of the aquifer bottom creates a change in pore water velocity from app. 75 m/year below the landfill to app. 200 m/year 400 m downgradient to the landfill. The predicted flow-field was then used for the nonreactive and reactive transport simulations.

CONSERVATIVE SOLUTE SIMULATION

Chloride was used as conservative species. The transport parameters used in the simulations were as determined by the tracer experiment. In the solute transport simulations the pollution source was incorporated as a stationary concentration at selected calculations points.

The aquifer solute response time, here defined as the time it takes before a change in boundary conditions has established a new stationary solute distribution concentration situation, is app. 6 years. Because the landfill is more than 20 years old, the percolate concentration in this case must be expected to have only a small decrease over the response time period, and therefor a stationary boundary condition assumption is realistic.

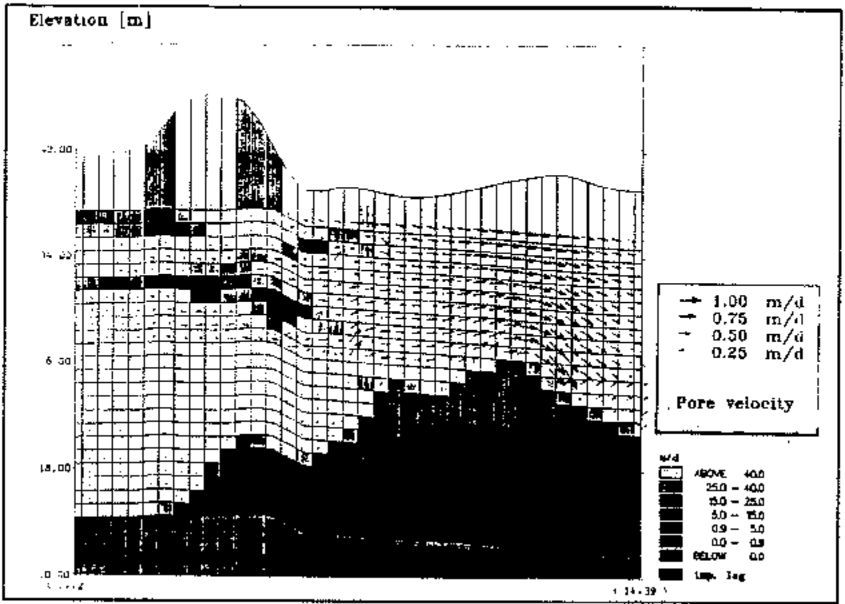


Figure 6: *Flow velocities and distributation of hydraulic conductivity in a vertical section in the flow direction.*

The chloride simulation results were very dependent on the choice of place and on the concentration of the chloride source. Simulations with a constant chloride concentration in the calculation points included in the landfill area failed to give good results compared to the measured values. In order to give satisfying simulation results the observed chloride concentration distribution on the downstream front of the landfill (Section 1), see figure 7, was used as representation of the chloride source in the simulations. With this source description the measured chloride concentration distribution, see figures 8-11, shows relatively good resemblance compared with the simulation results.

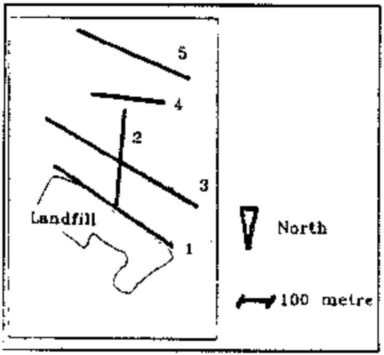


Figure 7: *Vertical sections used in the chloride simulations.*

BIODEGRADATION SIMULATIONS

Soil column experiments have indicated that the NVOC migrating from Vejen landfill can be considered unaffected by sorption [Kjeldsen, 1991]. Contrary to the chloride source which is distributed over the whole landfill, the NVOC

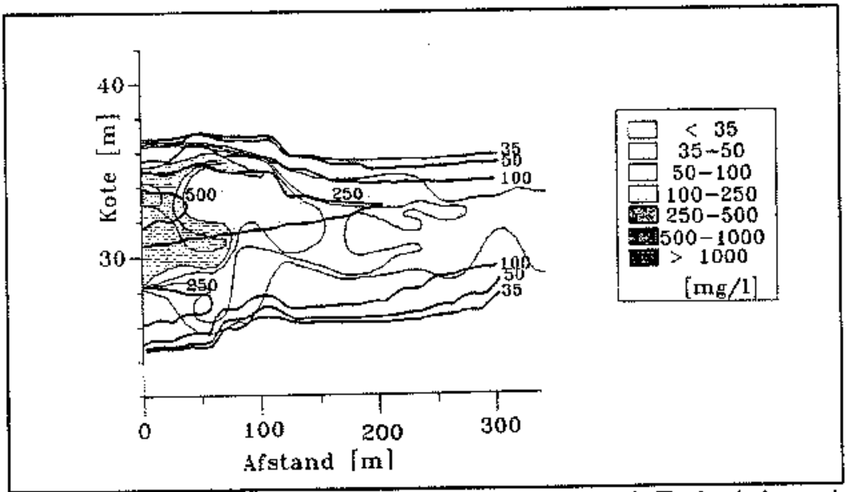


Figure 8: *Simulated and observed chloride concentrations in section 2. The hatched areas is observed values and the isolines is the simulated.*

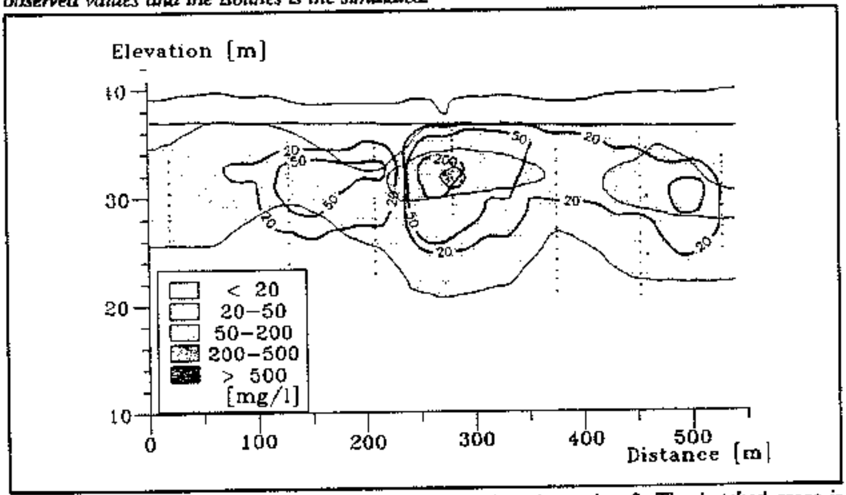


Figure 9: *Simulated and observed chloride concentrations in section 3. The hatched areas is observed values and the isolines is the simulated.*

migrates from a small well-identified location in the downstream front of the landfill. This makes it possible to decrease the model area to 100 x 400 meter in the NVOC plume simulations, and now with a 10 metre discretization in the horizontal directions and to keep the vertical discretization. The flow field in this model was calculated on the basis of the more coarse grid as boundary conditions, see figure 12. Because the NVOC source

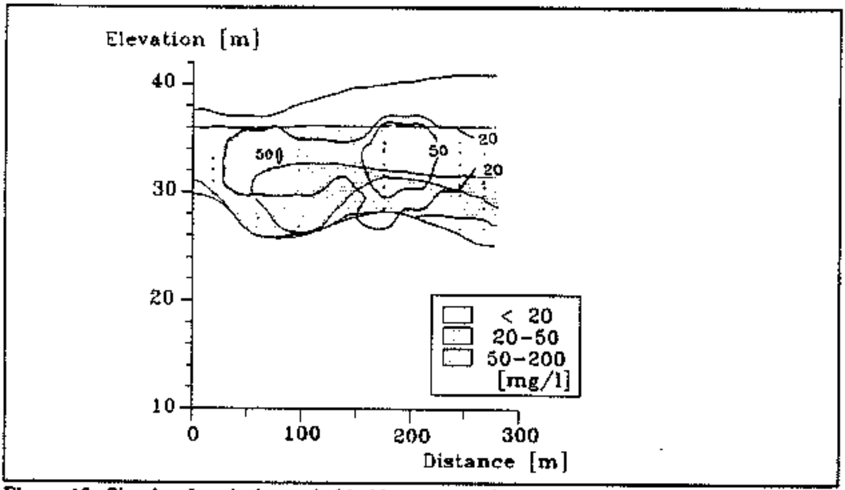


Figure 10: *Simulated and observed chloride concentrations in section 4. The hatched areas is observed values and the isolines is the simulated.*

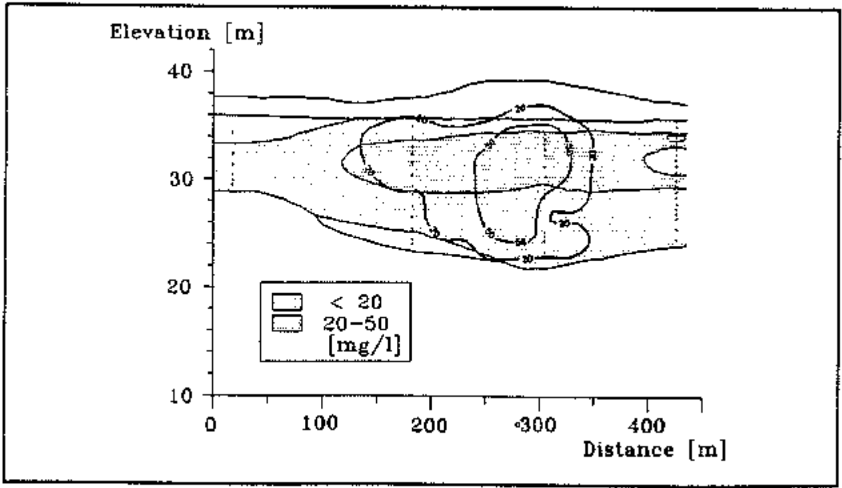


Figure 11: *Simulated and observed chloride concentrations in section 5. The hatched areas is observed values and the isolines is the simulated.*

only was detected in a 10 meter broad section of the front of the landfill, the NVOC source could be represented as a vertical profile in one vertical calculation point column with concentration values as shown in figure 13. The best fit was obtained using $k_1' = 3.0$ d^{-1}, $b = 0.0015$ d^{-1}, $Y = 0.04$, $Ks = 2000$ mg NVOC/l, max. biosize = 2.3 mg/l and min. biomass = 0.1 mg /l. Using these values a reasonably good resemblance between the

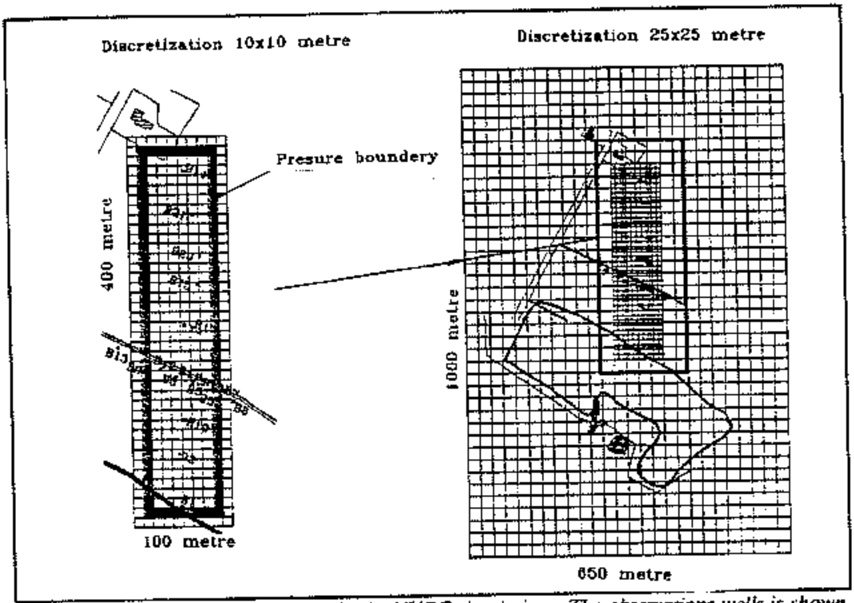


Figure 12: *The submodel area used in the NVOC simulations. The observations wells is shown.*

observed and measured values was obtained, see figure 14, showing a high retardation of NVOC through biodegradation. The decreasing NVOC concentration out throughout the aquifer was well simulated, and the direction fitted well. It has not been possible to compare the parameter values with others obtained at field-site investigations.

DISCUSSION AND CONCLUSIONS

It is the contact between oxidants and NVOC that decides NVOC mobility at Vejen landfill as well as at other landfills. The flow and chloride simulation results shown here demonstrate that, even for rather homogeneous aquifers, the flow-field and the resultant mixing can be highly complex, which in most cases will necessitate the use of a 3D-model. The amount of NVOC degraded has here been shown to be substantial, even though the actual biochemical processes at present is poorly described. Therefore, the degradation model is at present being extended, based on a degradation in sequential redox zones. The assumption is that the aquifer can be divided into zones with uniform chemical/biological properties, governed by the present dominating electron acceptor. Several biomasses the growth which is governed by one electron acceptor and NVOC will be included. Switching between redox environments will be controlled by inhibitions terms. The inhibition terms will be dependent on the electron acceptor concentrations.

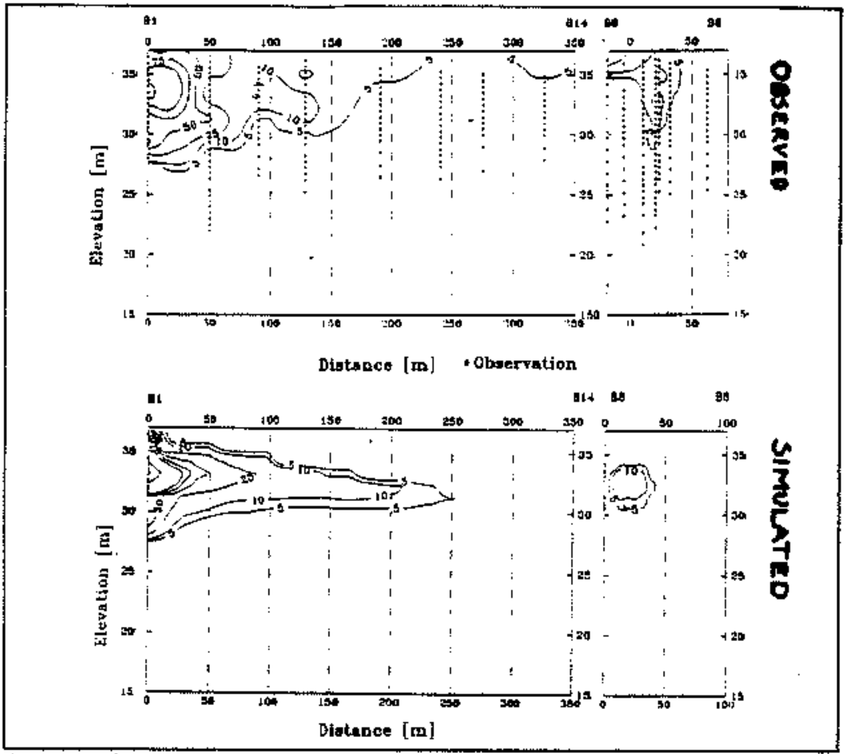


Figure 13: *Observed and simulated NVOC concentrations. The wells used in the start and end of the sections can be found in figure 12.*

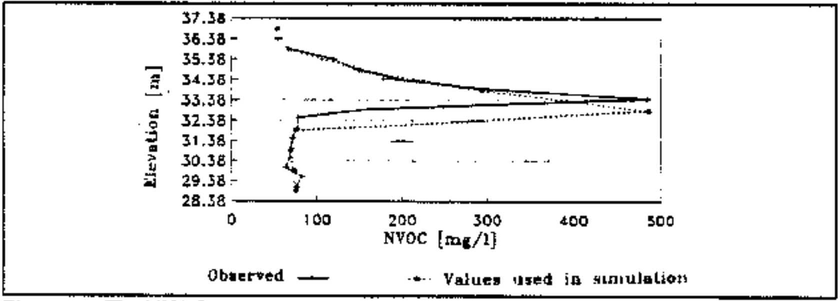


Figure 14: *The NVOC source observed in B1 and the values used in the simulations.*

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FOSFOR I AVRENNING FRA JORDEROSJONSOMRÅDER

Fosfor adsorbert til uorganiske finpartikler i fluvial sedimenttransport

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NVE, Oslo

ABSTRACT

This paper presents results from field studies in small catchments in the Eastern part of Norway during a year. The main object of the study was to deduce conditions of processes, intensity and quantity of phosphorus adsorbed to clay- and siltparticles in fluvial sediment transport from soil erosion areas. Hydrochemical analyses especially concerning phosphorus were given high priority.

Atumn precipitiation on ploughed agriculture areas gave the highest concentration of phosphorus and sediment transport. The early snowmelting period in spring gave small amount of sediment transport. During the last period of snowmelting with moisture soil on frozen earth some transport of clayparticles and phosphorus into the small rivers were observed.

1. INNLEDNING

1.1 Formål

Hensikten med de feltstudier og det analysearbeidet som ble utført for noen år siden, var å se nærmere på erosjons- og hydrokjemiske prosesser i bakkeplanerte jordbruksområder. Hovedvekten ble lagt på å utlede prosessbetingelser, intensitet og mengde av fosfor adsorbert til leir- og siltpartikler i fluvial sedimenttransport. Relasjoner mellom fosfor og aktuelle hydrokjemiske parametere vil bli belyst nedenfor.

1.2 Bakgrunn

1.2.1 Valg av studieobjekt

Et lite og oversiktelig nedbørfelt i Frogner på Romerike ble valgt til studieområde med referanser til større nærliggende felt. Hovedområdet ligger innenfor egen og nærmeste nabos eiendommer. Godt kjennskap til området også fra tiden før bakkeplaneringene startet, og mulighet for nærmest kontinuerlig overvåkning under observasjonsperioden, var noe av bakgrunnen for valget av dette studieområdet.

I denne delen av Norge har det vært utført meget omfattende planeringsarbeider i ravinerte leirområder under marin grense.

Fig. 1 viser den geografiske plasseringen av målestasjonen ved Melvold i Leiravassdraget. Prøvetakingsstasjonene i referansefeltene er også avmerket på figuren.

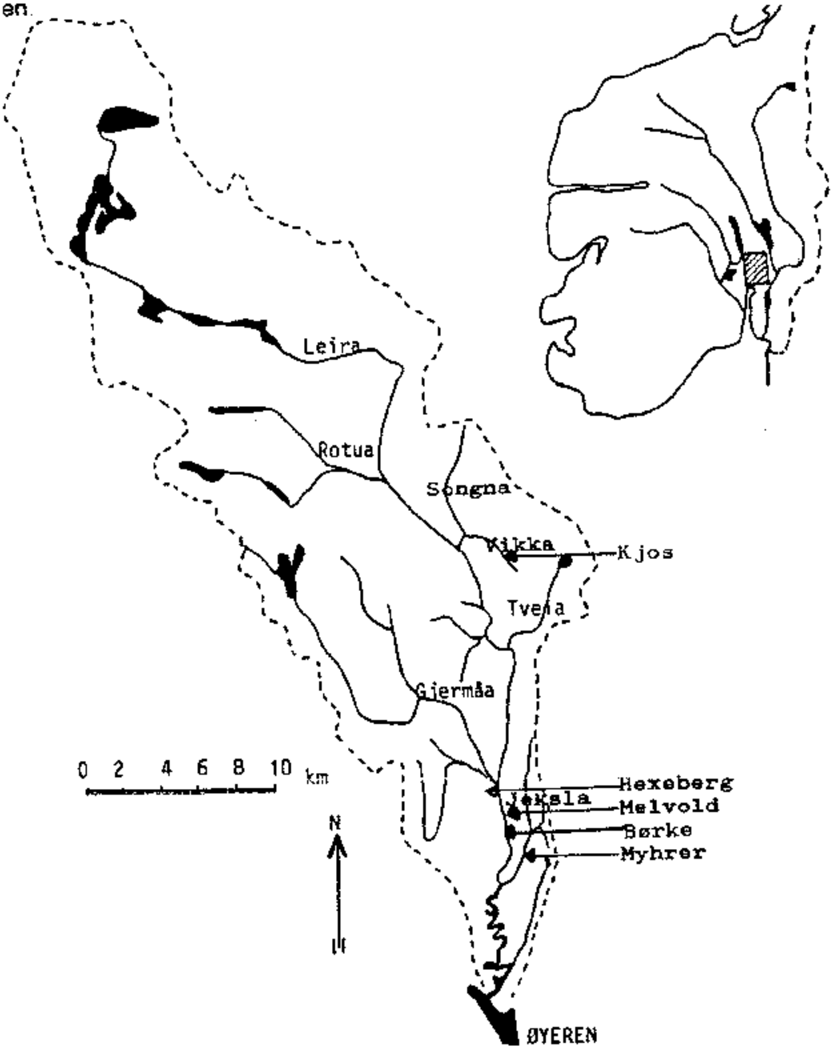

Fig. 1. Leiravassdraget på Romerike. Prøvetakingsstasjonene er avmerket.

1.2.2 Litt om hvordan bakkeplanering ble miljøproblem

Det ble ikke fokusert på jorderosjon som en kilde til forurensning fra landbruket, da planeringene av de ravinerte leirområdene på Romerike startet for noen tiår siden. En viktig årsak til at bakkeplaneringen startet var behovet for strukturrasjonalisering i landbruket med omlegging fra tungvinte og arbeidskrevende prosesser til mer mekaniske driftsmåter. Litt forenklet kan man si at det ble gitt gunstige økonomiske rammevilkår for omlegging av driften fra husdyrhold til korndrift. Det var først etter at det meste av de områdene som lå best til rette for bakkeplanering var omdannet til lettdrevne korndyrkingsarealer at fokuseringen på konsekvensene for miljøet startet, og problemstillingen kom på dagsorden.

Det siste tiåret har søkelyset i stadig økende grad blitt rettet mot Romeriksbøndene som er blitt fremstilt som noen store miljøsyndere. Det var derfor gledelig for meg som også er Romeriksbonde, da jeg nylig kunne lese i et vel anerkjent landbrukstidskrift (Norsk Landbruk nr 2/92) at Romeriksbøndene er bedre enn sitt rykte og forurenser mindre enn tidligere antatt. Dette kom som konklusjon på en del-rapport fra prosjektet: Forurensning som følge av leirerosjon og betydningen av erosjonsforebyggende tiltak (Bogen og Sandersen, 1991)

1.2.3 Litt om tiltak for å redusere jorderosjon

I de senere årene har forurensningsproblematikken i landbrukssammenheng stadig vært i fokus både hos forskere, miljøvernere, politikere, myndigheter og bøndene selv. Et resultat av samarbeide mellom forskningsinstitusjoner, miljø- og landbruksmyndigheter m. f., er at det har blitt satt igang en del prosjekter og tiltak med formål å redusere forurensning som følge av erosjon fra leirområder.

Av tiltak fra myndighetenes side vil jeg nevne: "miljøpakker", nye forskrifter om bakkeplanering (Miljøverndepartementet, 1989), nye tekniske retningslinjer for anlegg, drift og vedlikehold av planeringsfelt (Landbruksdepartementet, 1989) og nye tilskuddsordninger m.v. Eksempelvis vil jeg nevne den nye tilskuddsordningen for endret jordbearbeiding som ble satt i funksjon for bl.a. Akershus fylke høsten 1991. Dette tiltaket gikk ut på å endre jordbearbeidingsmønsteret slik at erosjonsutsatte åpenåkerarealer enten skulle overvintre i stubb eller tilsås. Det må nevnes at oppfølgingen både fra bøndenes og myndighetenes side har vært meget bra, slik at i vinter har ca 20 % av alt åpenåkerarealet i Akershus ligget i stubb eller vært tilsådd (Fylkeslandbrukskontoret i Akershus ,1992). Det ble i utgangspunktet regnet med at dette tiltaket ville redusere erosjonsrisikoen med mer enn 50 %.

Vegetasjonsdekket på erosjonsutsatte områder langs Romeriksvassdragene har denne vinteren sansynligvis hatt en langt bedre effekt enn forventet, siden det har vært lite snø og mye bar mark med varierende grad av tele. Slike vintre vil det vanligvis gå mye materiale ut i vassdragene selv under relativt korte nedbørperioder.

2. RESULTATER OG DISKUSJON

I det følgende vil jeg presentere noen resultater fra mine studier av erosjonsprosessene og gi en oversikt over noen av resultatene fra de kjemiske analysene som ble utført i forbindelse med ett års feltarbeide i Frognerområdet på Nedre Romerike.

2.1 Erosjonsprosessene

2.1.1 Erosjonsprosesser før bakkeplanering

Før planeringen av de ravinerte leirområdene i nedbørfeltet og referansefeltene startet, foregikk det naturlige erosjonsprosesser i ravinene.

Massebevegelse i skråningene mot bekkeløpene i bunnen av ravinene er en svært vanlig prosess i silt- og leirområder. Skråningsstabiliteten reduseres med økende porevannstrykk under snøsmelting og nedbørperioder. Bevegelse av løsmassedekket nedover skråningen øker med skråningsgradienten. Løsmasseskred og bakkesig som følge av fryse- og tineprosesser eller nedbør og tørke ble observert i undersøkelsesområdet. Videre foregikk det undergraving av skråningene som førte til at jord gled eller raste ut i bekkene. Såkalt "pipings" ble også observert og i et tilfelle ble slike forekomster registrert i nærheten av områder som senere viste seg å bli problematiske for anleggsmaskinene under planeringsarbeidene, dette skyltes at leirstrukturen var på grensen til å bryte sammen.

Overflateavrenning på pløyd mark, gjennom områder med sparsomt vegetasjonsdekke, langs dyretråkk og stier kunne observeres under nedbørrike perioder og spesielt på telen mark.

2.1.2 Erosjonsprosesser etter bakkeplanering

Overflateavrenning er en viktig prosess som fjerner løsmasser etter at vegetasjonsdekket er fjernet. I to av referanseområdene ble det foretatt parallellmålinger både før, under og etter anleggsperioden. Her ble det målt relativt store materialmengder som ble transport ut i bekkene både under og umiddelbart etter anleggsperioden. Generelt kan sies at overflateavrenningen øker når vegetasjonsdekket blir fjernet og den øker med hellingsgrad og hellingslengde. Dette vil i praksis si at overflateavrenningen øker etter at det er etablert lange sammenhengende skrånende dyrkningsarealer. Overflateavrenningen går raskt på telen mark og transporterer ofte ganske mye materiale under kraftige nedbørperioder eller på slutten av snøsmeltingsperioder.

Jordas struktur og naturlige dreneringsmønster ødelegges under planeringsarbeidene og pakking på grunn av kjøring med tunge maskiner forsterker denne effekten. Etter at bakkeplaneringsområdet har stabilisert seg, blir de planerte arealene grøftet og avløpet går i lukkede systemer. For at dreneringene skal fungere etter intensjonen, må dimensjoneringen av drenskummer og avløpsrør være riktig. Det oppstår lett ny ravinedannelse ved drenskummene og utløpene av drensrørene der hvor disse er dårlig sikret mot erosjon. Eksempler på underdimensjonering og tilslamming av avløpssystemene, samt nye ravinedannelser er observert flere steder i Frognerområdet. Dersom skjæringer og fyllinger som danner avslutningene på planeringene er dårlig utformet, vil disse være spesielt utsatte for erosjon før nytt veggetasjonsdekke blir etablert.

2.2 Fosfor og andre parametere

Vannkvaliteten i vassdragene påvirkes av næringssalter, partikkelinnhold og organiske stoffer.

Til den geokjemisk aktive fraksjonen (korndiameter < 63 µm) adsorberes næringsstoffer, metaller og organiske forbindelser. Kornfordelingsanalysene viste at omtrent en tredjedel av finmaterialet hadde en korndiameter < 1 µm. Ca 20 % av finmaterialet var under 0,45µm.

2.2.1 Fosfor og suspendert materiale

Fosfor i avrenning fra bakkeplanerte jordbruksområder ble studert i relasjon til utvalgte parametere med referanse til udyrkede og ikke-planerte områder.

Ut fra analyser utført med filtere som hadde en porevidde på 0,45 µm antar jeg at en større del av fosforet var partikulært bundet enn de resultater som analysetallene viste. Sedimenttransporttallene er nok også av samme grunn litt for lave (filter-porevidde 1µm).

Konsentrasjonsvariasjonene var store i løpet av det året undersøkelsen pågikk. Under høstflommen ble de høyeste konsentrasjonene av både suspendert materiale og totalt fosfor målt, mens under vårflommen var konsentrasjonene relativt lave. På slutten av vårflommen og under snøsmeltingsperioder i løpet av vinteren økte konsentrasjonene mot slutten av periodene. Perioder med liten vannføring både sommer og vinter, hadde liten transport av materiale og fosfor.

Analyseresultatene av parallellprøver fra uplanerte arealer viste lave konsentrasjoner for suspendert materiale og fosfor i forhold til prøvene fra de bakkeplanerte områdene. Prøvene fra de nyeste planeringene og der hvor det pågikk dreneringsarbeider viste som ventet, de høyeste konsentrasjonene av begge de nevnte parameterene. Konsentrasjonsvariasjonene for henholdsvis suspendert materiale og totalt fosfor er fremstilt som funksjon av tiden i figurene 2 og 3.

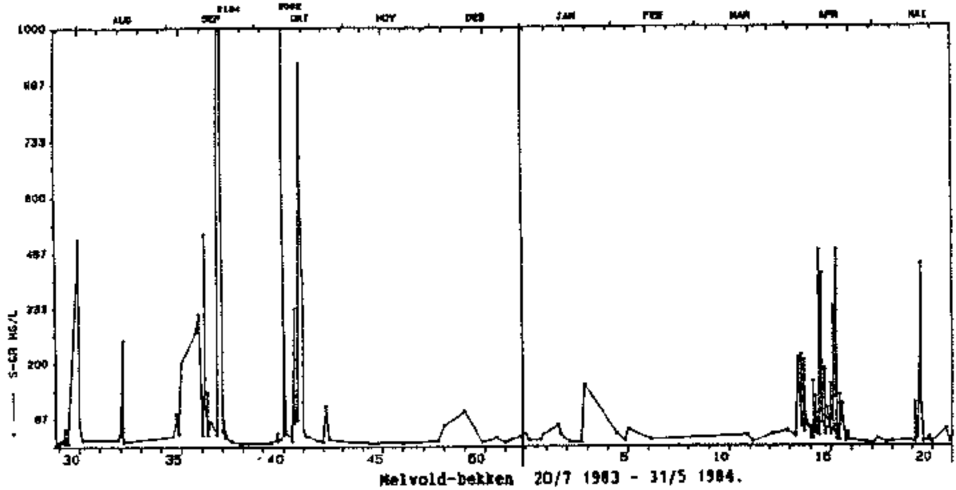

Fig. 2. Uorganisk partikulært materiale.

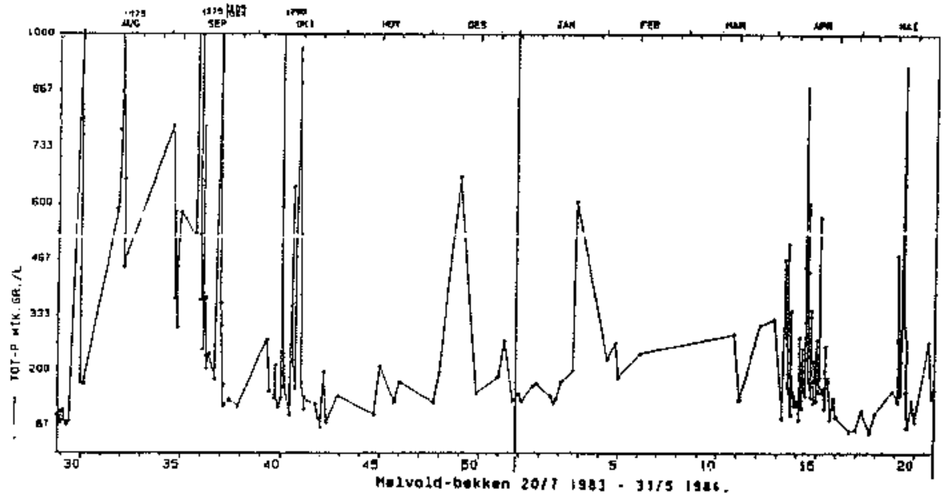

Fig. 3. Totalt fosfor.

Omlag 85 % av alt fosforet som ble transportert ut i vassdragene fra de undersøkte nedbørfeltene var partikulært bundet. I en del prøver viste analysene at nær 100 % av fosforet var partikulært bundet. Analyseresultatene for største delen av undersøkelsesperioden viste lave konsentrasjonsverdier for både løst og løst reaktivt fosfor. I drenskummer i noen av referanseområdene samlet det seg mye finmateriale som ble skyllet ut under flommene. Til dette finmaterialet var omlag 100 % av fosforet adsorbert.

2.2.2 Nitrogen

Nitrogen er et av de næringsstoffene som har størst betydning i avrenningen fra landbruksområder. Det ble utført et begrenset antall analyser på totalt nitrogen og disse viste høye konsentrasjoner, gjennomsnittet lå på 6,7 mg/l, spesielt høye verdier (12,4 mg/l) ble målt under høstflommen etter innhøstning og spredning av husdyrgjødsel.

2.2.3 Jern

Under perioder med relativt lav vannføring både sommer og vinter ble jernforbindelser utfelt i bekken. Fosfater og andre løste stoffer adsorberes lett til nyutfelt $Fe(OH)_3$. Høyeste og laveste målte jernkonsentrasjonsverdi var på henholdsvis 12,1 og 1,7 mg/l.

2.2.4 pH, konduktivitet og ionebalanse

pH og konduktivitet økte under perioder med lav vannføring. Regn og smeltevann, førte til fortynning og følgelig reduserte verdier for disse parameterene.

pH-verdien lå mestepaten av perioden relativt stabilt omkring nøytralitetspunktet.

Konduktiviteten varierte fra 7,4 til 111 mS/m, under snøsmeltingsperioden ble verdien redusert med 100 mS/m i løpet av 8 dager fra begynnelsen til maksimum av snøsmelteflommen.

Sesongmessige variasjoner for Ca, Na og Mg fulgte stort sett konduktivitetens variasjonsmønster.

Alkalitetsverdiene indikerte et høyt innhold av kalsiumkarbonat/bikarbonat og at vannet hadde en god bufferkapasitet ovenfor tilførsel av sure stoffer.

3. SLUTTBEMERKNINGER

Undersøkelsene viste at en høyere andel av fosforet var partikulært bundet enn tidligere antatt.

Konsentrasjon av suspensjonsmateriale og de stoffmengder som transporteres ut i vassdragene vil variere over året og fra år til år, dette vil være avhengig av bl. a. tilgjengelig erosjonsmateriale, nedbør og temperatur.

Selv om en mindre andel av sedimenttransporten enn tidligere antatt kommer fra de bearbeidede silt- og leirjordsområdene, så vil erosjonsforebyggende tiltak få relativt stor betydning for transport av sedimentært materiale og fosfor ut i vassdragene.

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OVERVÅGNING AF TRANSPORTEN AF NÆRINGSSTOF I DANSKE VANDLØB

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ABSTRACT

According to the Danish "Action Plan for the Aquatic Environment" the County Councils in Denmark has to establish monitoring stations for monitoring nutrient runoff to the coastal waters.

The established monitoring stations are covering about 50 percent of the land areas. Based on the results from the monitoring stations the total nutrient runoff from land is calculated.

The certainty of the total nutrient runoff includes elements from

1) The degree of area covering
2) Sampling frequency and calculation methods
3) Measurement of the freshwater runoff
4) Water sampling methods
5) Variation through night and day
6) Certainty of the nutrient analysis

Funen County Council has analysed the influence of the water sampling methods, the variation through night and day etc. Recommendations for monitoring nutrient runoff are given.

INDLEDNING

Det Danske Folketing vedtog i 1987 at iværksætte en handlingsplan for vand-miljøet (Miljøstyrelsen,1989) med det formål at reducere den samlede udledning af kvælstof med 50% og den samlede udledning af fosfor med 80%. De samlede investeringer i forureningsbegrænsende foranstaltninger udgør ca. 13 milliarder kr. I henhold til planen er etableret et landsdækkende overvågningsprogram af vandmiljøet med henblik på at eftervise effekten af investeringerne i vandmiljøet. Overvågningsprogrammet omfatter blandt andet monitering af udledning af næringsstoffer via vandløbene. Udgifterne til vandmiljøplanens overvågningsprogram beløber sig til ca. 110 millioner kr. årligt, svarende til en fordobling af den tidligere udgift til overvågning. Af midlerne til overvågningsprogrammet er ca. 17 millioner kr. årligt afsat til overvågning af udledning af næringsstoffer via vandløb.

OVERVÅGNING FØR VAND/MILJØPLANEN

Moniteringsprogram

Før vand/miljøplanens ikrafttræden var de danske amter i henhold til miljøloven også forpligtede til at overvåge blandt andet udledningen af næringsstoffer via vandløbene. Fyns Amt havde i 1985 således 33 stationer, hvor blandt andet næringsstofafstrømningen blev registreret. Vandføringen blev registreret kontinuerligt ved de 33 stationer.

Der blev udtaget prøver 12 gange årligt til bestemmelse af blandt andet indholdet af næringsstoffer. På baggrund heraf blev den årlige næringsstofafstrømning forbi den enkelte station beregnet ved hjælp af den såkaldte trapezmetode.

Ud fra næringsstofafstrømningen beregnet på 20 vandløbsstationer kan den samlede næringsstofafstrømning fra hele Fyn beregnes.

Omkostninger

Omkostningerne ved tilvejebringelse af et mål for næringsstofafstrømningen fra Fyn under den tidligere monitering kan opgøres således i 1992-priser inkl. moms:

12 årlige prøvetagninger ved 20 stationer	450.000 kr.

OVERVÅGNINGEN I HENHOLD TIL VAND/MILJØPLANEN

Moniteringsprogram

I henhold til vand/miljøplanen skal amterne foretage overvågning af blandt andet næringsstofafstrømningen.

Fyns Amt havde i 1991 således 40 stationer til registrering af næringsstofafstrømningen. Afstrømningen måles ved alle 40 stationer kontinuerligt.

I henhold til vand/miljøplanens overvågningsprogram skal der udtages 26 årlige prøver ved hver station til bestemmelse af blandt andet næringsstoffer.

På baggrund heraf kan den samlede næringsstofafstrømning forbi den enkelte station beregnes. Ved beregningen af den årlige stofafstrømning forbi den enkelte station anbefales anvendt den såkaldte lineær interpolationsmetode. (Danmarks Miljøundersøgelser,1990)

Ud fra kvælstofafstrømningen på 20 stationer kan den samlede næringsstofafstrømning fra Fyn beregnes.

Omkostninger

Omkostningerne ved tilvejebringelse af næringsstofafstrømningen fra Fyn kan opgøres således i 1992 priser incl. moms:

Kontinuerlig vandføringsregistrering 20 stationer	250.000 kr.
26 årlige prøvetagninger ved 20 stationer	950.000 kr.
	1.200.000 kr.

SIKKERHED VED TIDLIGERE OG NUVÆRENDE MONITERING

På baggrund af undersøgelser foretaget af Danmarks Miljøundersøgelser (Danmarks Miljøundersøgelser,1990) og Fyns Amt (Hedeselskabet,1987) er det fastslået, at sikkerheden på stoftransportbestemmelserne øges ganske betydeligt dels ved at ændre beregningsmetoden fra trapezmetoden til lineær interplationsmetoden og dels ved at øge prøvetagningsfrekvensen fra 12 til 26.

I tabel 1 og 2 er angivet et eksempel på, hvorledes sikkerheden i bestemmelsen af årstransporten af kvælstof og fosfor i Gelbæk øges med ændrede beregningsmetoder og prøvetagningsfrekvens. Opgørelserne i tabel 1 og 2 er baseret på intensive undersøgelser i Gelbæk i 1988/89. (Danmarks Miljøundersøgelser,1990)

Tabel 1: Root mean square error (RMS) i % for årstransporten af total-N i Gelbæk for året 1988/89 afhængig af prøvetagningsfrekvens og beregningsmetode.

Prøvetagninger pr. år	Beregningsmetode	
	Trapez	Lineær interpolation
12	60%	14%
26	31%	5%

Tabel 2: Root mean square error (RMS) i % for årstransporten af total-P i Gelbæk for året 1988/89 afhængig af prøvetagningsfrekvens og beregningsmetode.

Prøvetagninger pr. år	Beregningsmetode	
	Trapez	Lineær interpolation
12	108	44
26	73	38

Det fremgår af tabel 1 og 2, at sikkerheden øges betydeligt ved ændrede beregningsmetoder, mest for kvælstof, hvor sikkerheden forbedres med en faktor 4. Det fremgår endvidere, at sikkerheden også øges med forøget prøvetagningsfrekvens, mest for kvælstof, hvor sikkerheden øges med en faktor 3.

Ud fra tilsvarende analyser af data fra Odense å, Kratholm, må det vurderes, at sikkerheden er større end angivet i tabel 1 og 2 for stationer, der har et større opland, både i relation til beregningsmetode og frekvens.

Omlægningen af moniteringsprogrammet for overvågning af stofafstrømningen i vandløbene har på Fyn betydet en merudgift på 750.000 kr. Gevinsten herved er blandt andet en forøgelse af sikkerheden med en faktor 12 for så vidt angår årstransporten af kvælstof og med en faktor 3 for så vidt angår fosfor. Sikkerheden øges formentlig tilsvarende for de øvrige parametre, der omfattes af analyseprogrammet.

SIKKERHEDEN PÅ ENKELTELEMENTER I DEN NUVÆRENDE OVERVÅGNING.

De basale operationer i overvågning af næringsstofafstrømning er vandføringsmåling, prøvetagning, analysering og beregning.

Vandføringsmåling.

Døgnmiddelvandføringen, der indgår som et vigtigt element i beregningen af stofafstrømningen, beregnes normalt ud fra en række enkeltmålinger af vandføringen med hydrometrisk vinge.

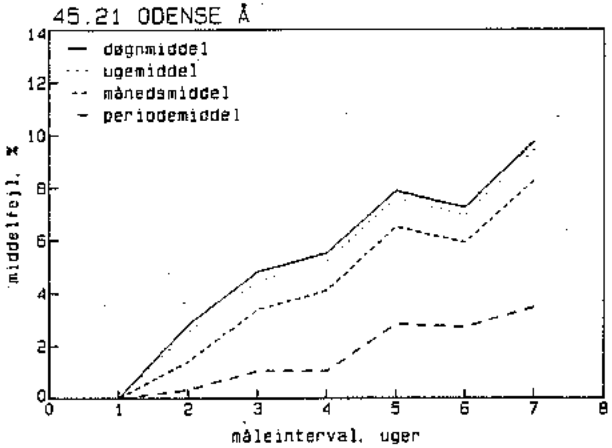


Fig. 1. Middelfejl i % som funktion af måleintervallet for målinger med hydrometrisk vinge i uger.

Antallet af årlige enkeltmålinger er af betydning for den sikkerhed med hvilken den daglige middelvandføring kan bestemmes.

Nye undersøgelser (Hedeselskabet,1991) se fig. 1 viser, at middelfejlen på de daglige vandføringer er ca. 7% beregnet på baggrund af 12 årlige målinger med hydrometrisk vinge og at middelfejlen tilsvarende er ca. 3% ved 26 målinger med hydrometrisk vinge.

Analysesikkerhed.

Koncentrationen af næringsstoffer ved de enkelte prøvetagninger indgår som et vigtigt element i beregningen af stofafstrømningen.

Der er derfor af interesse med hvilken sikkerhed laboratoriet kan bestemme disse koncentrationer. Nye interkalibreringer (Vandkvalitetsinstituttet,1990) viser, som det fremgår af tabel 3, at variationskoefficienten CV, for relevante størrelser ($C_N > 2$ mg/l, $C_P > 0.035$) af total-kvælstof og total fosfor varierer mellem 2 og 7%, henholdsvis 1 og 6%, hvis man holder sig til samme laboratorium. Variationskoefficienten er betydeligt større laboratorierne imellem. Variationskoefficienten defineres som standardafvigelse/medianværdi x 100.

Tabel 3: Variationskoefficienter (CV) i % for analyse sikkerheden på total-N og total-P. (CV_W = variationskoefficienten inden for det enkelte laboratorium, CV_B = variationskoefficienten mellem laboratorierne).

	Variationskoefficient	
	CV_W	CV_B
Total-N	2-7%	5-34%
Total-P	1-6%	3-15%

Arealdækning

I en situation, hvor stofafstrømningen fra et større landområde som fx Fyn (areal 3500 km^2) skal beregnes, er det af betydning, hvilke stationer, der udvælges i relation til hvilket areal de udvalgte stationer dækker.

I fig. 2 er angivet den procentmæssige dækning af Fyns samlede areal som funktion af antallet af målestationer. Den første station dækker det største areal, den anden det næststørste areal og så videre.

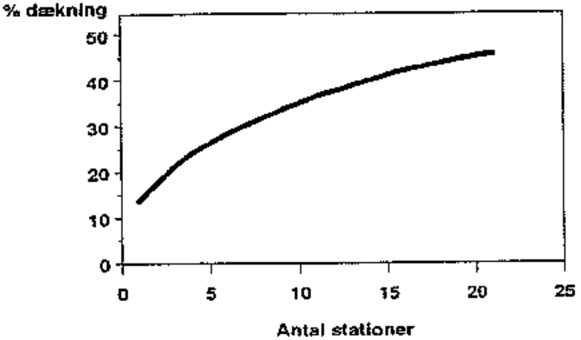


Fig. 2. Arealdækning på Fyn som funktion af antallet af målestationer.

Det fremgår heraf, at man ved monitering på en station i Odense å, Kratholm, er i stand til at dække ca. 14% af Fyns samlede areal. Den næststørste station dækker kun ca. 4% af Fyns samlede areal. Den nuværende monitering dækker ca. 46% af Fyns samlede areal.

Et interessant spørgsmål er selvfølgelig, hvorvidt det er muligt ud fra en bestemt målestation (fx den med størst arealdækning) at ekstrapolere resultaterne for de øvrige målestationer. På grundlag af 4 års monitering er der i tabel 4 og 5 for kvælstof og fosfor anført forholdet mellem en ekstrapoleret værdi og den faktiske beregnede værdi for de aktuelt beregnede oplande. Ekstrapoleringerne er sket ud fra den største målestation på Fyn, Odense å, Kratholm (486 km^2). For hver beregning er standardafvigelsen anført.

Tabel 4: Årsafstrømning af total-N. Forholdet mellem ekstrapoleret værdi og beregnet værdi for årene 87-90 med tilhørende standardafgivelse. Ekstrapoleringerne er sket ud fra målestationen ved Kratholm (486 km^2).

	Hele Fyn	Storebælts-oplandet	Helnæs bugt
Areal km^2	3500	300	90
87	0,942	0,809	0,959
88	1,112	1,076	1,323
89	1,181	1,110	1,316
90	1,245	1,037	1,356
s	14%	10%	33%

Tabel 5: Årsafstrømning af total-P. Forholdet mellem ekstrapoleret værdi og beregnet værdi for årene 87-90 med tilhørende standardafgivelse. Ekstrapoleringerne er sket ud fra målestationen ved Kratholm (486 km^2).

	Hele Fyn	Storebælts-oplandet	Helnæs bugt
Areal km^2	3500	300	90
87	0,981	1,103	0,898
88	1,027	1,062	0,915
89	1,027	1,969	1,073
90	1,036	1,017	1,967
s	2%	4%	9%

Ud fra disse få beregninger på fynske forhold kan vurderes, at der tilsyneladende introduceres en større fejl ved ekstrapolering af små oplande end ved ekstrapolering af store oplande - og at fejlen er større for kvælstof end for fosfor. Sidstnævnte var dog også at forvente, idet punktkilderne som udgør op mod 80% af fosforafstrømningen er holdt uden for ekstrapolationen.

Når det vurderes om ekstrapolation er hensigtsmæssig bør der i betragtningerne altid indgå overvejelser om, hvad stofafstrømningerne skal anvendes til. Hvis stofafstrømningerne skal indgå i vurderinger af recipientforholdene i en fjord eller et lukket farvandsområde kan den fejl, der introduceres ved ekstrapolation således være helt uacceptabel.

- **Døgnvariation**

Såfremt prøvetagningen til bestemmelse af stofkoncentrationer foretages inden for et bestemt tidsinterval i døgnet kan introduceres en systematisk fejl.

På Fyn sker næsten al prøvetagning til bestemmelse af stofafstrømning i tidsrummet fra kl. 8 til kl. 14 på hverdage.

Orienterende undersøgelser (Vandkvalitetsinstituttet, In press) i Odense å nedstrøms et stort renseanlæg (Ejby Mølle, 270.000 p.e.) viser betydelig variation hen over døgnet af såvel total-N som total-P.

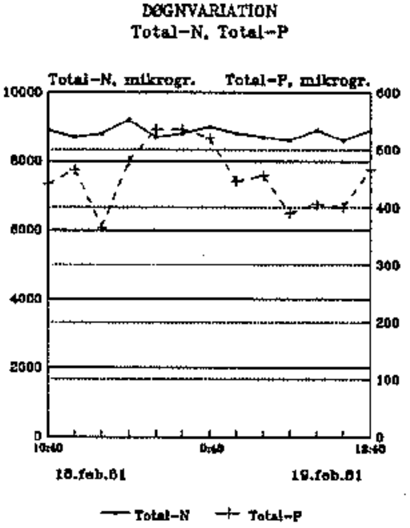


Fig. 3.
Døgnvariation af total-N og total-P i Odense å nedstrøms Ejby Mølle renseanlæg, 18. og 19. feb. 81.

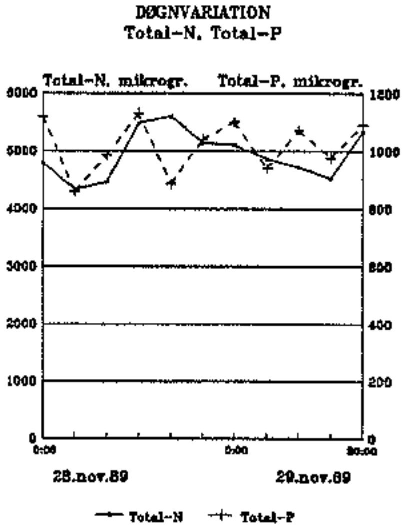


Fig. 4.
Døgnvariation af total-N og total-P i Odense å nedstrøms Ejby Mølle renseanlæg, 28. og 29. nov. 89.

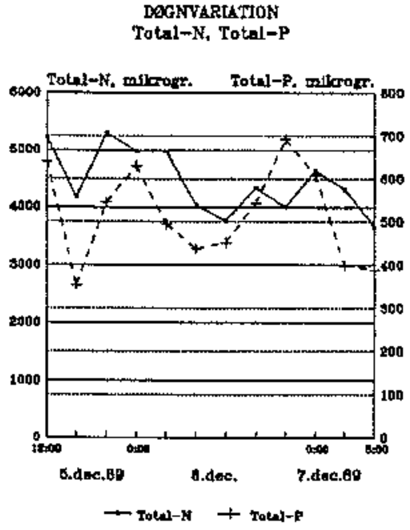


Fig. 5.
Døgnvariation af total-N og total-P i Odense å nedstrøms Ejby Mølle renseanlæg, 5., 6. og 7. dec. 89.

Undersøges hvor meget middelværdien af målingerne inden for det normale prøvetagningstidsrum fra kl. 8 til kl. 14 på hverdage, afviger fra middelværdien for perioden findes ud fra disse få betragtninger afvigelser som anført i tabel 6.

Tabel 6: Afvigelse af middelværdier på analyser af prøvetagninger udført i tidsrummmet fra kl.8 til kl 14 i forhold til middelværdien for hele perioden.

	18.-19.feb. 81	28.-29.nov. 89	5.6.7.dec. 89
Total-N	0%	-7%	-6%
Total-P	-4%	+4%	-10%

Det fremgår af disse få undersøgelser, at der kan introduceres en fejl på op til 10% på grund af døgnvariationer, såfremt en målestation placeres nedstrøms et stort renseanlæg.

Ud fra en umiddelbar betragtning skulle man tro, at fejlen ville være størst på total-P, som i hovedsagen stammer fra renseanlægget. Dette fremgår ikke umiddelbart af nærværende få undersøgelser.

Ud fra en umiddelbar betragtning skulle man endvidere antage, at den konstaterede fejl ville være systematisk. Dette fremgår imidlertid ikke umiddelbart, selvom der synes at være en tendens til underestimering.

Fejl af denne type vil normalt være afhængig af de lokale forhold.

- Prøvetagningsmetodik

Normalt foretages prøvetagningen til bestemmelse af stofkoncentrationen i overfladen. For så vidt angår total-fosfor vil en del af det tilstedeværende fosfor altid forefindes som partikulært fosfor. Afhængig af hastighedsfordelingen i vandløbets tværsnit vil det partikulære fosfor næppe altid være homogent fordelt over tværsnittet.

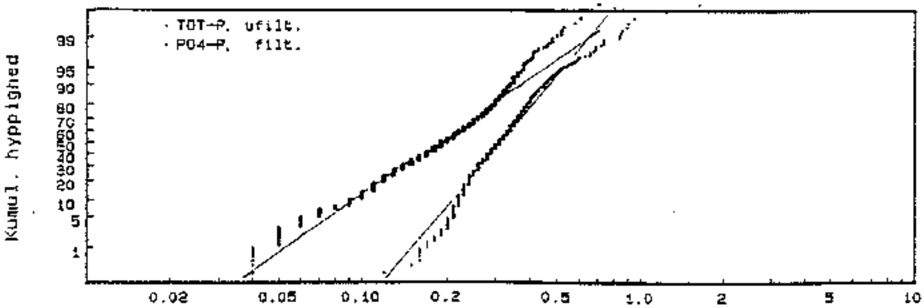


Fig. 6. Fraktilanalysediagram for fosforforbindelser, Odense å, Kratholm, 1979-89.

Analyser af fosfordata i Odense å ved Kratholm-stationen viser for perioden 1979-89, viser at ca. 60% af total-fosforen er uorganisk og ca. 40% af total-fosforen kan tilskrives øvrige fosforfraktioner, herunder partikulært bundet fosfor. Se fig. 6.

Orienterende undersøgelser (Vandkvalitetsinstituttet, In press) er gennemført i Odense å ved Kratholm med prøvetagning i forskellig dybde til bestemmelse af koncentrationen af total-fosfor. Der er udtaget prøver i 3 dybder, 10 cm under overfladen, 42 cm over bunden og 13 cm over bunden. I fig. 7 er vist prøvetageropstillingen.

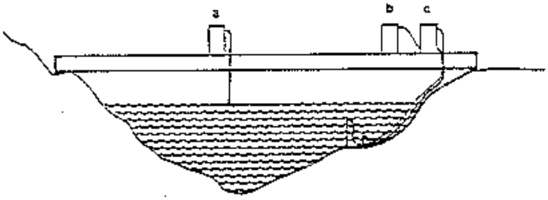


Fig. 7. Prøvetageropstilling i Odense å ved Kratholm.

I fig. 8 er vist resultaterne af prøvetagningen. En nærmere analyse af det spinkle datagrundlag viser, at koncentrationen af total-fosfor i de undersøgte tilfælde i gennemsnit underestimeres med ca. 15% ved prøvetagning i overfladen til den gennemsnitlige koncentration i vandfasen.

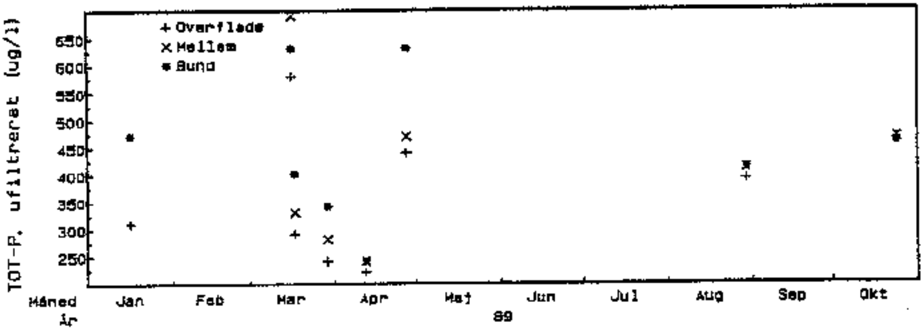


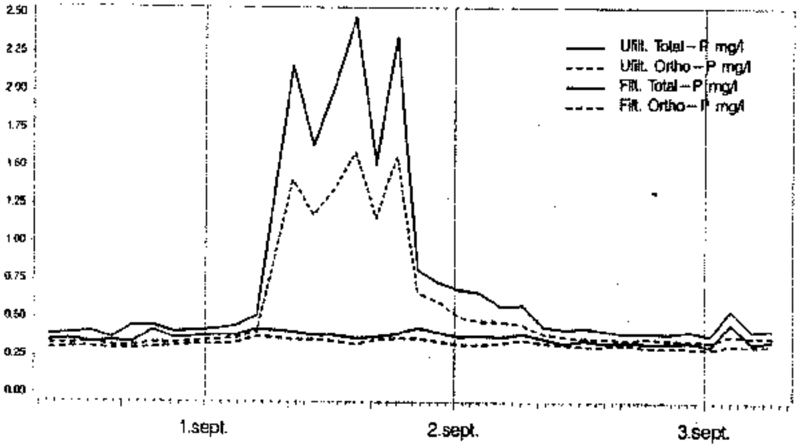
Fig. 8. Analyseresultater fra prøvetagning ved forskellig dybde i Odense å, Kratholm.

- Grødeskæring

Når der skæres grøde i et vandløb må antages, at der ophvirvles sedimenterede fosforforbindelser med en periodisk stigning i koncentration af total-fosfor til følge.

Orienterende undersøgelser i Odense å ved Kratholm har vist, at sådanne antagelser er korrekte, idet koncentrationen af total-P forhøjes med en faktor 6 under grødeskæringen.

Undersøgelsens resultater fremgår af fig. 9. Prøverne blev udtaget i overfladen, jf. sædvanlig praksis.



Figur 9. Forøgede fosforkoncentrationer i Odense å, Kratholm som følge af grødeskæring den 31.aug.- 3.sep. 88.

KONKLUSIONER

Ved tilrettelæggelse af et moniteringsprogram for stofafstrømning må følgende forhold tages i betragtning:

- der bør vælges de beregningsmetoder, der giver størst sikkerhed på det samlede resultat
- valg af prøvetagningsfrekvens bør nøje overvejes. I overvejelserne bør indgå sikkerheden på resultatet og omkostningerne
- arealdækning bør overvejes. I overvejelserne bør indgå sikkerheden på resultatet og omkostningerne. Hensynet til undersøgelsens formål og de lokale recipienter skal ligeledes vurderes

- der bør ved undersøgelser, hvor der skal vurderes udviklingstendenser benyttes samme laboratorium for hele tidserien

- prøvetagningsstationer bør af hensyn til evt. døgnvariation ikke lægges neden for et renseanlæg. Stationen bør i stedet placeres oven for og udledningerne fra renseanlægget lægges til - alternativt bør anvendes tids- eller flowproportional prøvetagning

- prøvetagningsmetodikken bør overvejes nøje

- prøvetagningsprogrammet bør tilrettelægges under hensyntagen til øvrige aktiviteter i vandløbet som fx grødeskæring

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STUDIES OF SOME ACID SPRINGS IN TILL, LOFSDALEN, SWEDEN

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ABSTRACT

The springs are situated in an area, which is very sensitive to acidification: cold-humid climate, acid rocks, stony sandy till, podzols and coniferous forest. The acid load is however, only one third of that in southwestern Sweden. Three springs in till and one brook were studied 1986-1990 by measuring runoff and water sampling. The discharge of the springs is small but fluctuates from 0.02-5 l/s. The runoff of the brook is of the same order as the largest spring but with a high peak during snow melt. The chemistry of the water in the springs and the brook is normally characterized of low ion concentrations, very low alkalinity and low pH. There are some pH drops down to or just below 5 in the springs, and still lower in the brook, simultaneously with zero alkalinity and fairly high concentrations of aluminium, iron, manganese and sulphate. The conclusion is that the "normal" groundwater is diluted by meltwater or rainwater during such "drops", the peak concentration of aluminium and manganese is a dissolution of metal precipitation in the soil profile and the high concentration of iron is mobilized from organic soils with anaerobic conditions.

INTRODUCTION

The objective was to study the fluctuations in discharge and water chemistry of some acid springs in till, especially during intensive snow melt and heavy rains as well as the influence of groundwater on the runoff and chemistry of a downstream brook. The study was a small subproject in the Swedish Integrated Groundwater Acidification Project (Knutsson et al 1990).

SITE DESCRIPTION

The springs are situated 15 km southeast of Lofsdalen close to the settlement Djursvallen (68°80'N; 13°80' E) in the southern part of the High Mountains of Sweden. The altitude of the area is between 600 and 700 m.a.m.s.l. The field research area consists of three springs with their catchments: 2.1 2.5, and 18.5 ha respectively (Fig. 1). The two smallest catchments border upon each other and one of the two springs (no 2) discharges to a peatland, from which a diffuse brook flows and then disappears downstreams in a sloping part of the peatland. The brook has a catchment area of 13.5 ha. The point, where the brook appears again, was in the beginning improperly called spring no 1. The third "spring" catchment is situated 1.5 km to the northeast on a steep slope with the peak at 705 m.a.m.s.l. and quite a

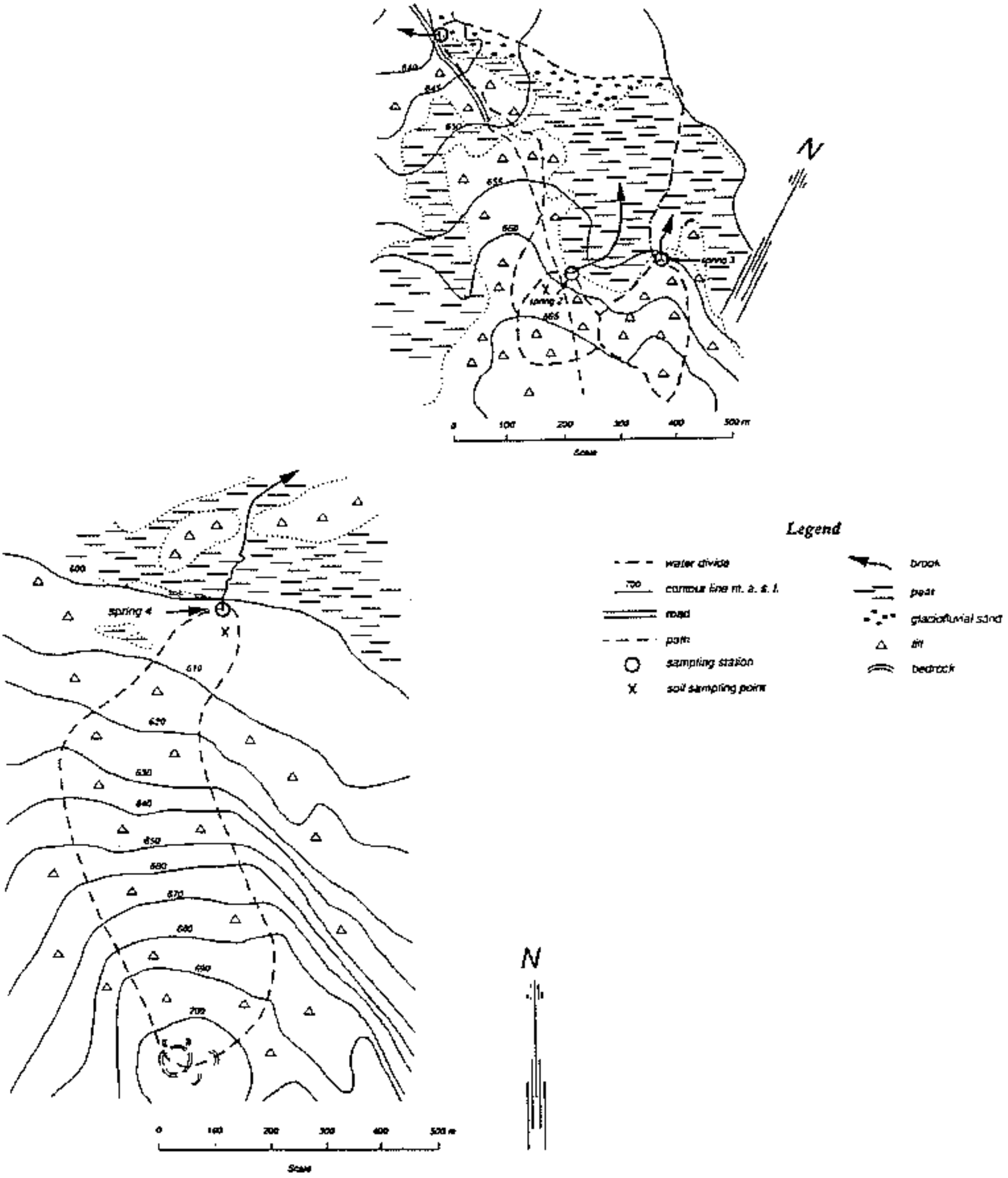


Fig. 1 Map of the catchment of spring no 2, 3 and the brook (above) in Djursvallen, Lofsdalen and the catchment of spring no 4 (below) in Djursvallen, Lofsdalen.

large spring (no 4) at the foot of the slope at 600 m.a.m.s.l. A small "peat hillock" is formed at the spring.

The climate is of cold-humid type with an annual mean temperature of +1°C (Taesler 1972) and an annual mean precipitation of 820 mm (1951-80) at the meteorological station Lofsdalen (Eriksson 1983). The annual mean precipitation during the research period (1986-90) was much higher: 915 mm at Lofsdalen and 875 mm at Djursvallen (Granat 1991). The fluctuations both from year to year (1065, 900, 883, 664 and 860 mm) as well as during the year were considerable. All figures are corrected according to Eriksson (1983). Almost half the precipitation is snow (43%, Eriksson 1983) and snow covers the land from the end of October to May (Taesler 1972), which means a heavy and mostly intensive snow melt during a couple of weeks or some days in the spring. The acid load is much less than in the southwestern part of Sweden (roughly a third of that), but very low pH-values (3.8-4.0) have been observed in precipitation originating from the southeast (Olofsson 1991). The total deposition of sulphate is calculated to 44 uEq/m² (Granat 1991, Lövblad 1991)

The bedrock within the area consists of quartzporphyry, which is a hard, acid and weathering-resistant rock. The bedrock northwest of the area is quartzite, which is still harder and still more acid and weathering-resistant than quartzporphyry. As the latest movement of the land-ice was from northwest, quartzite was tranported into the area. So the petrography of the glacial deposits is totally dominated by quartzite (49%) and quartz-porphyry (38%) which means that the buffering capacity of these deposits is very low.

The glacial deposits are dominated by stony, silty-sandy or stony, gravelly-sandy till, which covers the bedrock on the hills (very few outcrops) and forms areas of hummocky moraine. The low-lying terrain is occupied by vast peatlands with thin (roughly 1m) peat on fine-sandy glaciolacustrine sediments or till. Glaciofluvial deposits (sand and gravel) are found at the northwestern border of the research area (Fig. 1)

The soil profile is characterized by strongly developed podzols, at upslope and midslope locations as orthic-podzols with thick E- and B-horizons and at downslope locations as gleyic podzols with gleyic matters in the C-horizons. The leached E-horizon in the upslope location at spring no 4 is 12-20 cm and the reddish-brownish B-horizon is 20-30 cm and heavily enriched (hard pan) by aluminium-iron- and manganese-oxides as well as by humus.

The result of the petrography and the soil type **is that the Djursvallen region is very sensitive to acidification**, which was the main reason for localizing a field research area in that region. Another reason was that basis observations of temperature, precipitation (amount, chemistry) and runoff (amount, chemistry) are being made by Erik Olofsson in other projects (for example the programme for environmental supervision/PMK) in the same area.

METHODS

The field research area was observed during a period of four years (November 1986-December 1990). Runoff from the springs and the brook was measured continuously during certain periods and at least at the same intervals as the water sampling. This was made once a week on an average; more often during periods of snow melting and heavy rains and more seldom during "low flow". The samples were taken without filtering. Temperature was measured at the spot.

Alkalinity, colour, electric conductivity and pH were measured in all samples immediately in a field laboratory by Erik Olofsson. The samples were stored as cold as possible in the field and then transported to Stockholm. Chemical analyses of major and some minor ions in roughly half the samples were carried out in the laboratory at the Department of Land and Water Resources, KTH with the standard methods. Aluminium species in some water samples were determined by kinetic discrimination in a flow system at the Department of Analytical Chemistry, KTH (Clarke et al 1991).

A minor tracer test with potassium chloride as tracer was conducted by Gunnar Jacks and Erik Olofsson in the winter and spring of 1987. Observations on the amount and chemistry of precipitation were made by Erik Olofsson in the PMK-project. Those data were placed to our disposal by Lennart Granat and Gun Lövblad. Some data are presented by PMK (1987-1989).

RESULTS

The discharge of the springs is small (mean values 0.2-0.9 l/s) and fluctuates during the year as well as from year to year. Spring no 4 is the largest spring and has a maximum flow of 5 l/s after snow melt and a minimum flow of 0.07 l/s during long winter periods (Fig. 2). Spring no 3 is the weakest and with a descending trend: maximum flow 0.54 l/s and minimum 0.02 l/s, whereas spring no 2 has less fluctuations: maximum 0.82 l/s and minimum 0.16 l/s (Fig. 3). This means that the groundwater storage of spring no 2 is relatively larger than that of the other springs. The runoff of the brook is of the same order as the largest spring but fluctuates more than the discharge of the springs with a high peak during snow melt, when the V-notch was sometimes flooded. However, during long, cold periods the runoff is of the same order as that of spring no 2 or still lower (compare chemistry at p.7.)

The chemistry of the water in the brook and the springs is normally characterized by low ion concentrations. The conductivity in the spring water varies betweeen 1.0-2.4 mS/m and the concentration of some ions are close to or below the detection limit (e.g. NO_3 -N and NH_4-N). The ion composition is presented in Fig. 4. The balance between anions and cations is tolerable in the water of the three springs, considering the analyses at the detection limit of many ions, but is not so good in the water of the brook. The reasons for this unbalance may be the high content of organic material (in solution and/or in suspension) in the water of the brook and sometimes in the water of the springs (cf. the colour in Fig. 2) as well as changes of some ions (e.g. NO_3, NO_4, Al, Fe and Mn) during storage. However, the fluctuations

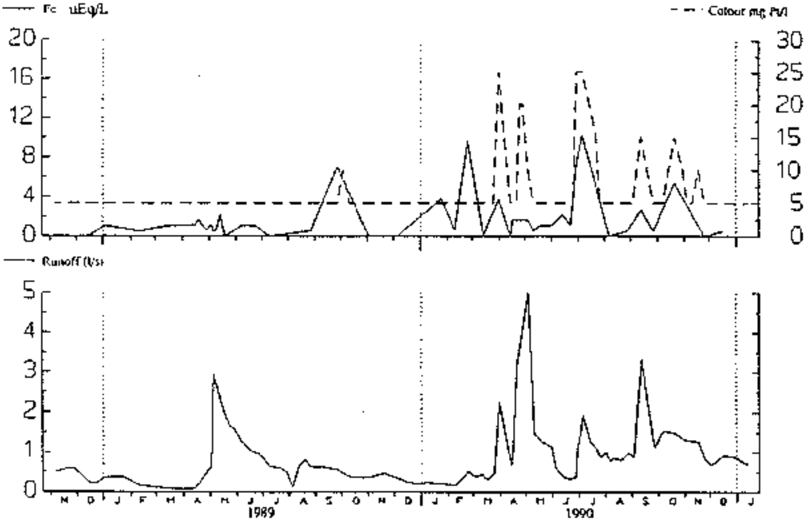


Fig. 2 Runoff (below) and the fluctuations of colour and Fe^{3+} (above) in spring no 4, Djursvallen, Lofsdalen.

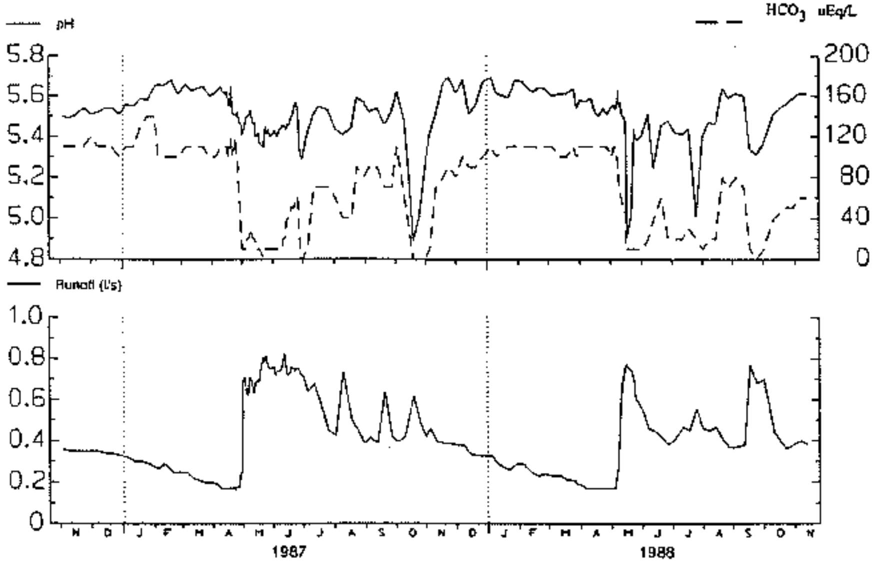
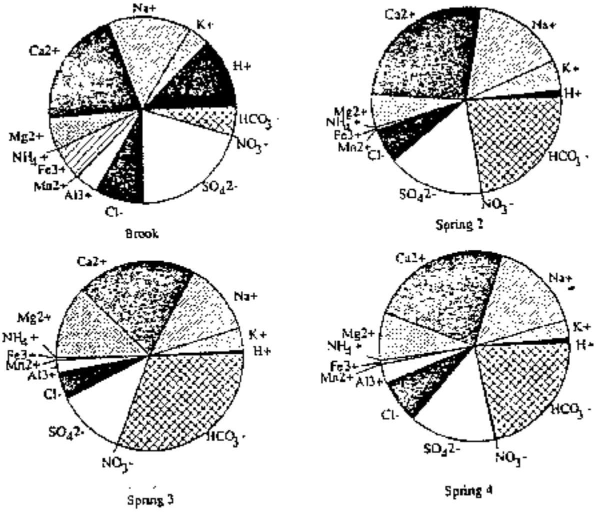


Fig. 3 Runoff (below) and the fluctuations of pH and alkalinity (HCO_3) (above) in spring no 2, Djursvallen, Lofsdal

of alkalinity, pH and some ions as well as the discharge of the dissolved substances are of great interest.



Brook

Spring 2

Spring 3

Spring 4

Fig. 4 Ion composition of the water in spring no 2, 3, 4 and the brook, Djursvallen, Lofsdalen

Alkalinity and pH. The concentrations of HCO_3 are very low; spring no 2, 0-140 uEq/L, spring no 3, 6-220 uEq/L and spring no 4, 0-140 uEq/L. The alkalinity is low or zero during and after snow melt in May as well as after the rainy period in October, sometimes also after heavy rains in the summer (Fig. 5). The pH-values are also low, but normally stable 5.5-5.7 (Fig. 3). There are some pH-drops down to around 5 or just below (in spring no 2). The alkalinity is at the same time very low or zero, but some metals; aluminium, iron and manganese have their highest concentrations (see below). The statistical treatment of data shows that there is a negative correlation between discharge in the springs as well as runoff in the brook and alkalinity and pH in the water; very considerable regarding alkalinity in spring no 2 (see also Fig. 3). The fluctuations of alkalinity and pH in the brook differ from those in the springs but the pH-values during winter periods are close (5.6-5.8) to those in spring no 2 and 3. This means that the runoff of the brook during wintertime is groundwater, whereas the runoff with pH 4.4-4-5 during spring and summer to a great extent consists of melt water and water from the peatland. This is also shown by the statistical treatment of data as there is a strong positive correlation between runoff and water colour in the brook.

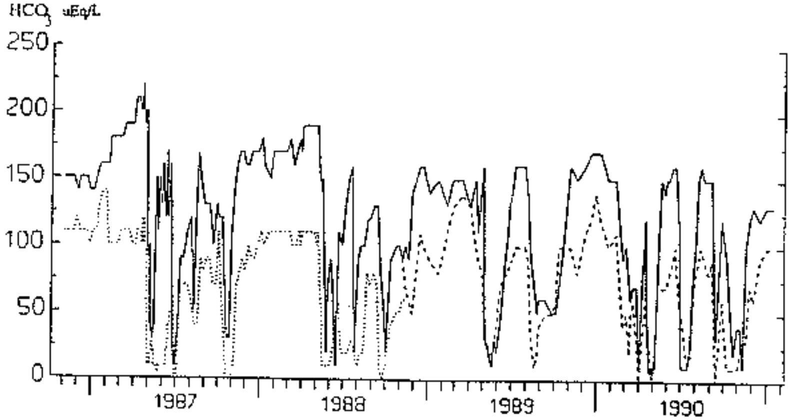


Fig. 5 Fluctuations of alkalinity (HCO_3) in spring no 2 (.....), spring no 3(—) and spring no 4 (- - - -). Djursvallen, Lofsdalen.

Cations as calcium, magnesium, potassium and sodium in spring water have similar fluctuation pattern (and similar correlation to discharge) as those of alkalinity and pH. The concentrations are low; calcium 42-105 uEq/L, magnesium 9-20 uEq/L, potassium 8-33 uEq/L and sodium 24-56 uEq/L in spring no 2.

Cations as aluminium, iron and manganese have low mean concentrations in the spring water; aluminium 7.9-9.6 uEq/L, iron 1.1-1.6 uEq/L and manganese 0.02-0.24 uEq/L, but there are a few peaks with much higher concentrations (in spring no 4); aluminium 28.9 uEq/L, iron 10.2 uEq/L (Fig. 2) and manganese 1.1 uEq/L .The alkalinity was at the same time zero and pH near 5. A brown-red precipitation was observed in spring no 2 during short periods with zero alkalinity and pH around 5. The mean - max- and min-values of aluminium in the brook were very similar to those in spring no 3 and 4, whereas the mean - and max-values of iron and manganese in the brook were much higher than those in the springs; the mean values about ten times higher.

Analyses of aluminium species in some water-samples were carried out by kinetic discrimination in a flow system at the Department of Analytical Chemistry, KTH (Clarke et al 1991). As the total content of aluminium in normally very low in the investigated springs, the content of "quickly reacting aluminium" was below the detection limit. However, water from a very small spring with very low pH: 4.86, in the same area had a content of total aluminium of 32 uEq/L of which 25% was "quickly reactive". Water in the brook with pH 4.55 was dominated by "quickly reactive" aluminium, which is the toxic Al-fraction. (Fig. 6). No effect could be determined because of long time storage as well as of filtering or not but some species could have been changed during the speedy transport from the field to the laboratory (Sparén, 1991).

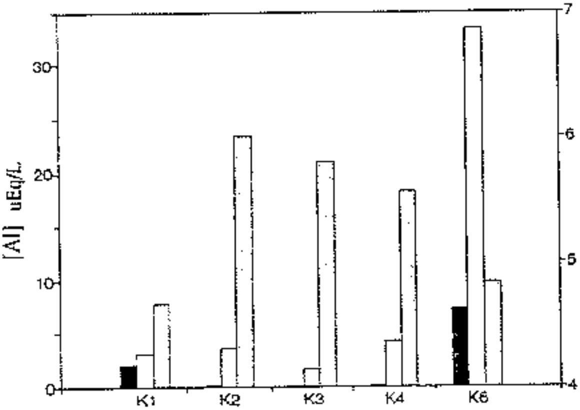


Fig. 6 Aluminium speciation on samples from four different springs and one brook at Lofsdalen in July, 1991. "Quickly Reacting Al" (Al_{qr}) was measured by FIA (filled, black bars), total dissolved Al (Al_{tot}) by ICP-OES (empty bars) and pH (filled, grey bars) was measured in the field. The Al_{qr}) values for K2-K4 were below the limit of determination of the FIA method. (Sparén, 1991).

Anions as chloride, nitrate and sulphate have very low concentrations in the spring water as well as small fluctuations. However, there is a rather strong positive correlation between runoff and sulphate content in the brook, also marked as a peak of sulphate in the melt water.

CONCLUSIONS

The marked drops in alkalinity, pH and concentrations of the main cations in the spring water during and after snow melt and rainy periods in combination with maximum spring discharge mean that the "normal" groundwater is diluted by water with extremely low ion concentration but high concentration of sulphate. This water must be meltwater or rainwater flowing directly on the discharge areas and/or percolating to a groundwater body very close to the surface of the ground and somewhere taking preferential pathways. The result of the tracer test gives support to this conclusion: tracers injected in the snow pack gave a tracer peak in the spring water during and after snow melt . This is in contrary to the result of the studies of spring discharge in till areas of similar type in the county of Småland, Southern Sweden, where the chemical fluctuations during the year were very small or did not exist even if there were considerable fluctuations in the discharge (Johansson 1987). However, the precipitation in that area is much lower and there is no heavy snow melt or rains.

The fairly high peaks in the concentrations of aluminium and manganese in the springs seem to be a result of dissolution of metal precipitation in the soil profile at very low pH. The peak concentrations of iron in the springs have been mobilized from peat-covered mineral soils with anaerobic conditions and very low pH. The peaks in the concentration of iron and manganese in the brook are still higher than in the springs and the mean concentration is ten times that of spring no 2 (belongs to the same catchment). This means that these metals must be mobilized from all discharge areas, including the vast peatland. The phenomenom of high metal concentrations is observed in several other springs and brooks during "high flow" in the during "high flow" in the Lofsdalen region (Jacks et al 1986, Olofsson 1991) but not in an alpine catchment in central Norway with otherwise similar chemistry (Blakar et al 1990). However, a study of the hydrochemistry in crystalline areas of northern Fennoscandia shows high concentrations of iron and to some extent also aluminium and manganese in streamwater from areas with organic soils. The metals are transported in complexed forms with humic matter (Lahermo 1991). These metals have a strong negative impact on biota in water. The relationship hardness/alkalinity is displaced from the "natural" state (caused by weak acids), which indicates ion exchange due to acidification and insufficient weathering (Fig.7).

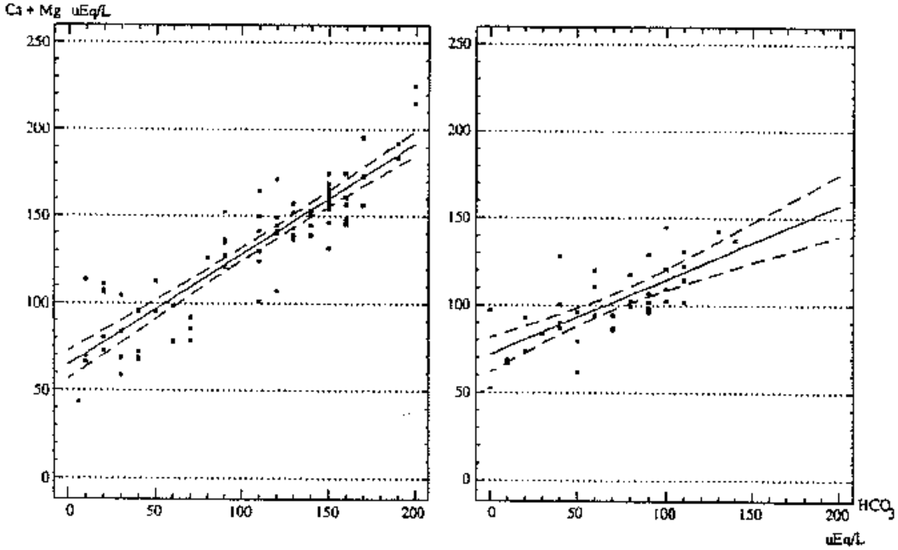


Fig. 7 Relationship hardness (as Ca+Mg)/alkalinity (HCO_3) in spring no 3 (left) and in spring no 4 (right), Djursvallen, Lofsdalen. Regression coefficient 0.90 respectively 0.72, confiden interval 95.

ACKNOWLEDGEMENTS

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LÅNGSIKTIG ÖVERFÖRING MELLAN GEOSFÄR OCH BIOSFÄR BESKRIVEN GENOM SEDIMENTSTUDIER VID ÄSPÖ HRL

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ABSTRACT

Glaciala och postglaciala sediment har studerats på Äspö såväl som i skärgården kring ön.

Påverkan på sediment av utströmmande grundvatten är en huvuduppgift inom projektet.

Omkring 30 element har studerats i den fasta fasen av sedimenten, t ex Na, Cs, Br, Fe, Th, U och sällsynta jordarter (REE). Dessutom har halten porvatten av Na, K, Ca, Br, Cl, SO_4, NO_3 m fl studerats.

Anomalier av Cs, Rb, Cl och Br visar en möjlig påverkan på sedimenten av uppströmmande grundvatten.

Faktoranalys har utnyttjats för att bestämma sammansättningen för porvatten i sedimenten med olika typer av grund- och havsvatten.

Jämförelser av sammansättningen av t ex REE i sediment i utströmningsområden, sprickmineral och marina sediment etc gör det möjligt att studera långsiktig transport mellan geosfär och biosfär.

INTRODUKTION

Studier av transport av olika element i utströmningsområden har tidigare genomförts (Sundblad et al, 1991). Detta har främst gällt sjösediment. Vatten med olika ursprung och kvalitet har visat sig kunna ge upphov till olika sorption i kontaktzonen mellan geosfär och biosfär.

Inom det presenterade projektet har inriktningen varit att studera marina sediment i anslutning till underliggande sprickzoner. En fråga har varit om det är möjligt att påvisa att grundvatten läcker upp genom sediment.

MATERIAL OCH METODER

Sediment har provtagits både ytligt (0 - 15 cm) samt ned till berggrunden, se Figur 1. Dessutom har prover tagits på morän, torv och underliggande sediment på Äspö.

En del sedimentprover har centrifugerats för att ta ut porvatten. Andra prover har torkats där totalmängden av olika element skulle bestämmas.

Aktiveringsanalys (INAA) har använts på fastmaterialet och ett 30-tal olika element har kunnat bestämmas. Jonkromatografi för att bestämma F, Cl, Br, NO_3 och SO_4 i porvattnet har utnyttjats.

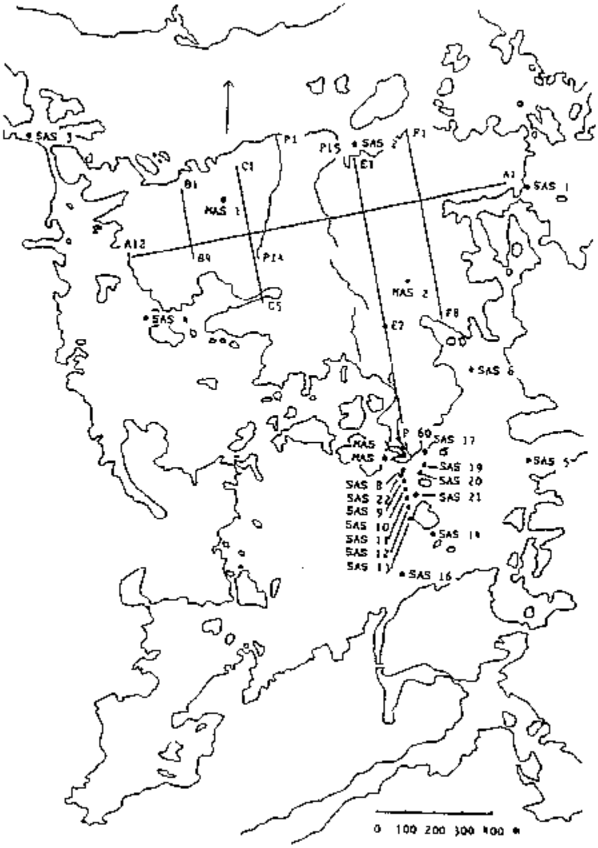

Fig. 1. Äspö, provtagningspunkter.

RESULTAT

En karaktärisering av de sedimentprover som tagits visar på betydande likheter på såväl land som havssidan, se Fig. 2. De översta lagren består av material med högt organiskt innehåll, medan bottenskikten utgörs av lerhaltigt material, som troligen avsatts i samband med eller strax efter att inlandsisen drog sig tillbaka för drygt 10 000 år sedan.

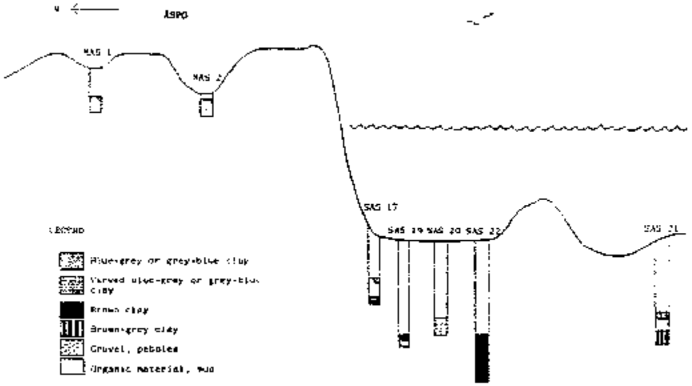

Fig. 2. Schematisk bild över sedimentprofiler.

Nedan har sammanställts några analyser av halten av fastmaterial, se Tabell 1.

Tabell 1

Halten av Th, U, Fe, Cs, La och Ce.

					Element		
Lokal	Djup (cm)	Th	U	Fe	Br	Cs	Ce
21	10	9.7	13.0	3.1	453	2.1	89
	160	7.5	9.0	1.7	2 500	2.0	49
	330	26.0	5.0	5.8	125	9.2	123
	410	18.0	2.0	4.2	700	6.4	90
22	10	10.3	9.0	3.5	493	2.3	172
	285	8.2	10.0	1.8	2 200	2.0	66
	425	23.0	8.0	4.6	85	6.0	119
	560	23.0	5.0	6.0	30	8.6	123

Från tabellen kan utläsas att thoriumhalterna i leran ligger relativt högt jämfört med halterna i de ovanförliggande sedimenten med organiskt material. När det gäller uranhalterna är förhållandena mer utjämnade.

Bromvärden visar på stora skillnader mellan de olika skikten. Utvärderingen har visat på en positiv korrelation mellan halt av brom i sediment och organisk innehåll. Kd-värden för Br i de övre skikten är 0.2 m^3/kg medan värden inom lerskikten är ca 0.005 m^3/kg. Motsvarande värden för Cl är 0.002 respektive 0.0004 m^3/kg.

Porvattenhalter presenteras i Figur 3 och 4. Från figurerna framgår att kloridhalterna är mycket likartade oavsett djup. Detta kan bero på likartade salthaltsförhållanden vid sedimentationen. Emellertid visar sulfatkoncentrationen en klar gradient med minskande värden mot djupare sediment vid lokal 22 men inte 21. Detta skulle kunna förklaras av diffusion. Med tanke på den tid som gått sedan sedimentationen skulle profilen ha blivit mycket mer utjämnad. En möjlig förklaring kan vara att en mycket liten uppströmning genom sedimenten skulle kunna orsaka en sulfathaltskurva med detta utseende.

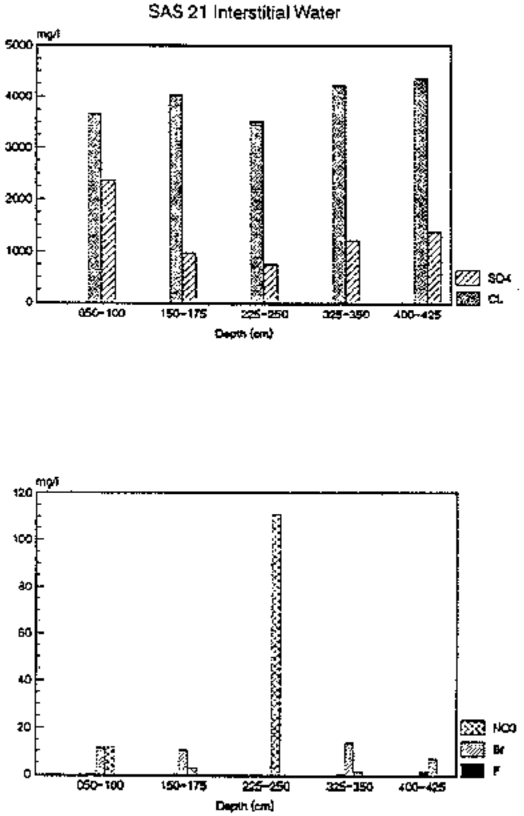

Fig. 3. Porvattenhalter vid lokal 21.

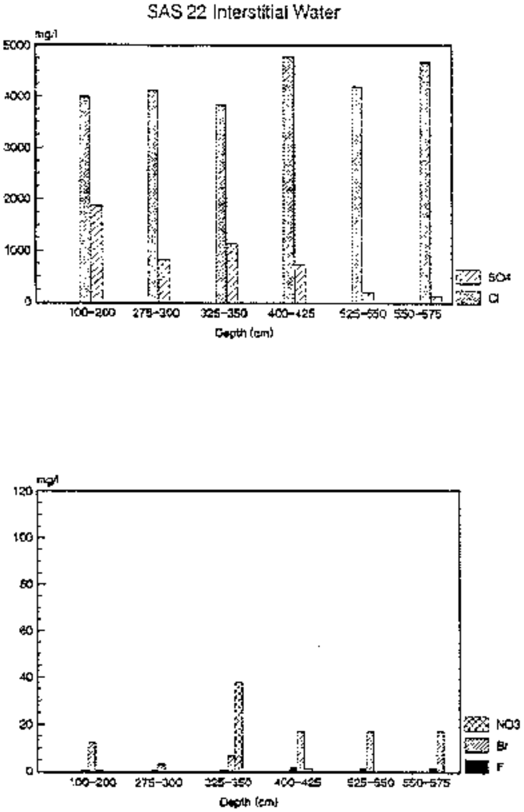

Fig. 4. Porvattenhalter vid station 22.

Faktoranalys har använts för att se på sambandet mellan porvattenhalter avseende Na, K, Ca, Cl, Br, Mg och SO_4 samt olika lokaler och djup. I Figur 5 och 6 redovisar de två första faktorerna, som tillsammans förklarar 90 % av den total variansen.

Två blandningslinjer kan urskiljas;.en som representeras av linjen Östersjö- och Oceanvatten. Den andra av fyra grundvattenklasser (A - D) som identifierats vid borrningar under Äspö.

I Figur 5 redovisas två lokaler (referenser) som ligger utanför några mer betydande spricksystem under sedimenten. De två lokalerna 17 och 21 ligger väl samlade i intervallet Östersjövatten (nuvarande) och ytliga grundvatten.

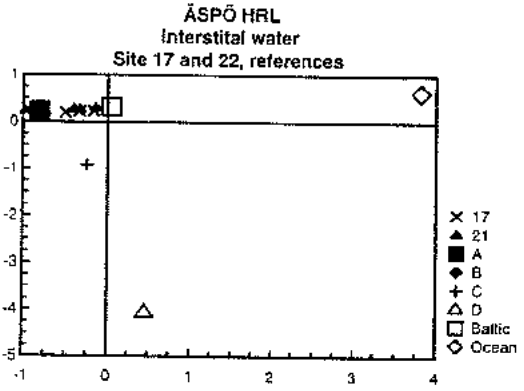

Fig. 5. Faktoranalys porvatten Lokal 17 och 21.

Figur 6 representerar lokal 22 över sprickzon NE1, strax söder om Äspö. De tre bottenskikten (4 till 6 m under sedimentvattenytan) skiljer sig väsentligt från övriga prov. Dessa två nivåer ligger på blandningslinjen Östersjö- och Oceanvatten, vilket skulle tyda på att det kan härstamma från Östersjövatten med högre salthalt än nuvarande. Detta skulle i sin tur innebära att ingen signifikant uppgående grundvattenström äger rum. Detta motsägs till viss del av vad som sagts tidigare. Emellertid har ett komplicerat strömningsmönster under och runt Äspö noterats (Smellie, Laaksoharju, 1992, som troligtvis innebär att fler djupproppar behövs för att täcka in hela sprickzonen.

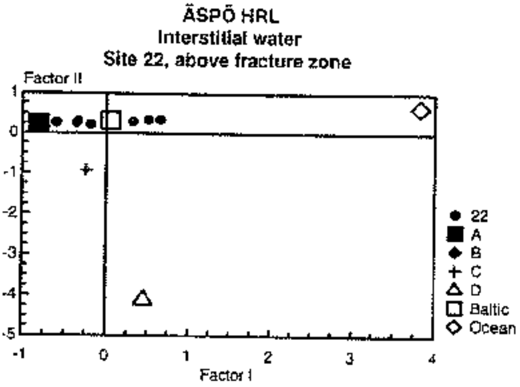

Fig. 6. Faktoranalys provatten Lokal 22.

SLUTSATSER

De sedimentstudier som genförts har hittills visat att de kan vara till hjälp för att förstå och kunna prognosticera överföringen mellan geosfär och biosfär.

Insamlat material kommer att analyseras vidare när det gäller spårelement som kan hjälp till med tolkningen av långsamma transporter i sedimenten. Ett sådant ämne kan exempelvis vara cesium.

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THE NORDIC FRESHWATER INITIATIVE TO DUBLIN AND RIO

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ABSTRACT

In recognition of the shortcomings of traditional top-down and sectoral approaches to freshwater management, the Nordic countries have launched *the Nordic Freshwater Initiative* as part of the preparatory process for the UN Conference on Environment and Development in Rio in June 1992. This initiative have highlighted the importance of considering freshwater as a finite and vulnerable resource to be managed in a coordinated and integrated manner. The *Copenhagen Statement*, issued as the main result of the initiative, stresses the need to manage land and water resources *at the lowest appropriate levels*, and to consider water as an *economic good* with a value reflecting its most valuable potential use.

BACKGROUND

The World is today - more than ever - subject to increased pressure on land and water resources caused by population increase and industrial development.

Global water consumption has doubled in the 40 years from 1940-1980, and is expected to double again before the turn of the century. The majority of this consumption (some 70-80%) is for agricultural purposes; industrial activities account for some 20%; and domestic use for only about 6%.

The way in which water resources is being managed has increasingly severe environmental implications, including the accelerating soil and water degradation, the degradation of natural ecosystems and freshwater pollution.

The question now confronting us is: Will this development lead to water crises in many parts of the World, as predicted by some? Or will we be able to improve our management of the World's water resources through cautious and substainable development?

If the answer to this question is to be based on the experiences from the follow-up of the Action Plan adopted at the World Conference on Water in Mar del Plata in 1977 it is indeed discouraging.

Mar del Plata gave rise to the International Drinking Water Supply and Sanitation Decade 1981-1990 (IDWSSD) and with it considerable progress in drinking water supply and sanitation development. It did not, however, lead to improved management of freshwater as a fragile and finite resource. Progress in water resources assessment, protection of the aquatic environment, and integrated management of land and water resources have been disappointing. If new directions and real progress are not achieved in this respect as a matter of priority, those who predict an era of water crises may indeed be proven right.

In 1992, 15 years after Mar del Plata, the global freshwater agenda is being discussed as part of the Earth Summit in *Rio* in June 1992 (UN Conference on Environment and Development - UNCED), and, in preparation for that, at the International Conference on Water and the Environment in *Dublin*.

The UN family of specialized agencies have prepared thorough and comprehensive global strategies for freshwater resources planning and management. These strategies form the basic input to the Dublin and Rio conferences, and hence the backbone of the freshwater resources component of the *'Agenda 21'* to be adopted in Rio as the basis for environmentally sustainable development in the next century.

However, based on such global strategies, will Rio become another Mar del Plata signalling good intentions but no real commitments for improved water management in the future? Or will Rio mark the turning point at which all nations start committing themselves to a sustainable management of their natural resources?

THE NORDIC EXPERIENCE

The Nordic countries (in this context Finland, Norway, Sweden and Denmark) have felt a strong commitment to contribute to an operational outcome of the Dublin-Rio process on freshwater resources development and management.

The Nordic countries have a long-standing cooperation with countries in Africa, Asia and Latin America on water development, which is one of the most important sectors of their development assistance, both quantitatively and qualitatively. Nordic aid to this sector has traditionally focussed on water and sanitation for human settlements, with priority to rural areas and small towns. Denmark alone disbursed on the average about 300-400 million Danish Kroner annually (or 40-60 mill. US$) throughout the IDWSSD.

Although considerable progress has been made in the quality and sustainability of water supply and sanitation development, it is becoming increasingly obvious that this development has suffered from significant shortcomings in relation to the water resources aspects.

Hence, water supply and sanitation development has been too sectoral, with inadequate attention to the integration with other, related sectors, not least the water consuming agricultural sector. Insufficient consideration has been given to the protection of land and water resources in the process; and although major progress has been made with respect to community involvement, overall water resources aspects have been largely neglected. Water supply and sanitation development has often been based on a rather top-down master planning approach.

The shortcomings of this traditional water supply and sanitation development are becoming increasingly apparent, as for example by

- handpumps drying up because of falling groundwater tables caused by motorized pumping for irrigation, and surface water supplies being threatened by uncontrolled upstream abstractions for agricultural use
- surface water schemes being threatened by catchment degradation causing soil erosion and declining low flows.
- increasing water quality problems in both surface and groundwater.
- conflicts in the competition for scarce water resources for domestic, agricultural (irrigation), industrial, livestock and other uses.

THE NORDIC FRESHWATER INITIATIVE

On this background, the Nordic countries have found that the Dublin-Rio process offers a unique opportunity to highlight these problems, and to initiate a process of developing operational guidelines for improved water resources management in the future.

The Nordic Freshwater Initiative has had two main objectives:

- to contribute to the development of *operational guidelines* for integrated water resources planning and management in the developing countries, with focus on rural areas and small towns, and
- to *involve the developing countries* actively in the process.

The initiative has resulted in a number of workshops with active participation of water professionals from developing and developed countries. It has been seen as a direct contribution to the preparatory work for the Dublin and UNCED conferences, the organizers of which have been actively involved in the workshops.

UN documents have been reviewed, and special emphasis has been put on five case studies in Africa and Asia dealing with various problems relating to water resources management. The issues highlighted in the case studies include environmental protection, conflicts between various users of water, and participatory planning and utilization of water.

The Nordic Freshwater Initiative has arranged and hosted the *Copenhagen Informal Consultation* on Integrated Water Resources Development and Management in November 1991, with 45 participants from 27 countries. The CIC adopted the ***Copenhagen Statement*** and resulted in the *Copenhagen Report*, both of which were provided as an input to the Dublin Conference.

CASE STUDIES

Examples of water management problems and possible improvements

Five case studies on integrated water resources management have been conducted by professionals from the Nordic countries in collaboration with colleagues in the respective countries of study.

One example is the *Case Study on Local Water Management in the Ismani Rural area in Tanzania*. In this case, in a rural river catchment in the Iringa Province, low flows are presently sufficient, but allow no further economic development e.g. based on extended irrigation. Costs of structural measures (dams, deep boreholes etc.) are prohibitively high. Water development in the area has already indicated conflicts between user groups such as competition over water between domestic and commercial users (irrigation, livestock); water quality degradation in intake areas caused by settlers; and government institutions failing to pay their share of the fees to the village water funds.

The suggested improvements include:

- decentralization of the water management system with the aim of decisions being taken at the lowest appropriate levels. Only major sources serving bigger areas with conflicting interests should be managed at higher levels; minor sources can be managed at household, - user group, - village level
- assistance of community workers to achieve better cooperation with settlers in the intake areas
- introduction of a pricing system with water meters for house connections, as well as for farmers with livestock and irrigation

The suggested water resource management hierarchy is illustrated in Figure 1, which indicates appropriate levels of management for different scales of water resources. Hence minor water sources may be managed at user group level - with recourse to the local water or scheme committee - while large water resources need to be managed at district or regional (and/or river basin) levels.

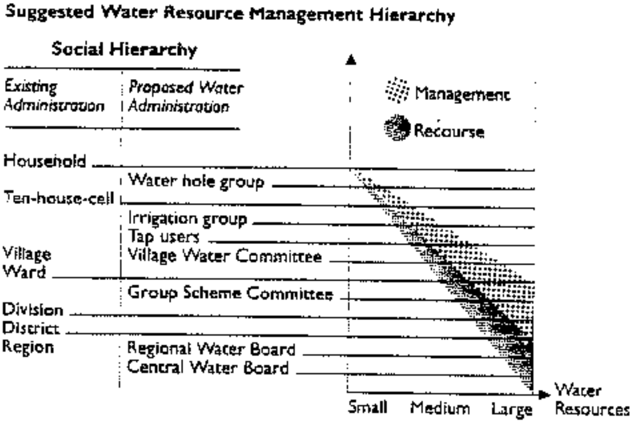

Figure 1: Rural river catchment, Tanzania:
Suggested water resource management hierarchy

The other case studies have focused on

- water resources management at river basin level in *Zimbabwe*
- water resources and supply management at intermediate level in *Burkina Faso*
- users' participation in water supply development in *Kenya*
- land and water resources management at watershed level in Tamil Nadu, *India*

THE COPENHAGEN STATEMENT: KEY PRINCIPLES FOR LAND AND WATER RESOURCES MANAGEMENT

These examples, and other similar experiences from Nordic-supported water development projects, point to a number of key aspects of local water management which have not been adequately considered in the past. These experiences have been reviewed as part of the Nordic Freshwater Initiative, and new possible ways of managing and maintaining water resources have been proposed.

The conclusions of the Nordic Freshwater Initiative, as summarized in the Copenhagen Statement, and elaborated in the Copenhagen Report, are briefly as follows:

Freshwater must be recognized as a finite and vulnerable resource, which is vital for the sustenance of life, for all development activity, health and environmental maintenance. Two key principles should be the prime components of future strategies for sustainable development and management of water resources:

1. *Water and land resources should be managed at the lowest appropriate levels*

2. *Water should be considered as an economic good, with a value reflecting its most valuable potential use.*

Management at the lowest appropriate levels

Centralized and sectoral (top down) approaches to water resources development and management have often proved insufficient to address local water management problems. While recognizing the need for a central mechanism capable of ensuring the national economic and social interests, the role of governments needs to change, to enable users, local institutions and the formal and informal private sector to play a more direct part.

The levels at which effective management decisions can be taken and problems can be solved will vary widely from country to country and from situation to situation. The fundamental principle remains, however, that in any given situation, water resources should be managed at the lowest appropriate levels, taking into account the need for integration with land use management.

Demand-driven water resources development and management is emphasized. To prepare the ground for the active involvement of beneficiaries, they must have choices and a sense of ownership and responsibility.

Demand-driven institutional responsibility will often call for changes in existing institutional arrangements and legislative frameworks, and so capacity for water management should be developed when and where there is a clear demand. As a consequence, the role of government should change from one of command, control and execution, to that of creating and maintaining an enabling environment for management at appropriate levels.

While integrated land and water resources management necessarily must consider the natural (hydrological) boundaries of the resource, it must at the same time take place within the socio-political structures of the country concerned. Hence, in identifying the most appropriate institutional context for any water resources management decision or action, the socio-political and hydrological management structures must be reconciled. In particular, it must be decided at each level whether land and water management institutions are needed, and if so, whether they should be advisory or executive.

In addition to the hierarchical structures at local, intermediate, national, and international levels, interest groups at all levels will play a role in pursuing water interest, including the private sector, non-governmental organizations, cooperatives, corporations, and users' groups.

The interactions between the socio-political and the water management hierarchical structures are illustrated in Figure 2, which indicates possible catchment and river basin committees or authorities at different socio-political levels.

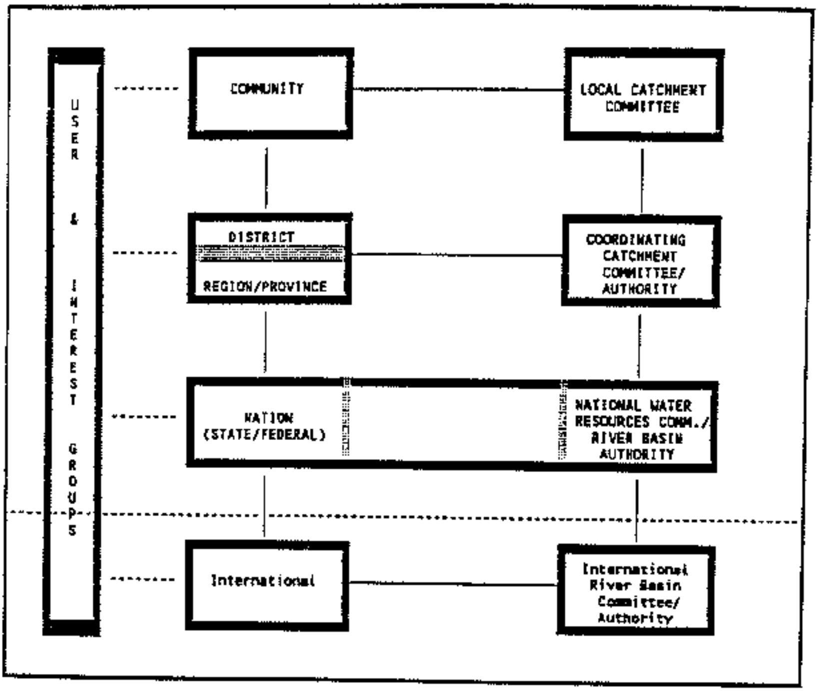

Figure 2.: Interactions between the socio-political and the water management hierarchical structures

Water as an economic good

Access to sufficient water of adequate quality for basic subsistence is a fundamental human need. However, efficient allocation of water resources can only come from a full recognition of the costs and benefits associated with the various alternative uses taking into account future needs. In other words, water is an economic good. Failure to recognize this key principle has contributed substantially to wasteful and environmentally damaging uses of water.

Making water accessible and usable involves *direct costs* in form of capital and labour. An additional cost - the *opportunity costs* - reflecting the value (or benefits foregone) of the water in its most valuable alternative use has to be taken into account. Finally, the *environmental costs* (or 'externality cost' in terms of benefits foregone by polluting the water) must be considered when water quality is degraded, or alternatively, cost imposed on the polluter to prevent his actions to affect water quality. A schematic illustration of these concepts is shown in Figure 3.

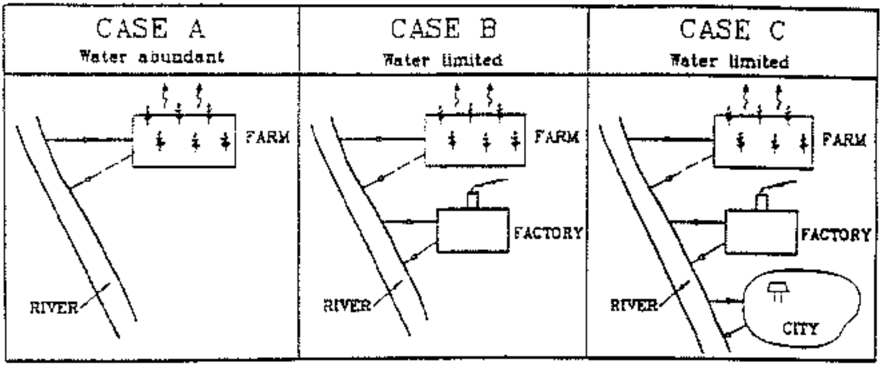

Figure 3:	Schematic example of three different cases of water use
Case A:	Direct cost to farmer
Case B:	Direct cost to farmer + opportunity cost as value of water in best alternative use (the factory)
Case C:	In addition to Case B: Direct cost to factory + opportunity cost as value of water in best alternative use (the city) + environmental cost of avoiding pollution or cleaning effluent

Whether or not different categories of users are charged the full economic cost of providing their water supplies, that cost must be apparent and accounted for in resource management strategies. Charging for water use is essential not only for inducing conservation and protection of water resources, but also for creating a sense of ownership and responsibility for these water systems.

Operational implications

To strengthen the local level and decentralize the decision-making process, institutional hierarchies for integrated land and water resources management should be created, while at the same time constituting a proper 'enabling environment' at the national level.

The national level must set the agenda and provide the necessary infrastructure for local decision-making, within an overall national policy and legislative framework. National focal points for water management exist in many countries, but are often dormant and ineffective. Hopefully the Dublin-Rio process will bring new life to such institutions and enable them to prepare and implement *national action plans* for integrated water resources management.

Important pre-conditions for succeeding in building effective water management structures are

- that awareness building, motivation and incentives be provided at all levels from local communities to national politicians. Valuable lessons can be learned from the IDWSSD in this respect.

- that high priority be given to the building of institutional capacity, within available financial and other resources. Local generation of financial resources and optimal utilization of existing institutions are important objectives in this respect.

- that cross-sectoral integration and coordination for integrated land and water management be given high priority by authorities at all levels

- that governments give high priority to creating a legislative framework for water management - from operational local water rights to a national water law - which can be enforced at all levels, and

- that the private sector be encouraged, wherever appropriate, to ensure effective water management, within publicly defined general policies.

TO RIO AND BEYOND

The International Conference on Water and the Environment in Dublin was held in January 1992. This conference, attended by five hundred participants from more than a hundred countries, arrived at four guiding principles for water management (contained in the ***Dublin Statement***):

1. *Freshwater is a finite and vulnerable resource, essential to sustain life, development and the environment*

2. *Water development and management should be based on a participatory approach, involving users, planners and policymakers at all levels*

   (- with specific reference to *decisions at the lowest appropriate level*)

3. *Women play a central part in the provision, management and safeguarding of water*

4. *Water has an economic value in all its competing uses and should be recognized as an economic good*

Hence the Dublin Statement (and associated Dublin Report) reflects the conclusions of the Nordic Freshwater Initiative, and international consensus is emerging on the importance of new directions and strategies for water management based on the above key principles.

These principles were to a large extent included in the *'Agenda 21'* document as negotieted at the Fourth Preparatory Committee Meeting for UNCED (PrepCom 4) in New York in March 1992. Agenda 21 is expected to be adopted by UNCED in Rio de Janeiro in June 1992 (expectation dated April 1992, at the time of submission of this paper).

It is hoped that these principles, and the comprehensive analyses and recommendations leading to them, will be widely disseminated so that governments and sector specialists may adopt them in formulating and implementing national action plans for water resources development and management.

In the Nordic countries it is believed that a new era of conscientious and sustainable integrated water resources management is indeed called for, and that all countries must endeavour to contribute to action programmes after Rio which respect water as a fragile and finite resource to be managed as such. Future water crises can be, if not avoided, then at least reduced, if nations take this opportunity to let statements and strategies be followed by action.

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VASSDRAGSPLANLEGGING - PLANLEGGING I VASSDRAG ETTER PLAN- OG BYGNINGSLOVEN

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ABSTRACT

The Planning and Building Act is the legislation for area use planning and planning for exploitation of natural resources in Norway. The last couple of years, the Directorate for Nature Management has initiated and supported the use of the planning legislation for planning and management of the water courses on the local level. This is a strategy for the making the local authorities responsible for the management of water courses as a part of the overall planning and nature management on the local level.

INNLEDNING

Bærekraftig utvikling; Begrepet ble introdusert av Brundtland-kommisjonen og er den norske oversettelsen av Sustainable development. Begrepet er brukt og misbrukt og oppfatningene av hva bærekraftig utvikling egentlig innebærer er mange og sprikende. Under ligger for de fleste en erkjennelse av at menneskene i dag påvirker miljøet rundt seg på en måte som fører til store endringer i naturen, og at disse endringene kan medføre store konsekvenser for våre livsbetingelser. Mange legger også i dette at menneskene ikke har rett til å påvirke livsbetingelsene for dyr og planter på en måte som får store konsekvenser for disse livsformene.

Oppdraget Brundtlandkommisjonen fikk fra FN var å lage "Et program for globale reformer". Dette innebar bl a å utarbeide en langsiktig miljøstrategi for å fremme en bærekraftig utvikling fram til og forbi år 2000.

Den norske strategien for oppfølgingen av kommisjonen rapport er klargjort i St.meld.nr.46 (1988-89). Et av de viktigste elementene i denne strategien er at miljøhensyn skal inn som et premiss ved alle typer planlegging og aktivitet. Konsekvensene på miljøet må vurderes når vi utformer vår politikk, i vår utnyttelse av naturressurser og når vi planlegger utviklingen av vår livsform. Sektorisert planlegging har ikke ivaretatt disse hensynene. Det er nå alle sektorers og næringsutøveres ansvar å sørge for at miljøkonsekvensene av det de foretar seg blir vurdert. Målet om en bærekraftig utvikling skal ivaretas igjennom en sektorovergripende politikk.

FLERBRUKSPLANER I NORSKE VASSDRAG, ET TILBAKEBLIKK

Flerbruksplanlegging i vassdrag, vannbruksplanlegging, barnet har mange navn. Slik planlegging har vært drevet i norske vassdrag i flere år. Det har vært arrangert studieturer til utlandet og utenlandske erfaringer og modeller har vært forsøkt overført til norske forhold.

Jeg vil trekke fram noen generelle forhold omkring disse aktivitetene og denne planleggingen:

- initiativet til planleggingen har gjerne kommet fra miljø med en sektorinteresse i vassdraget, ofte har interesser knyttet til vannkraftproduksjon eller fagmiljøene omkring disse vært de tyngste drivkreftene
- de som har drevet fram planleggingen har ofte vært personer med faglig bakgrunn som ingeniører, hydrologer osv, mens planleggere og personer med samfunnsvitenskapelig bakgrunn ikke har vært involvert
- planarbeidene har konsentrert seg om konflikter og interessemotsetninger tilknyttet vannstrengen og vannressursene
- planleggingen har hatt som siktemål å avklare interessekonflikter mellom sektorer og næringsinteresser med tanke på handlingsprogrammer og tilpasning av bruk for å dempe konflikter
- planleggingen har vært ad hoc- preget, den har vært gjennomført som prosjekt og ikke som løpende planlegging

Det er også viktige forhold omkring vassdragene som sjelden har blitt tatt opp i disse planene:

- de har ikke tatt opp arealbruk av bruk av ressurser langs vassdraget utenfor vannstrengen
- de har i liten grad forholdt seg til den sektorovergripende planleggingen som foregår i kommuner og på

fylkesplan

- de har i liten grad forholdt seg til overordnede politiske målsetninger
- de har i liten grad forholdt seg til det politiske miljøet og de beslutningsprosesser som foregår der
- muligheter for offentlig medvirkning under arbeidet med planene har ofte vært begrenset
- de har ikke fungert som retningsgivende for andre enn de som har vært involvert i planprosessen
- planene har vær vanskelige å følge opp fordi de har vært drevet fram av prosjektteam som avslutter sitt arbeid når planene har vært ferdige
- planene har ofte vært handlings- og tiltaksrettet og i liten grad vært egnet for langsiktig ressursdisponering
- planene har konsentrert seg om brukerinteresser og utnyttelse av naturressurser og interesser knyttet til vern har kommet i bakgrunnen

Det er ikke min hensikt å dømme alle flerbruksplaner nord og ned. Det ville vært langt fra riktig eller rettferdig. Det er gjort mye godt arbeid og det har vært lagt ned mye god vilje i slike planer. Dessuten er det selvfølgelig laget gode og dårlige planer slik at generelle karakteristikker ikke kan vise alle nyansene i det som har vært gjort.

Likevel har nok mange som har vært med i slike planarbeider kunnet oppsummere at de gikk inn i arbeidet med større glød og forventninger enn de hadde da de var ferdige.

Som en generell oppsummering vil jeg peke på tre svakheter ved slike planer som jeg mener er de viktigste:

- planene har ikke vært knyttet opp mot overordnede målsetninger og det politiske miljøet, og dermed heller ikke til de beslutninger som fattes der og den planleggingen som legges til grunn for disse beslutningene
- planleggingen har vært betraktet som et teknisk problem om interesseavklaring mellom involverte parter og det samfunnsmessige aspektet og kompetanse på samfunnsplanlegging har ikke vært betraktet som et nødvendig element i flerbruksplanleggingen

- flerbruksplanene har blitt planprosjekt som avsluttes etter prosjektperioden og er ikke ført videre som en løpende planprosess med et liv utover prosjektperioden

PLAN- OG BYGNINGSLOVEN, NATURFORVALTNING OG VASSDRAG

Plan- bygningsloven er den sentrale loven i Norge når det gjelder planlegging og ressursdisponering. I lovens formålsparagraf står:

> "Planlegging etter loven skal legge tilrette for samordning av statlig, fylkeskommunal og kommunal virksomhet og gi grunnlag for vedtak om bruk og vern av ressurser og om utbygging."

Når Regjeringen sier at "målet om en bærekraftig utvikling skal ivaretas igjennom en sektorovergripende politikk", er det viktigste verktøyet vi har Plan- og bygningsloven. Formålet med loven er nettopp å ivareta det sektorovergripende perspektivet i forhold til planlegging, vern og bruk av ressurser.

Natur- og miljøforvaltningen arbeider derfor aktivt for å utvikle mulighetene som ligger i Plan- og bygningsloven i arbeidet for å oppnå en bærekraftig utvikling. Vi mener også at mye av ansvaret for å sette en slik politikk ut i livet må ligge hos de kommunale myndighetene. Her fattes kanskje de viktigste beslutningene i forhold til hvordan utviklingen skal bli, og her er mulighetene for reel påvirkning størst.

Vassdragsnaturen, og da inkluderer jeg både vannstrengen og de tilgrensende arealene, er generelt en av de naturtypene med størst spennvidde når det gjelder flora og fauna og de er svært viktige i de økologiske systemene. Vassdragene er også fremtredende landskapselement. Brukerinteressene spenner fra vannkraftutbygging til jordbruk og friluftsliv. Vassdrag er et møtested for mange interesser.

Behovet for et verktøy som ivaretar sektorovergripende hensyn er derfor særlig stort i forvaltningen av vassdragene. I naturforvaltningen arbeider vi målbevisst for å aktivisere Plan- og bygningsloven i forvaltningen av vassdragene og prøver ut potensialet som ligger i dette lovverket.

Plan- og bygningslovsystemet gir muligheter for løsninger på flere av de områdene der den tidligere flerbruksplanleggingen har hatt svakheter:

- planleggingen er i prinsippet tverrsektoriell og ivaretar behovet for planlegging i hele vassdragsmiljøet, dvs både i vannstrengen og i de tilgrensende områdene
- de er delvis bindende og i alle fall retningsgivende for sektorenes aktiviteter og planlegging
- planene behandles politisk og har slik en politisk forankring
- det er rutiner for høring av planer og offentlig medvirkning
- lovverket har har rutiner for jevnlige revisjoner av planene

Tverrsektoriell planlegging

Å binde planene i vassdragene opp til Plan- og bygingslovsystemet representerer et helt annet grep enn den tradisjonelle flerbruksplanleggingen.

I flerbruksplanene møttes ofte representanter for sektorinteresser og prøvde å komme fram til ordninger som avdempet konflikter. Men når de ansvarlige for planlegging egentlig har som hovedoppgave å ivareta sektorinteresser, blir oppgaven tverrsektoriell planlegging fort vanskelig.

I Norge har fylkeskommunene og kommunene som oppgave å drive tverrsektoriell planlegging. Det eneste naturlige er derfor også å overlate ansvaret for tverrsektoriell planlegging i vassdragene til disse. Det vil i første rekke bety kommunene.

Sektorenes planlegging og aktivitet i forhold til kommuneplaner og fylkesplaner

Vedtatte kommuneplaner skal legges til grunn ved planlegging, forvaltning og utbygging i kommunen. Fylkesplanene skal legges til grunn for fylkeskommunal virksomhet og være retningsgivende for kommunal og statlig planlegging og virksomhet i fylket.

Dette betyr at alle særinteresser skal ta hensyn til disse planene i sin planlegging og aktivitet. Disse planene sier noe om hva som kan foretas med hensyn til vern av areal og ressurser og areal- og ressursbruk.

Særlovene som forvaltes av sektormyndighetene, regulerer så hvordan tiltak kan utføres med hensyn til f eks sikkerhet (Vassdragsloven), forurensning (Forurensningsloven) osv.

VASSDRAGSPLANLEGGING OG NATURFORVALTNINGENS ENGASJEMENT

Naturforvaltningen kaller sitt barn vassdragsplanlegging. Navnet mener vi er mer dekkende enn de tidligere nevnte, fordi det er planlegging for disponering av arealer og ressurser i vassdragsnaturen, ikke planlegging kun for "flerbruk" eller "vannbruk".

Vi har gitt økonomisk støtte til slik planlegging. Vi har også gitt bidratt faglig, men på det feltet har støtten fra fylkesmennenes miljøvernavdelinger vært større enn fra oss. I 1991 ble det gitt økonomisk støtte til mellom 25 og 30 kommuner. I 1992 vil tallet bli noe større. Disse planene har som regel tatt opp vassdragsavsnitt og bare sjelden hele vassdrag.

Vi stiller flere krav til planarbeidene for å gi slik støtte:

- planene bør knyttes formelt opp mot plan- og bygingslovens regelverk og rutiner
- planene bør behandles som kommunedelplaner eller innarbeides i den ordinære kommuneplanen og i kommunale handlingsprogram
- både politikere og statlige sektormyndigheter må delta i planarbeidet

Det er ennå for tidlig å evaluere planene som vi har støttet. I løpet av året vil vi antagelig kunne dra erfaringene fra disse planarbeidene. For oss vil det være flere ting som er interessant å få evaluert. Noen av de viktigste er:

- har nasjonale målsetninger for bruk av vassdrag og vassdragsnære arealer kommet til uttrykk i planen
- har planene evnet å fange opp det tverrsektorielle aspektet
- er planene blitt en naturlig del av den kommunale planleggingen og har kommunene fått et "eierforhold" til forvaltningen av vassdragene og planleggingen i vassdragene
- har det vært lokal mobilisering omkring planleggingen og forvaltningen av vassdragene og har det kommunale

engasjementet også muliggjort medvirkning fra lokalsamfunnet

- har vassdragsplanleggingen påvirket statlige etaters virksomhet i vassdragene og kommer målsetningene i vassdragsplanene også til uttrykk i disse etatenes planer

Vårt videre arbeid med vassdragsplanlegging har som målsetning at det skal kunne bli bekreftende svar på alle disse spørsmålene.

HYDROLOGICAL BACKGROUND TO BUKSEFJORDEN
- THE FIRST HYDROPOWER PLANT IN GREENLAND

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ABSTRACT

In 1990 the Greenland Landsting (Local parliament) decided to build the hydropower plant at Buksefjorden - the first hydropower plant in Greenland. The Buksefjord catchment is situated around 50 km south-east of Nuuk, the capital of Greenland. The hydropower potential consists of the catchment to the main lake/natural reservoir and 8 subcatchments. The hydrological fieldinvestigations were started in 1981, and the work has included monitoring as well as numerical simulations and statistical analysis. The hydrological back-ground to the powerplant is reviewed, and examples of the used techniques in the dataanalysis as well as keyfigures of the powerplant are presented.

INDLEDNING

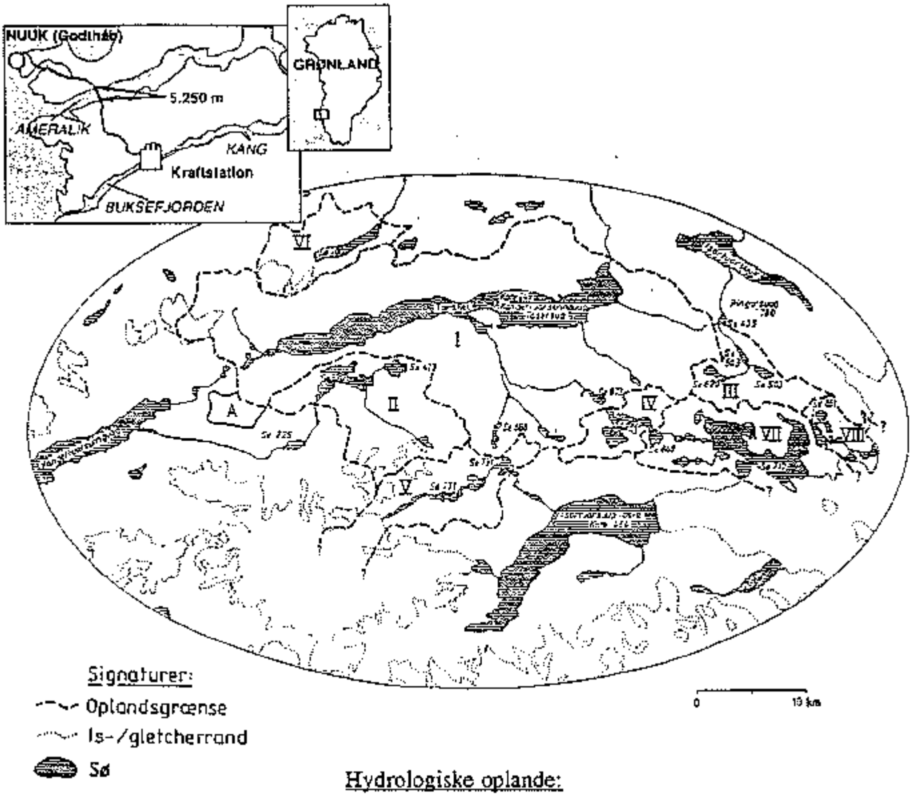
Energikrisen i 1973/74 medførte en øget interesse for udnyttelsen af de grønlandske vandkraftpotentialer.

I 1975 påbegyndte man kortlægningen og undersøgelserne af de største potentialer, der kunne tænkes udnyttet i forbindelse med minedrift eller ved etablering af stærkt energikrævende industrier, f.eks. fremstilling af ammoniak eller aluminium.

I løbet af få år blev interessen imidlertid drejet mod en række mindre vandkraftpotentialer, som i kraft af deres størrelse og beliggenhed var interessante i forbindelse med energiforsyning af byerne.

Siden 1980 har der været anvendt over 100 mio. kr. til hydrologiske, glaciologiske og anlægstekniske samt miljømæssige undersøgelser af vandkraftmulighederne i mere end 20 områder.

I 1986 besluttede det grønlandske landsting, at den fremtidige energiforsyning hovedsageligt skal baseres på udnyttelse af vandkraft, og i 1990 indgik man kontrakt med konsortiet Nuuk-Kraft omkring opførelsen af Grønlands første vandkraftværk, vandkraftværket i Buksefjorden.



Hydrologiske oplande:

I : Kangerluarsunnguup Tasersua (Kang), kote 249
II : Sø 370
III : Område syd for Pingorsuaq
IV : Sø 892
V : Sø 731
VI : Sø 700 (Amitsorsuaq)
VII : Sø 710
VIII : Sø 851 (området øst for sø 710)
A : Bækindtag, syd

Figur 1 Oversigtskort, hovedopland og potentielle overføringsoplande.

Vandkraftværket, der forventes klar til ibrugtagning i oktober 1993, skal forsyne Grønlands største by - Nuuk/Godthåb - med energi, og er med et samlet anlægsbudget på 1.000 mio. kr Grønlands hidtil største anlægsprojekt.

De hydrologiske og anlægstekniske undersøgelser der ligger til grund for beslutningen om bygning af vandkraftværket, er udført at Grønlands Forundersøgelser (tidl: Grønlands tekniske Organisation/Nuna-Tek, sektionen for vandkraftundersøgelser). De hydrologiske målinger i området blev startet i 1981, og på baggrund af en kort årrække med målinger og et intensivt analyse og modellerings arbejde, er et solidt hydrologisk grundlag for vandkraftværket tilvejebragt.

BASSINBESKRIVELSE

Buksefjordsbassinet (grønlandsk: Kangerluarsunnguaq), figur 1, er beliggende på 64°N og 50-51°W, ca. 50 km sydøst for Nuuk.

Bassinet er karakteriseret som nedbørsbassin (regn og sne) med ablation fra lokalgletchere. Det hydrologiske opland (opland I) regnet opstrøms for udløbet af hovedsøen Kangerluarsunnguup Tasersua (forkortet: Kang), er opgjort til 582 km^2.

Udover hovedoplandet (opland I) findes en række potentielle udvidelsesmuligheder i form af mindre deloplande II-VIII, hvorfra vandet kan overledes til Kang.

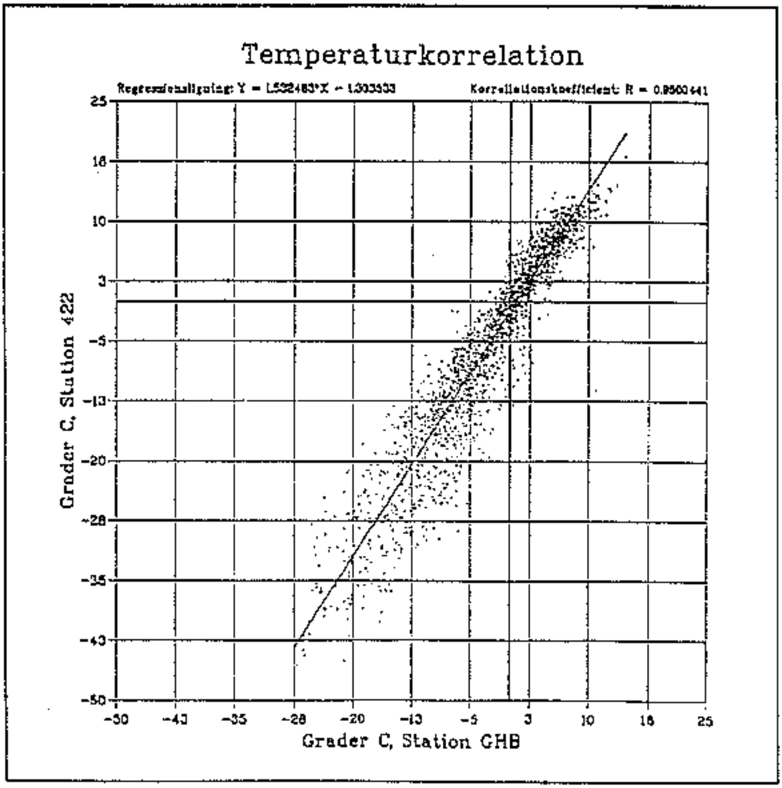
Den 30 km lange Kang sø udnyttes som reservoir. Søen har et overfladeareal på 75 km^2, og opdæmmes med en 15 meter høj betondæmning. Vandindtaget placeres 16 meter under det naturlige vandspejl, hvorved reservoiret vil kunne udnyttes med reguleringshøjde på 28 meter og et samlet reservoirvolumen på 1.900 mio. m^3.

DATAINDSAMLING

Til bestemmelse af den resulterende afstrømning til hovedoplandet, opland I, blev der i 1981 etableret en automatisk målestation ved Kang-søens udløb.

Målestationen er instrumenteret for måling af de væsentligste hydrologiske parametre i vandkraftsammenhæng: vandstand (afstrømning), lufttemperatur og nedbør. I perioden frem til anlægsfasen er der løbende udført vandføringsmålinger til opbygning og kontrol af Kang-søens udløbsfunktion.

Et net af manuelle nedbørsmålere placeret i hovedoplandet har bidraget med oplysninger om nedbørens højde- og afstandsvariationer, og snetakseringer samt satellitbilledanalyse har givet overblik over nedbørens fordeling både i tid og rum.



Figur 2 Temperaturkorrelation, Nuuk - Kang (St.422)

Tabel 1 Heatingfaktorer. Differens på månedsmiddeltemperaturen mellem Kang (st.422) og Nuuk i perioden 1981-1989.

Måned	Jan	Feb	Mar	Apr	Maj	Jun	Jul	Aug	Sep	Okt	Nov	Dec
°C	- 1.6	- 1.5	0.5	0.3	2.0	1.1	1.3	0.5	0.0	0.6	0.2	- 2.5

HYDROLOGISK ANALYSE OG MODELARBEJDE

På grund af den relativt korte måleperiode (1981-89), blev det besluttet at forlænge afstrømningsserien for bassinet ved hjælp af en hydrologisk afstrømningssimulering baseret på lange tidsserier af nedbør og temperatur data målt i Nuuk.

Temperaturoverførsel

Temperaturdata fra Nuuk blev sammenlignet med data målt i bassinet. Nuuk's kystnære beliggenhed og målestationens placering i den østlige ende af bassinet med udprægede fastlandsklima, resulterede i en overførsel at data ved hjælp af en lineær overførselsfunktion kombineret med en funktion som beskrev årstidsvariationen, en 'heatingfaktor', figur 2 og tabel 1.

Homogenisering

Nedbørsdata for Nuuk, tilbage til starten af dette århundrede blev analyseret og testet for homogenitetsbrud opstået ved bl.a ændringer af måleprincip og flytning af måler, figur 3 & 4.

Nedbørsoverførsel

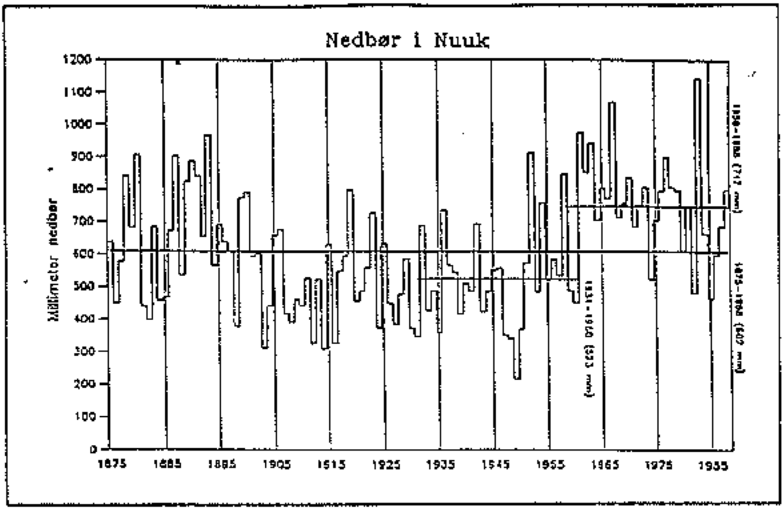
Korrelation mellem den homogeniserede nedbørsserie fra Nuuk og nedbørsserien målt i bassinet gav ingen brugbar overføringsfunktion for enkelte nedbørshændelser. Som det ofte ses er enkelt hændelser af nedbøren vanskelig at korrelere over større afstande, hvilket her forstærkedes af at de to målelokaliteter lå i to udprægede forskellige nedbørsregioner. Således valgtes det at anvende en simpel overføring hvor nedbør faldet i bassinet i middel blev fundet til at være 0.35 af nedbøren i Nuuk.

Modelberegning, afstrømning fra hovedoplandet

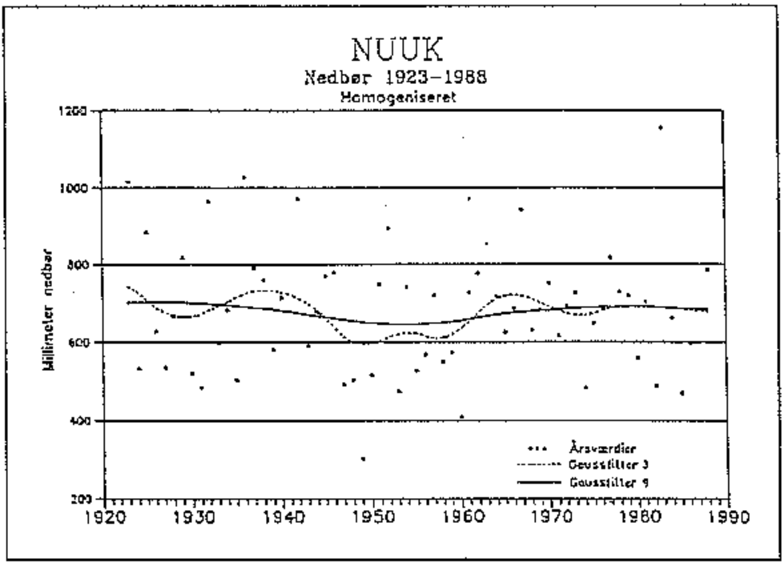
Til beregning af det hydrologisk grundlag for opland I er en modificeret version af NAM modellen anvendt. Modellen er tilpasset grønlandske forhold, idet specielt sneroutinen er ændret.

Ved modelkalibreringen er sammenhængen mellem temperatur og nedbør målt i bassinet forsøgt beskrevet i forhold til den resulterende afstrømning.

På baggrund af de overførte tidsserier og modelparametrene fundet ved kalibreringen, er der efterfølgende udført modelsimuleringer for perioden 1959-1988 til bestemmelse af årsmiddelafstrømningen afstrømning for opland I, tabel 2.



Figur 3 Årsnedbør, Nuuk 1875-1988.



Figur 4 Homogeniseret nedbør, Nuuk 1923-1988, langtidsmiddel.

Beregning af afstrømning fra overføringsoplande

På baggrund af kendskab til områdets nedbørsfordeling og afstrømningen fra opland I blev afstrømningen for de enkelte overføringsoplande indledningsvis estimeret ved forholdsberegning. I 1989 etableredes yderligere automatiske målestationer i de to primære overføringsoplande opland II og V. Og på baggrund af en relativ kort måleperiode på disse stationer, kunne afstrømningen for de sidstnævnte overføringsoplande verificeres. Tabel 3.

Flomanalyse

Til brug for dimensionering af dæmningen ved hovedreservoiret, er en analyse af 1000 års tilløbsflommen gennemført. Analysen er baseret dels på målte flommer i årene 1981-88, dels på simulerede flommer i perioden 1959-88, sorteret efter type (sne, regn, sne&regn flommer). 1000 årsflommen (Q1000) for hovedoplandet (opland I) er beregnet til 207 m^3/s, og Q1000 for hele området (med overføring af alle oplande) er beregnet til 318 m^3/s. Designflommen er herefter udarbejdet på baggrund af en analyse af varigheden af de observerede og simulerede flommer, og reservoirets kritiske varighed.

VANDKRAFTANLÆGGET

Vandkraftværket ved Buksefjorden er udformet som et traditionelt "norsk" fjeldanlæg, hvor kraftstation, transformer station og de vandførende tuneller ligger inde i fjeldet. Kraftværket har en faldhøjde på 261 m og et samlet reservoirvolumen på 1.900 m3. Fra reservoiret ledes vandet gennem en 10.600 m lang tilløbtunnel til kraftstationen. Kraftstationen er udstyret med to Francis turbiner med generatorer, hver på 15 MW, og der er plads til yderligere en turbine med generator i kraftstationen. Afløbstunnelen er 1300 m lang og leder vandet ud i havet.
Fra kraftstationen overføres energien til Nuuk via en 56 km lang, 132 kV højspændingstransmissionslinie. Linien krydser to fjorde, hvoraf krydsningen over Ameralikfjorden (der starter i 1013 m højde og ender i 444 m højde) er på 5.376 m - verdens længste frie spænd.
Vandkraftværkets gennemsnitlige årlige energiproduktion er på 185 GWh, hvoraf man i 1993 regner med at benytte 55 GWh til lys og kraft, mens resten er disponeret til elvarme.

HYDROLOGISK OVERVÅGNING & DRIFT AF KRAFTVÆRKET

Selve kraftværket opereres ubemandet fra en driftcentral i Nuuk. Mht. de fortsatte hydrologiske målinger i området, forventes disse at omfatte dels en kontinuerlig dataindsamling (nedbør, vandstand/vandføring, temperatur) på automatiske målestationer med datatransmission til kraftstationen og derfra

Tabel 2 Afstrømning fra Kangerluarsunnguup Tasersua (Kang), opland I.

Tidsperiode	Beregningsmetode	Årsafstrømning
1981 - 1989	målt	217 mio. m^3
1959 - 1989	Simuleret med målte nedbørdata fra Nuuk	228 mio. m^3
1959 - 1989	Simuleret med homogeniserede nedbørdata fra Nuuk	208 mio. m^3
1959 - 1989	Forholdsberegning ud fra homogeniserede nedbørdata fra Nuuk	215 mio. m^3
1923 - 1989	Forholdsberegning ud fra homogeniserede nedbørdata fra Nuuk	212 mio. m^3

Tabel 3 Beregnet afstrømning fra potentielle overføringsoplande.

Opland	Oplandsareal km^2	Oplandets middelkote (m.o.h.)	Beregnet årsafstrømning 1981 - 1989 mio. m^3
I	582	680	217
II	119	840	60
III	56	695	8
IV	36	1000	13
V	100	1005	60
VI	54	995	24
A	12	840	5

videre til driftcentralen, dels ved periodiske kontrol og referancemålinger i området.

FREMTIDIG UDBYGNING AF VANDKRAFT I GRØNLAND.

Grønlands Hjemmestyre forventer i 1992 at gennemføre en revision af planerne for den fremtidige udbygning af vandkraftanlæg i landet. Denne forventes at indeholde planer om bygning af vandkraftanlæg i såvel syd, vest som formodentlig øst grønland. I hvilket tempo disse planer vil blive omsat til praksis er endnu usikkert, men de foreløbige beregninger tyder på at det vil være samfundsmæssigt rentabelt at bygge yderligere 4 bynære vandkraftværker i de kommende 10 år.

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STATUS FOR UTVIKLING AV VASSDRAGSSIMULATOR

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Marit Lundteigen Fossdal	Vassdragsregulantenes forening	Norge

ABSTRACT

A computer system called the *Modular Interactive River System Simulator* is now under development in Norway. The simulator is aimed for two purposes: 1) Multi purpose water resources planning and 2)Optimal operation of hydro power systems. The simulator is planned to include more than 15 different water related models within a common user interface and with one common database to facilitate the data communication between different models and simplify data storage and data integrity. The user interface will be based on modern principles, with emphasis on graphics and on-line help for the user. This paper describes the status for the work on the model, and plans for the rest of the development which will be finalized by mid 1993. The rest of 1993 will be used for testing in three rivers in Norway.

1. INNLEDNING

Utviklingen av en såkalt Vassdragssimulator ble startet opp på initiativ fra Vassdragsregulantenes forening (VR) i 1990 (Erlandsen et. al, 1990). Utviklingsprosjektet har en tidsramme fra 1990 til avslutning i 1993, og en økonomisk ramme på 13.65 Mill. kr. (Killingtveit, 1991A). Etter planen vil selve programutviklingen være fullført i midten av 1993, og deretter skal den prøves ut i tre såkalte prøvevassdrag: Meråkervassdraget (Stjørdalsvassdraget), Gjengedalsvassdraget og Bjørkelangen i Haldenvassdraget.

Prosjektet er styrt av en brukerdominert styringskomite, og utføres i samarbeide mellom 7 vannfaglige institusjoner i Norge. Ansvaret for prosjektledelse er lagt til SINTEF NHL. Dette innlegget summerer opp status for arbeidet pr. idag, med hovedvekt på de moduler som nå er besluttet inkludert i simulatoren. Arbeidet går hittil i hovedtrekk etter planen, både tidsmessig og økonomisk. Redusert finansiering i 1992 kan medføre at en del planlagte aktiviteter forskyves til 1993, men dette forventes ikke å påvirke sluttføringen av prosjektet i 1993.

2. HOVEDTREKK I SIMULATOREN

Hovedtrekk i oppbygging av simulatoren er beskrevet tidligere (Fossdal og Killingtveit, 1990) og blir ikke gjengitt her. Et viktig trekk er oppdelingen i tre separate "lag", brukergrensesnitt, modeller og database slik som vist på Figur 1. Dette gjør oppbygging og bruk modulær, og letter spesielt senere vedlikehold og videreutvikling av modellen. I hovedsak vil brukergrensesnittet være nyutviklet, og programmert i moderne "vindusorienterte" programmeringsspråk (C, C++), mens de fleste modellene vil være eksisterende FORTRAN-baserte beregningsmodeller som ønskes endret så lite som mulig internt.

Datautveksling mellom database og beregningsmodeller skal utføres med et standardisert sett rutiner (et bibliotek). Det er lagt stor vekt på å lage en logisk datamodell som definerer alle typer data som skal inngå i simulatoren, og relasjoner mellom disse. (Sælthun, 1992). Datamodellen og rutiner for databaseaksess er forøvrig utarbeidet sammen med og koordinert med det såkalte ID-prosjektet. (Botnen m.fl., 1989). Dette betyr at programvare som utvikles i de to prosjektene vil kommunisere med databasen på samme måte, og også kunne utveksle data med hverandre på en effektiv måte.

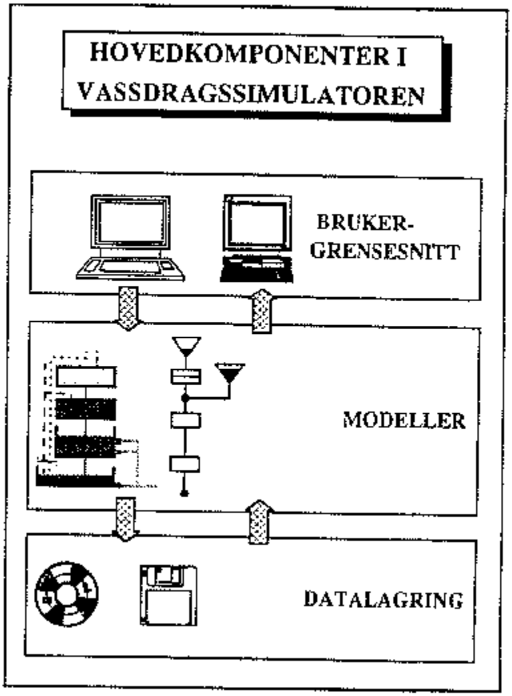

Figure 1 Hovedstruktur i oppbyggingen av vassdragssimulatoren

Systemarkitektur

Systemarkitektur i simulatoren er lagt opp med følgende hovedformål som bakgrunn:

- Å skille brukerdialog, beregningsprogram og database klart fra hverandre
- Å bruke eksisterende, velprøvde beregningsprogram med minst mulig endringer i selve beregningsalgoritmene
- En modulær oppbygging som muliggjør oppdatering/utskifting av programmoduler uten endringer i andre deler av simulatoren, og slik at bare den delen som er endret behøves å bli distribuert
- Lagring av alle data skal skje i en felles relasjondatabase

Hovedstrukturen som er definert for å imøtekomme disse kravene er vist på Figur 2. Et viktig element her er de såkalte parametereditorer som er programmoduler som skreddersyes til hver enkelt beregningsmodell. All brukerinteraksjon i forbindelse med dataoppsett til de enkelte modellene skal utføres gjennom parametereditoren. Gjennom denne vil brukeren definere oppsett av inngangsdata og legge disse tilrette for hver modell i form av filer eller tabeller i databasen. Pre- og postprosessorer vil deretter legge data tilrette for kjøring av de enkelte modeller. På denne måten kan modeller som ikke ønskes forandret, beholdes uforandret. Dette er viktig for å kunne bytte modellene ut med nye versjoner som må forventes å komme. Rent teknisk vil alle beregningsprogram bestå av selvstendige eksekverbare program som dermed kan byttes ut uten at det påvirker andre deler av simulatoren.

Kvalitetssikring

Det er lagt stor vekt på standardisering under programutviklingen. Dette er også tatt vare på gjennom det kvalitetssikringssystem som er spesifisert (Wathne, 1992) og som i stor grad bygger på ID-prosjektets kvalitetssikringsplan.

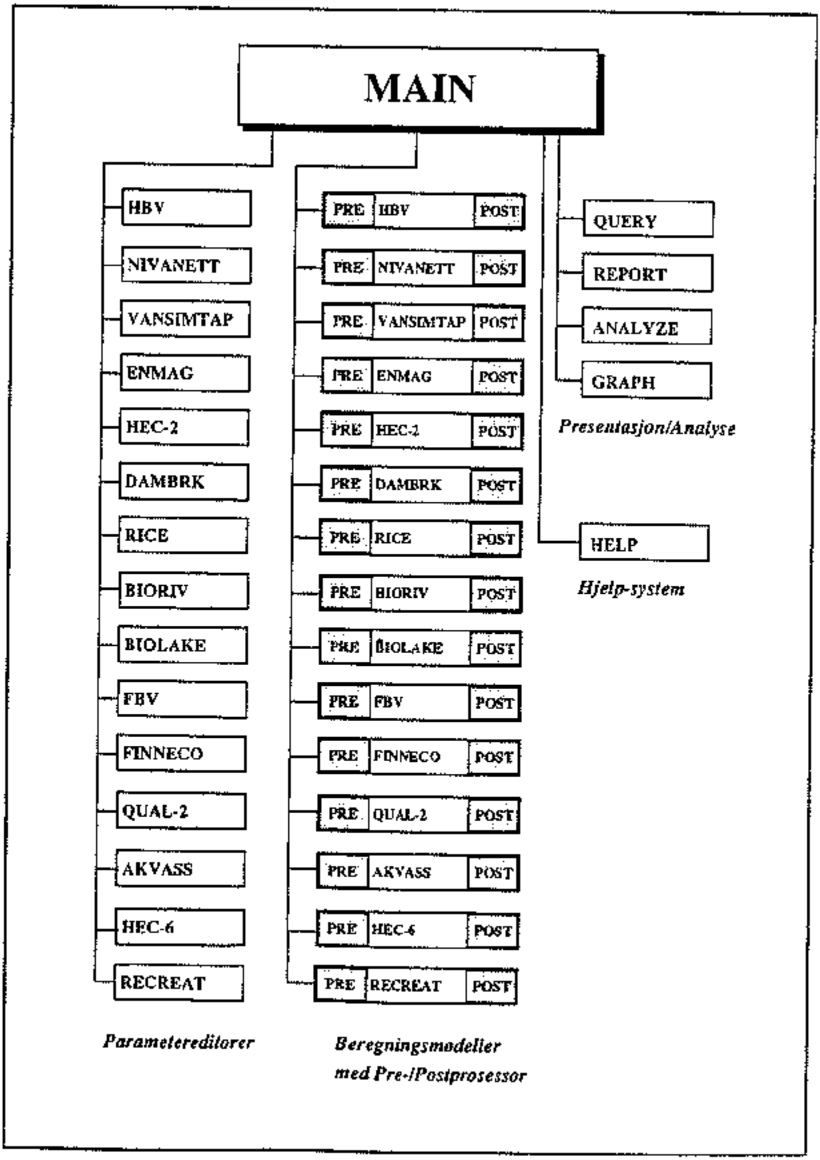

Figure 2 Programmoduler som skal inngå i vassdragssimulatoren

3. MODELLER SOM SKAL INNGÅ I SIMULATOREN

Nesten alle modeller som skal inngå i simulatoren er nå valgt ut. Nedenfor følger en opplisting av de valg som er gjort. For de fleste av modellene er arbeidet med tilpasning til simulatoren godt igang, og ser ut til å kunne gjennomføres etter planen. Modellene som skal inkorporeres i simulatoren kan deles inn i 4 hovedtyper, slik som vist på Figur 3.

Modelltype 1: Input fra nedbørfeltet

Nedbør-avløp: HBV-modellen

Urbant avløp: NIVANETT

Modelltype 2: Fysiske, kjemiske og biologiske prosesser i vassdraget

Stasjonær strømning: HEC-2

Ikkestasjonær strømning: DAMBRK

Ismodell: RICE

Vanntemperatur: RICE

Vannkvalitet innsjøer: FINNECO

Vannkvalitet elver: QUAL-2

Erosjon/sedimenttransport: HEC-6 (?)

Modelltype 3: Vannkraftsystemet

Enkle system (Ett-magasin): ENMAG

Fler-magasin systemer: VANSIMTAP

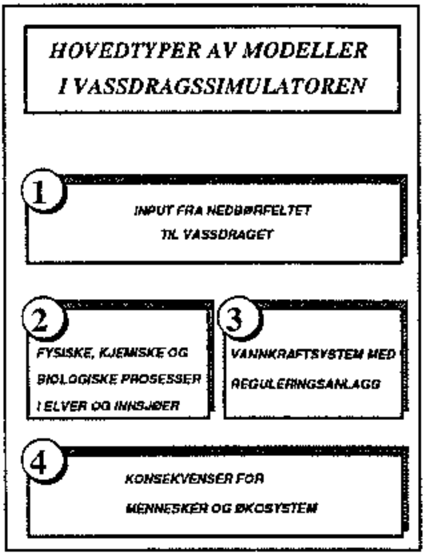

Figure 3 Modellene som inngår i simulatoren kan deles inn i 4 hovedgrupper

Modelltype 4: Konsekvenser for økosystem og mennesker

Fiske-habitat: Fysisk beskrivende vassdragsmodell (FBV-modellen)

Biologiske forh. i innsjøer: BIOLAKE (Skal nyutvikles etter spesifikasjon fra NINA)

Biologiske forh. i elver: BIORIV (Skal nyutvikles etter spesifikasjon fra LFI)

Friluftsliv/Turisme/Rekreasj.:Nyutvikles - Basert på FBV-modellen

Grunnvann på elvesletter: AKVASS

4. BRUKERGRENSESNITT

Simulatoren blir utviklet for kjøring på UNIX-arbeidsstasjoner, og skal kjøres under X-Windows med Motif. En betydelig del av utviklingsarbeidet utføres på PC med programmering under Windows. Det legges stor vekt på å få så stor del av programkoden som mulig flyttbar, og et objektorientert programutviklingsmiljø er valgt for å lette dette arbeidet (Glockenspiel CommonView). All kode for brukergrensesnittet skrives i C/C++ og kan ved rekompilering flyttes mellom PC/Windows og UNIX/X-Windows. Andre deler av simulatoren er pr. idag ikke mulig å kjøre under Windows, men standardiseringen og flyttbarhet av kode ansees

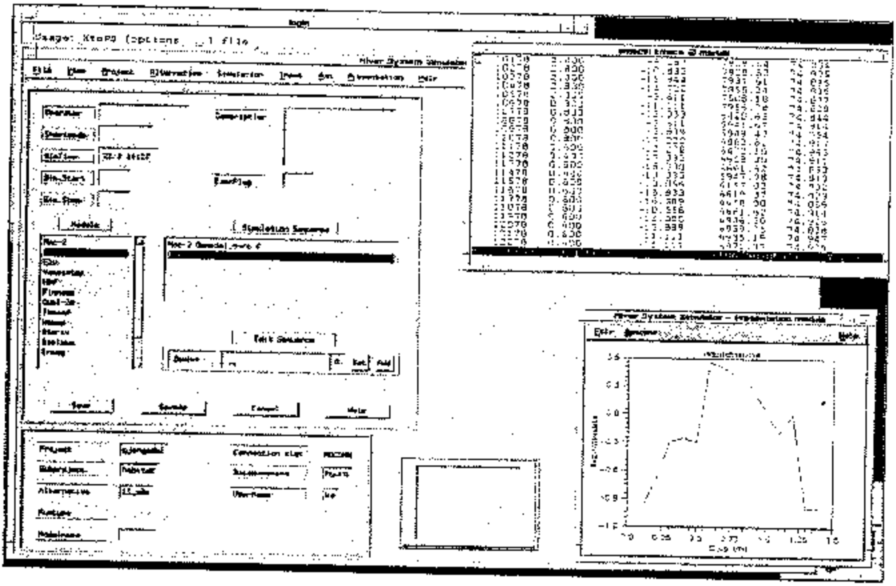

Figure 4 Eksempel på arbeidsmiljø ved kjøring av vassdragssimulator på UNIX arbeidstasjon under X Windows med Motif

likevel som svært viktig for å møte framtidig utvikling der videreutvikling av Windows synes å kunne gi en ny og langt bredere basis for kjøring av simulatoren. Brukergrensesnittet er basert på standard dialogformer med menyvalg i flere nivå, og mulighet for bruk av mange vindu på skjermen. En illustrasjon av det arbeidsmiljø dette vil gi på skjermen er gitt på Figur 4, som er hentet fra en prototyp av simulatoren som er brukt under arbeidet med kravspesifikasjon for brukergrensesnitt. (Killingtveit, 1991B) (Alfredsen, 1992).

Det kan her nevnes at en vil prøve på å bruke en del av brukergrensesnittet som utvikles under ID-prosjektet som "innfallsport" til simulatoren. Dette vil kunne gi enklere bruk av simulatoren for personell ved kraftverk og driftssentraler, som forventes å bli spesielt fortrolig med det brukergrensesnitt som utvikles under ID-prosjektet.

Det er også satt igang en forstudie ved NVE på bruk av GIS-basert (GIS=Geografiske Informasjons Systemer) brukergrensesnitt mot simulatorem. Med dette tenkes spesielt på bruk av kartbasert presentasjon og geografisk stedfesting av objekter. Forprosjektet ved NVE ventes å klarlegge muligheter, en evt. implementasjon av et fullt GIS-basert brukergrensesnitt må trolig vente til den såkalte Fase 4 i utviklingarbeidet, som tidligst kan starte i 1994.

5. DATABASE OG DATAUTVEKSLING

Et viktig prinsipp for simulatoren er at alle data skal lagres i en sentral database, slik at data som evt. brukes i flere modeller bare skal lagres på ett sted. Dette er viktig for å sikre dataintegritet, og hindre at forskjellige versjoner av data oppstår og brukes på en uønsket måte. Det har også vært et viktig krav at databasen skal organiseres på en måte som reflekterer de faktiske fysiske/administrative forhold i den virkelige verden. Dette har medført behov for oppbygging av en logisk datamodell som beskriver hvilke data som skal inngå i databasen og hvordan disse er relatert til hverandre. Den logiske datamodell er bygget opp i nært samarbeide med ID-prosjektet (Sælthun, 1992). For å realisere datamodellen rent fysisk benyttes en moderne relasjonsdatabase (SYBASE) som også er valgt av ID-prosjektet. Utveksling av data mellom beregningsmodeller og database skal skje med standardiserte rutiner som utvikles under ID-prosjektet, basert på Embedded SQL.

6. UTFØRENDE INSTITUSJONER

Arbeidet med utvikling av Vassdragssimulator krever faglig innsats fra en rekke ulike miljø. Tilsammen 8 ulike institusjoner er pr idag involvert i arbeidet, med ulike typer oppgaver som skissert nedenfor. Arbeidet krever en betydelig innsats i form av koordinering, og her spiller en aktiv innsats fra styringskomiteen en stor rolle. Arbeidet med simulatoren har allerede medført bedret faglig kontakt mellom institusjonene, Dette forventes å øke ytterligere under den planlagte utprøvingen i tre prøvevassdrag i andre halvdel av 1993.

NHL	Norsk hydroteknisk laboratorium	Prosjektledelse Programmering av hovedgrensesnitt Hydrauliske modeller (HEC-2, DAMBRK) Nedbør-avløpsmodeller (HBV) Fysisk beskrivende vassdragsmodell (FBV) Grunnvann på elvesletter (AKVASS) Programmering i BIORIV/BIOLAKE/RECREAT
EFI	Elektrisitetsforsyningens forskningsinstitutt	Kraftverkssimulering (VANSIMTAP) Utvikling av basisprogramvare gjennom ID-prosjektet, spesielt databaseaksess Nedbør-avløpsmodell (HBV)
NVE	Norges vassdrags- og energiverk	Datamodell for simulatoren Nedbør-avløpsmodell (HBV) Erosjon- og sedimenttransport (HEC-6 ?) GIS-basert brukergrensesnitt
NTH	Institutt for vassbygging	Forstudier for programutvikling Video/Bilde integrasjon Kraftverkssimulering (ENMAG)
NIVA	Norsk institutt for vannforskning	Vannkvalitet i innsjøer (FINNECO) Vannkvalitet i elver (QUAL-2)
NINA	Norsk institutt for naturforskning	Biologiske forhold i innsjøer (BIOLAKE) Biologiske forhold i elver (BIORIV)
LFI	Laboratoriet for fersvannsøkologi og innlandsfiske ved Univ. i Oslo	Biologiske forhold i rennende vann (BIORIV) Fiskehabitat i rennende vann (FBV)
TD	Telemark distriktshøgskole	Vannbasert rekreasjon og friluftsliv (RECREAT)

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THE ECOSYSTEM APPROACH TO WATER MANAGEMENT

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INTRODUCTION

Today, there is no disagreement, either in theory or in practice, that water resources must be managed. Whether we consider the local sources for the water supply of our own town or village or the national, even multinational water-resource bases, we are facing the need for using and protecting water so that:

- Water quantity is sufficient and does not suffer long-term reduction below natural replenishment;
- Water quality is not suffering and water quality standards are maintained;
- Realistic economic goals are met, in both the short and the long term.

These principles are fundamental for water sustainability.

Rural people living close to their natural resource base know that Nature sets her own limits and will avenge transgressions. In a way, modern thinking has come full circle 1(after lengthy departures) and now embraces that same wisdom. A recent headline in TIME magazine (29 July 1991) highlights the problem: "The very prosperity created by the Colorado river in the American West threatens the river's survival". Rivers are finite resources and as such create competition and tension and even contribute to international hostilities.

We must learn and remember that water is a part of our physical environment and the ecosphere itself, where man is an actor. That statement may sound extremely banal; the consequences of forgetting are not. As the economic exploitation of water has dominated over its function in maintaining ecosystems, there is a need for an innovative approach to water management. How?

It is easy to point to strategies for water management which could have serious and inadvertent side-effects.

One might wish, for example, to accord top priority to the economic sector having the highest current economic yield and maximizing that sector's output. Extreme water-power development could be one such water use. Dry river runs without fish life could be one of the consequences. Irrigation of cash crops is very common in many semi-arid climates. Soil erosion or excess salinity can be some of the consequences.

Another type of strategy might be to develop the water resources (or focus attention on pollution problems) as they appear in one particular phase of the hydrological cycle or in one particular location in the catchment. Again, unforeseen consequences tend to appear. Over-exploitation of groundwater, without due account being taken of natural recharge, will lead to lowering of the groundwater table, possibly irreversible mining of fossil water and a host of connected problems, such as increased pollution risk or damage to urban structures. Exploiting groundwater in one area may reduce surface-water resources in neighbouring rivers. Examples of unchecked sewage disposal causing widespread pollution in downstream reaches or lower-lying aquifers, are almost classical in the water literature.

A third kind of water-management problem stems from incomplete knowledge of water as the centerpiece in natural systems. Economic development normally entails land-use changes; and land-use changes will always lead to changes in water circulation, some of which could be negative or even disastrous. Well-known examples are increased risks of soil erosion and flooding in areas of forest clear-cutting. Urbanization is one of the most radical changes in a catchment. Associated hydrological and water management problems include increased flood runoff, reduced infiltration, and consequently, reduced groundwater yield from local aquifers and particular pollution mixes and paths.

Examples such as these are numerous and the scientific and technical literature abound with detailed descriptions. One lesson to be learned (and one which is gradually coming into focus in water management) is that piecemeal, sector-oriented planning and use of water resources tend to cause long-term problems. Strategies which apply a holistic view stand a better chance of succeeding. This means trying to integrate all relevant users, to keep in mind all phases of the hydrological cycle (and to remember that land-use changes will also change the cycle) and to view the catchment as an entity.

The so-called ecosystem approach is such a strategy. An ECE seminar on the ecosystems approach to water management was held in Oslo in May 1991 [1]. The main results from that seminar are incorporated in this article in the conviction that the management problems which have to be solved are of universal concern as is the ecosystem approach as a strategy for their solution.

SOME DEFINITIONS

A distinction should be made between *environment* as the complex of air, water, land and living organisms surrounding us and *ecosystem*, in which man is an active part - is, indeed, the major actor. The difference between environment and ecosystem has been compared to the difference between *house* and *home*. An ecosystemic view will include both social, economic and environmental considerations. Man does not simply interact with an external environment but is locked into one life-supporting system [1].

This perception is very important when applying the ecosystem approach to water management. It means, for instance, that not only must water be available in sufficient amounts and with acceptable quality but also that management solutions should be socially sustainable. In this respect, we are talking about solving water-related conflicts between individual users or user groups, even countries; we are talking about the costs and revenues involved; we are talking about the aesthetic value of water; we are talking about the need for public participation in the decisions dealing with water.

Ecosystems strive to maintain their balance of internal energy flow and minimize energy loss. External impacts may disturb the equilibrium, determined by the tolerance of system components. The function of ecosystems in maintaining the desired equilibrium in nature leads us to the management need to conserve or restore, when necessary, natural aquatic complexes. [1,2]

In brief, the ecosystem approach is characterized by:

- The integrated use of knowledge from various fields of spesialization (hydrology, biology, technology, economics, law etc.). Only after a synthesis of available and relevant knowledge has been prepared, should a decision be made;
- Focus on links between environmental elements and man in a holistic perspective, in which man is an actor and not only an economic/technical user;
- A multi-media approach (land, water, air, living organisms) which, at the same time, is geographically comprehensive, e.g. whole catchments.

A healthy ecosystem has been compared to a house of cards: carefully constructed and balanced, the cards support one another; the effect of too many stresses of the ecosystem is similar to that of removing too many cards from the house - the entire construction collapses [2].

PRACTICAL APPLICATION

The ecosystem approach may be easier to apply in water bodies which have near-pristine conditions. In such cases, the aim of management is often to maintain and protect. In cases of badly degraded waters it may be practically impossible to apply an ecosystemic view everywhere, simultaneously, and to the same standards. Some general guidelines for practical purposes may be outlined, however, and some general tendencies described:

(a) Legislation

The principles of ecosystem-based water management should be incorporated into national and international legislation and policy statements. Among those principles most frequently considered are:

- The "polluter pays" principle;
- Environmental impact assessment (EIA);
- The precautionary principle;
- The principle of sustainable use of water;
- The critical load concept.

The first two have been in existence for a long time and have demonstrated their usefulness - and their limitations. An EIA, for instance, seldom questions economic development as such or considers the long-term goals for healthy ecosystems. The standardization of EIAs and a stronger position on transboundary problem-solving are needed. The *"polluter pays" principle* must be supplemented in the future with the perception of water as an economic good (see section (e) below).

The *precautionary principle* states that where there are threats of serious or irreversible damage, lack of full scientific certainty should not be used as a reason for postponing measures to prevent environmental degradation [3]. The precautionary principle is seen as a basis for sustainable development.

Sustainable development (in this context referring to water use) was coined by the World Commission on Environment and

Development (WCED)[4] and is taken to mean a development which meets the needs of the present without compromising the ability of future generations to meet their own needs.

The so-called *critical load* concept is related to the principle of protecting the most sensitive user and is defined as follows in the context of acidification of surface waters: the loading of one or more pollutants, below which significant harmful effects on specific sensitive elements of the environment are not likely to occur, according to present knowledge [5];

(b) Institutional arrangements

Practical application of integrated management often stumbles on a highly fragmented organisational structure. Ministries, regional offices and sector-interest agencies often compete in a confused way. Current thinking seems to favour administration of water use through one ministry or one national water authority. Further, there is a trend towards giving management responsibility to regional and local authorities. This approach may facilitate co-ordination with land-use planning, which often is a local or regional responsibility. It would also allow local knowledge and preferences to bear more strongly on water-related decisions. It is interesting to note that many countries base their water administration on ecosystem units (e.g. river authorities in France and the water boards in the United Kingdom);

(c) Planning

Several countries have made (or are making) water-resource planning an integrated part of land-use planning. Water master plans exist in some countries and they may include studies of elements of water ecosystems (such as water quality and biological species). However, studies of ecosystem functioning as a whole and balancing of long-term goals for various user sectors are scarce indeed. More systematic development of nation-wide water master plans or other strategic plans could improve the role of ecosystem-based water management, not least to avoid conflicts in transboundary situations;

(d) Impact assessments

All activities in the catchment which may threaten the quality or sustained yield of water or its biological diversity should be analysed by environmental impact assessment - EIA - prior to authorization. Many countries either have formal EIA requirements or similar procedures. What is needed in the future is to rephrase the question: "What will be the environmental impact of this or that proposed economic development?" as "What set of economic developments are compatible with sustainable water use and ecosystem integrity?".

(e) Economic measures

To foster this shift of mentality, it will be helpful when elements of aquatic ecosystems can be assigned an economic value. Only then can cost-benefit and cost-effectiveness calculations be complete. Admittedly, this is complicated. We can no longer regard water as a gift from nature, to be exploited freely at the will of each individual user or user group. Water-pricing policies are at the centre of debate and the consensus is growing that water is an economic good and should be treated as such. Water users are increasingly being charged for real market costs. An exception is, understandably, the basic supply needed for maintaining life and good health;

(f) Ecosystem evaluation and classification

In order to be able to allocate resources for water management in a systematic way, the evaluation of system health and classification of water quality and use are needed. Methodologies for evaluation have traditionally been founded on chemical characteristics, whereas modern trends are to assess water quality according to biological indicators (e.g. algal blooms as indicators of excessive lake eutrophication or bottom fauna for assessing river water quality). Even for water classification methods, the current trend is towards reliance on biological indicators such as bio-diversity;

(g) Integrated monitoring

For the evaluation of ecosystem conditions, monitoring data are needed. In line with the integrated nature of the ecosystem approach, modern monitoring programmes include physical, chemical and biological elements. Integrated monitoring keeps track of inflows and outflows to the catchment of water and its chemical and biological components, as well as the internal dynamics within the catchment. In spite of the complexity of integrated monitoring, it is superior to other monitoring systems in providing insight into cause-effect relationships and for assessing the success of water management aims, including sustainability.

Nevertheless, other monitoring systems also have roles to play. Operational national networks will, for instance, provide long-term data necessary for establishing statistical distributions and natural variation spectra. A recent survey shows, unfortunately, that since 1977, the level of activity -- in terms of hydrometric stations, storage of data and number of qualified hydrological staff - has declined seriously in many developing countries [6]. This unfortunate development means less reliable design of water schemes, inferior irrigation management and inaccurate flood forecasting. High-quality monitoring is also a precondition for reliable forecasting of ecosystem behaviour;

(h) Public participation

One of the basic principles on which an ecosystem approach should be founded is that the public should take part in decision-making. Success depends on both consultation with, and active support from, the local population. Participation should, of course, reflect the diversity of interests involved and voluntary organizations may therefore play prominent roles. Individuals and organizations may need education for the better understanding of ecological principles and thus being able to make valid judgements.

EXAMPLES

Ecosystem approaches can be applied to management problems on all scales. Indeed, our globe can be seen as "an organism whose health depends on the health of all its parts" [4]

One example of regional, if not global, application is the decision to base renegotiation of the ECE protocols on the reduction of sulphur and nitrogen emissions on the critical loads concept (see section (a) above), instead of using flat-rate percentages for all countries. The underlying idea is to reduce acidifying deposition to such an extent that the whole environment is protected. The citical load for a certain pollutant may be different and site-specific for various receptors, such as soils and lakes. In order to protect the whole environment, the ultimate critical load should not exceed the lowest of these critical loads.

On a smaller, but still international scale, an ecosystem approach is being applied to the restoration and protection of the Great Lakes of Canada and USA. The Great Lakes Basin covers some 520 000 km^2, supporting more than 35 million people. The agreement between the two countries on the Great Lakes water quality is based on the recognition that "restoration and enhancement of the boundary waters cannot be achieved independently of other parts of the Great Lakes Basin ecosystem with which these waters interact". The concern for the Great Lakes ecosystem was fuelled by the breakdown of Lake Erie fisheries in the 1950s and 60s caused by eutrophication from excessive nutrient inflow from sewage and farm runoff.

During the 1970s, vigorous efforts were successful in redusing the inflow of phosphates. Mayflies, which had suffocated in the eutrophic conditions returned; mayfly predators, including commercial fish species like perch and bass, also returned.

Still, the effects of toxic substances in the Great Lakes pose serious problems and their elimination is a top-priority goal, focusing in particular on industrial processing methods, product substitutes and waste-disposal practices. Water management is becoming human management.

The lesson learnt in Norway, in the case of Lake Mjøsa, is that there is no end to saving a lake (see Fig.1 and 2). The lake is Norway's largest - 365 km^2. Its catchment is 16 500 km^2 with 200 000 inhabitants. Of these, 55 000 use Lake Mjøsa as their drinking-water source. The present water quality does not satisfy drinking-water standards.

Warning signs appeared about 1950, but it was not until the late 1970s that algal growth, unpleasent smell, toxic substances and other such phenomena became so serious that an action plan for saving the lake from an ecological disaster was put into operation. Between 1976 and 1981 1.4 billion NOK (more than US $200 million) was spent on 42 new purification plants, 280 km of new sewage piping, and improvements to old drainage systems. Local people were discouraged from using detergents containing phosphates (sales are now banned), farmers were advised on the use of manure and other fertilizers and industrial discharges were reduced. Conditions were considered satisfactory and the campaign was called off in 1981. During the years 1984-85 already, however,Lake Mjøsa began to smell unpleasant again and algal growth increased rapidly. A new short-term plan was completed 1987-89 and a longer-term action plan is under way.

An interesting result of the Lake Mjøsa restoration efforts, is the development of models for quantifying the benefits of mitigation measures in terms of the practical significance for residents, as opposed to quantification of reduced inputs of substances. Mitigation measures are ranked according to cost-effectiveness criteria, where political judgement enters into the equation. It is expected that implementation of the plan will solve eutrophication problems, that drinking-water standards will be achieved, that toxics will no longer threaten the ecological integrity of the lake and that the lake ecosystem will be in balance. History also shows, however, that remaining in balance requires continuous surveillance and attention.

The ecosystem approach to water management is equally relevant to developing and developed countries, as shown in a recent study on water management of the Save River Basin, Zimbabwe, a region characterized by high evaporation. Of an annual rainfall of 600-700 mm, only about 10 per cent appears as river runoff. Soil erosion is a major problem, the rate of which is markedly influenced by the population density. The erosion rates from grazing in so-called communal land areas have been estimated at 75 t ha^{-1} yr^{-1}, as opposed to areas of lower population density. The erosion-caused loss of land is actually far more detrimental than the ensuing loss of storage capacity in silted-up reservoirs. In Zimbabwe, the aim has traditionally been to maximize yields per hectare, presupposing that water is more freely available than irrigable land. With the present, changed approach, water is considered a scarcer commodity than land. Irrigation schemes now aim to achieve maximum crop yield per unit of water rather than per unit of land.

Development schemes in this region, including new reservoirs and irrigation, as well as resettlement, obviously have to integrate a range of natural constraints and land-use aspects to obtain sustainability. Government policy emphasizes local delegation of responsibility, and increased farmer participation in design, financing and management [7].

At the other extreme of natural environments - the Arctic - the natural susceptibility sets very narrow limits for human intervention without harm to ecosystems. Water management in such environments becomes a very delicate balancing act.

THE FUTURE

The above-mentioned ECE Seminar on the ecosystem approach to water management prepared a set of recommendations for consideration by the relevant ECE bodies. In brief, what seems to be needed is *operationality*.

We have probably arrived at a point of consensus that water resources simply must be managed in a way which ensures sustainable yields and acceptable quality. There is no alternative. The ecosystem approach provides a framework for recognizing that everything influences everything else and that humans are dynamic parts of nature. Still partially missing are agreed standards, management procedures, classification bases, decision-making models, monitoring systems and other practical tools. If we could agree on this internationally, we would at the same time move towards possible solutions to some of the gravest problems facing us.

The solution will require new thinking. It will also require a higher level of close co-operation between professionals in various water-related fields, and the decision-makers.

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Fig.1 Pollution downstream from a potato starch factory draining to Lake Mjøsa. Serious pollution problems have led to broad-scale action plans for restoring lakewater quality.

(Photo: H. Holtan, NIVA)

Fig.2 Pollution problems of Lake Mjøsa are caused by a mixture of municipal and industrial waste, as well as agriculture. The arable land is often cultivated right down to the lakeshore.

FLOOD CONTROL ON THE MIDDLE REACHES OF THE RIVER IIJOKI

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ABSTRACT

Possibilities were examined for preventing flooding on the middle reaches of the River Iijoki caused by the inadequate ability of the river to conduct water away during the rising stage of the spring high water season. The problem cannot be solved without some new construction work.

Several alternative methods exist for preventing flood damage: dredging of the river, construction of embankments at the village of Kurenalus, a combination of dredging and embankments, and various means of floodwater storage.

The best means of river improvement, however, would be to construct a resevoir of volume 250 million m^3, which would ensure that floods in the middle reaches of the river of the extent that occur once in 200 years would not cause damage in the area around Lake Pudasjärvi or in the village of Kurenalus. The same effect could be achieved (but only at Kurenalus) by building about 5 km of embankments. It is impossible to reduce flood flow sufficiently using sluicegates constructed primarily for log floating purposes or by improving natural bifurcations, and the same is also true of temporary reservoirs.

None of the alternatives is economically viable from a flood control point of view, and there is also a significant risk of damage to the hydroelectric power stations further downstream if the discharge in the river is increased too much.

GENERAL SURVEY OF THE RIVER BASIN AND HYDROLOGICAL CONDITIONS

The river basin of the River Iijoki is situated between the river basins of the River Kemijoki and the River Oulujoki. It begins almost on the eastern border of Finland and extends to the Gulf of Bothnia, the river mouth being about 40 km north of Oulu (Fig.1). The lenght of the main river bed is 370 km, including several series of lakes. The main river begins 250 m above sea level. 70 km of the lower reaches of the River Iijoki have been exploited for production of hydro-electric power (five hydro-electric power stations). A further four small hydro-electric power stations are also to be found in the upper reaches of the watercourse.

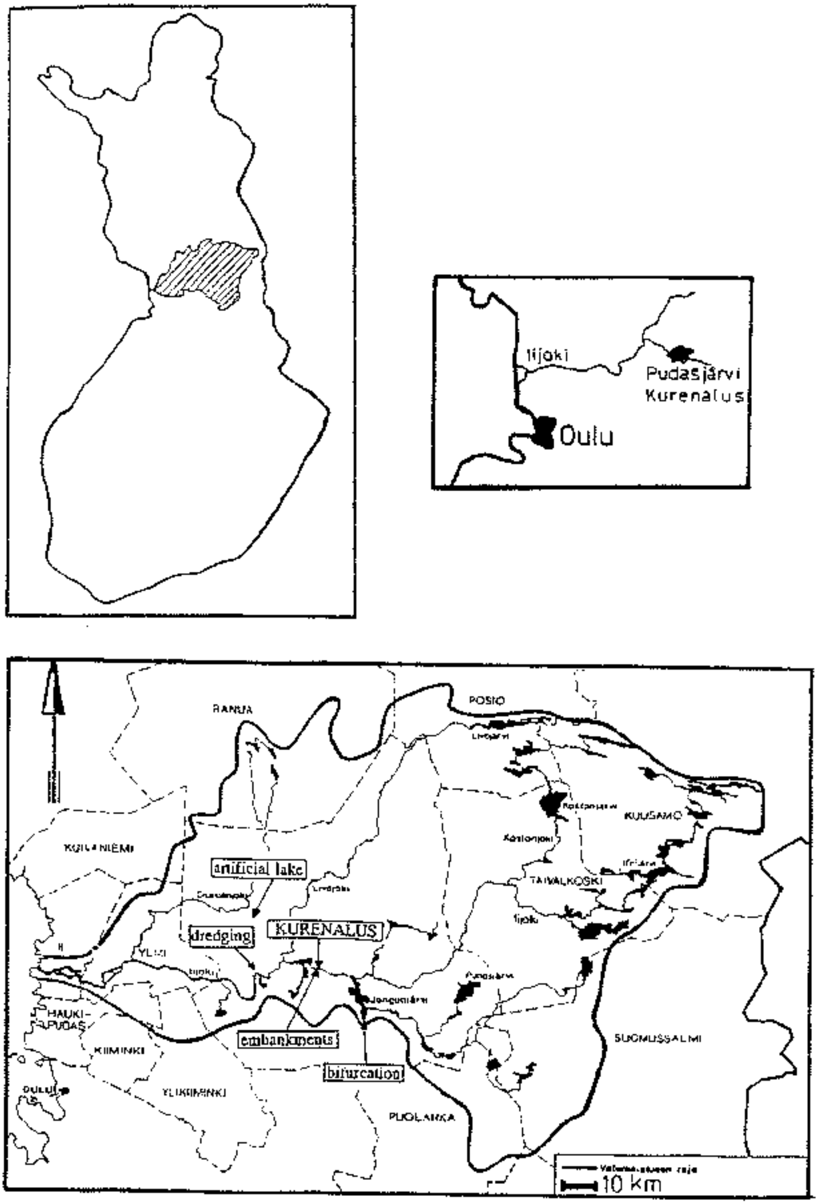

Figure 1. The River Iijoki watercourse.

The catchment area of the River Iijoki is 14,319 km^2. It is the seventh biggest river basin in Finland. The lake percentage of the River Iijoki is 5,7 % which is lower than Finnish average, namely 10 %. The mean discharge of the River Iijoki is 176 m^3/s and maximum discharge 1,429 m^3/s.

The general fluctuation index for the discharge of the River Iijoki (i.e. the mean maximum discharge : the mean minimum discharge) is 25. The general flood index (GFL) shows how many times greater the biggest flood is compared to the median (or ´normal´) discharge. The media value is more suitable for comparative purposes than the mean value because half of the time the discharge of the river is greater than media and half of the time smaller than the median. Thus the general flood index is the relatio between the mean maximum discharge and the median of the monthly flow.

The maximum flood index (HFL) shows how much bigger the flood may be in comparison to the normal discharge. The maximum flood index is thus the ratio between the maximum discharge and the median of the monthly flow.

The general flood index for the River Iijoki is 6,9 and the maximum flood index 9,7 (Mansikkaniemi, H. 1986).

Flood indices reveal the size of floods and the fluctuation of river discharges. With their help it is possible to compare the floods of rivers of different sizes. It is in fact surprising that the flood indices of many of the rivers in Ostrobothnia that are famous for being prone to severe flooding are relatively small. For example, for the River Kalajoki the general flood index = 14,0 and the maximum flood index = 26,0 and the corresponding values for the River Kyrönjoki are 9,0 and 14,0 for the River Aurajoki 25,1 and 63,6. On the basis of these flood indices one may assume that the extensive spring flooding in the River Iijoki water basin are caused more by the morphological features in the river valley, by the flatness of the basin and by the smallness of the river bed than by an abnormally and extremely large volume of water flowing in the river.

FLOODS ON THE MIDDLE REACHES OF THE RIVER IIJOKI AND FLOOD PROTECTION ALTERNATIVES

The flood calculations for the River Iijoki present, among other things, a forecast for the severest probable flood. The risk of such a flood accurring is put at 0,1 %, i.e. it would occur on average only once in every 1000 years. The severest probable flood might raise the water level in the village of Kurenalus (c. 5000 inhabitants) to 1,5 m above the level of the exceptional spring flood recorded in 1982, and it should be noted that the discharge of the river in 1982 corresponded to the volume expected only once every fifty years. The damage caused in Kurenalus by the severest probable flood would have been noticeably greater. However, the building of flood protection works at Kurenalus capable of handling such exceptional flooding is not justified since the rise of the water level at the downstream hydro-electric power stations would be so great that the damage caused there would be far greater than the damage caused in the village of Kurenalus.

Several traditional methods of flood protection have been considered the middle reaches of the River Iijoki: dredging of the river, and/or the construction of embankments, and the increasing of the volume of a water reservoir. In addition the effect on flooding of the use of floating dams for guiding the flow of logs down the river has been estimated, as also the effect of the possible construction of so-called dry temporary reservoirs. The effect on the peak flood of increasing the spilling over of the flow of the river into the River Kiiminkijoki (so-called bifurcation) has also been studied. The measures needed for these various alternatives, together with estimates for their cost and some of their environmental impact have also been examined.

Dredging and embankments

Two main alternatives for river dredging have been studied. Their effect on the water level if a flood similar to the 1982 exceptional one were to repeat itself would be a fall of approximately 0,5 m in the village of Kurenalus. The first alternative would improve the flow of the river by dredging the lenght and the breadth of it in such a way that the cross section of the river would, from a hydraulic poin of view, be the best possible and that the movement of the dredged material would be the smallest possible. The second alternative would involve dredging with the same desired effect as the first one but the excavation and movement of of earth would not extend below the summer water level. In addition a study was also made of the possibilities of building an additional river channel and thus reducing the amount of dredging required.

Depending on the alternative chosen, 170,000 - 300,000 m^3 of earth would have to be either dredged or excavated and moved. The clearing of the river bed above summer water level would lead to a widening of the river bed by several tens of meters. The necessary extra river channel would be about 900 meters long and over 20 meters wide.

The impact on the water course of the dredging work would depend greatly on the way the work is carried out, the quality of the earth to be moved and the quality of the bottom of the water course, the retardation and the discharge. Harmful effects would generally be temporary, resulting from the turbidity of the water during the work, but more long-term effects may also have an influence on living organisms. From an ecological point of view, and also bearing the usefulness of the watercourse in mind, it is considered that the limit for the increase in suspended solids would be 3 mg/l, and that any smaller increase than that would be unimportant. The estimated value for the amount of suspended solids resulting from the dredging work exceeds this proposed limit. Moreover, it is to be supposed that the dredging would lead to an increace in the electrical conductivity of the water, an accentuation in the water colour, and an increase in the iron and phosphorus content. The influence of the dredging on the acidity and oxygen content would generally be small for indeed cleaning the river bed would improve the flow, which would in turn improve in some cases the oxygen levels. It should be noted that vertically deep dredging of the river bed would have an adverse effect on living organisms both in the bottom water levels of the river and on the river bed itself, destroying them completely in the dredged area. Fish would also suffer a permanent setback with loss of natural shelters. Finally the dredging would also change the river landscape.

To protect the population centre of the village of Kurenalus from floodwaters four different embankment alternatives were studied. All the four alternatives would require the building of embankments along almost complete lenght of the river bank in the inhabited and built-up areas, the embankment shape and height varying as result of attempts to find technically and economically realizable solutions. Depending on the solution chosen, the embankment work would probably need about 100,000 m^3 of earth. Each alternative includes plans for organising the drainage of the areas behind the embankments.

The environmental effect of the embankments, unlike the dredging, would be minimal. Nevertheless, the measures taken would noticeably alter the river landscape, though the evaluation of the detrimental effects on the landscape´s aesthetic, historical and general pleasantness values would depend heavily on each individual´s point of view. However, it is possible that at the local village level the alteration of the river landscape and the partial hiding of the river behind high embankments would be seen as harmful and undesirable. Following heavy rain and during the flooding season, it is possible that some leaching from the embankments would occur, but it would be of no significance for the quality of the river water.

It is to be notable that the combining of the dredging and embankment works, while neither fundamentally improving the overall flood protection nor lowering the risk of flooding except in the inhabited areas, would lead to a considerably greater impact on the environment than either measure would have individually. On the other hand, the combining of two measures, allowing the concimitant lower height of embankments, might lead in the public's perception of the works' negative effects on the surroundings and on the environment.

Storing of floodwater in a reservoir

Three different alternatives for storing of floodwater were considered: a power economy reservoir, a floodwater reservoir, and a condensation water reservoir of peat-fired power station. The power economy reservoir corresponds, as far as size is concerned, to the Kollaja reservoir, discussed earlier in connection with the construction of the middle reaches of the River Iijoki. The basis for the size of the floodwater reservoir is the elimination of flood damages comparable to those in the peak flooding recorded in 1982 from the Pudasjärvi lake group and the population centre of the village of Kurenalus, without causing any further severe flood damage to the lower reaches of the River Iijoki. The sizing of the reservoir needed for peat-fired power station was based on the evaporation area required for the cooling of theis kind of a plant.

The net volume of a power economy reservoir is 250 million m^3, that of a floodwater reservoir 140 million m^3, and that for a condensation water reservoir of the peat-fired power plant 50 million m^3. At the lower limit of regulation, the surface area of each reservoir is 10 km^2. At the upper limit of regulation, the area of a power economy reservoir is 50 km^2, the figure for a floodwater reservoir being 35 km^2, and for a condensation water reservoir of the peat-fired power plant 20 km^2.

In the Pudasjärvi area, the water level of the maximum discharge of exceptionally severe floods can be lowered by about 0,6 - 1,0 m by constructing a floodwater reservoir. The effects of a power economy reservoir are at least of the same order during unusually high flooding. The condensation water reservoir of a peat-fired power plant does not have any significant effect on the floods of the population centre of the village of Kurenalus and the Pudasjärvi lake group, for example in a similar situation as in the peak flood year of 1982.

He environmental effects of the reservoir construction are, if compared to other methods of flood control, considerably great. Environmentally hazardous effects are obvious both during construction work and at a later stage. The underwater excavation work carried out during the construction period increases the solids content in the watercourse downstream of the construction site. Furthermore, experience allows the assumption that the quality of water in a newly-built reservoir is exceptional in the first few years of operation. The most typical features are, in addition to the high degree of coloration and percentage of solids in the water, high iron and phosphorus content in the humus or fixed in particles.

If the reports on the reservoir alternatives do not include the incoming discharge conducted from the River Iijoki outside flood seasons, the oxygen forecast for each reservoir is poor. This is the case in every alternative despite the fact that the formation of ice cover in the whole reservoir area is doubtful, because of the condensation water taken by the peat-fired power plant. All these above-mentioned effects are of significance also for the living organisms in the reservoir and the lower reaches. For example, the mercury content in the predatory fish is higher in reservoirs than that fish in natural, untouched watercourses.

Due to the channel and dam structures, the construction of a reservoir also causes notable changes to the landscape in the areas of operation. For example, land areas which would become waterlogged amount to several hundreds of hectares in each alternative. A change in landscape can be regarded as positive in some degree, for the reservoir to developed can be expected to be used for purposes of fishing economy and recreation. A reservoir is, however, nowhere a natural lake, as far as landscape is concerned.

Despite the fact that the intention is to exploit the peat resources in the reservoir area as effectively as possible before the construction, formation of rafts of peat is to be expected to some degree. The effect which these have on the area in that they lower its recreational value may in fact be considered to be substantial by the users.

The possibilities to construct dry temporary reservoirs

A dry temporary reservoir refers to such topographically favourable bog or forest areas where floodwater can temporarily be stored. As the name suggest, a dry temporary reservoir is not always filled by water, but drained after the flood peak.

In the River Iijoki river area, three dry temporary reservoir areas are to be found, but the introduction of these does not make it possible to significantly affect the flooding on the middle reaches. The dry temporary reservoir areas are located far away from the population centre of the village of Kurenalus, and the primary aim is to eliminate the flood damages which might occur there. The distance of the nearest dry temporary reservoir from the population centre of the village of Pudasjärvi (=Kurenalus) is over 30 km. Furthermore, the fact must not be ignored that floodwaters are stored in these low-lying areas even in the present situation.

A dry temporary reservoir can be regarded mainly as an artificially formed flood area. The species of plants and organisms in natural flood areas have evolved by according to the conditions, the rise of water on land areas being essentially related to the ecology of the region. The species have thus been adapted to the changing circumstances. Only part of the original species of a man-made flood area have adjusted to the rise of water onto land areas during flood seasons. On the contrary, whether the species of areas which earlier were not covered by water will be preserved and adapt to the new situation may be questionable.

The changes in the water quality as a result of short-time storing can be assumed to be insignificantly small. It is possible, however, that the effests are considerably unfavourable on the lower reaches, if the dry temporary reservoir is drained too rapidly. Resulting from too rapid drainage, the stream velocity can grow so high that the soil particles start moving. This leads to an increase in the solids content of the water on the lower reaches as well as in turbidity.

Use of floating dams for flood control

The River Iijoki has been dredged for floating purposes, and, to guarantee the sufficiency of water, floating dams have been constructed in it. All in all, there have been 44 floating dams in the River Iijoki watercourse, two of timber and the rest 42 of concrete (Lammassaari, V. 1990). In the River Iijoki river area there are 13 floating dams which can be used, their gross water storage capacity totalling 125 million m^3.

In principle, it is also possible to use the lakes regulated for floating purposes for the storing of floodwater. On the other hand, it should be noted that the use of dams is, according to permits, only possible for the needs of floating, and in the future, in connestion with the improvement work in association with the abolishing of floating regulations, floating dam structures will be pulled down. The decrease in the flood peak achieved by the use of floating dams in the population centre of the village of Kurenalus depends essentially on well-timed closing of floating dams, and also on what the total volume available for water storage is at the time of closing. Utilizing all floating dams, the discharge values of the Kurenala population centre can be cut down by about 30 - 50 m^3/s at maximum. As a result of this, for example in a situation similar to 1982, the water level at the population centre of the village of Kurenalus will decline by a little less than 0,10 m.

The storing of floodwater on the upper reaches behind the floating dam can be carried out in practice so that no damage is done to the environment. Possible hazards are mainly related to an increase in the flood susceptibility in the waters above the floating dam, but actual damage to the nature can be avoided. In principle, by using floating dams the condition on the lower reaches can be improved, considering for example fishing economy. For the fry living in the rapids, the most hazardous are particularly the low discharges in the summer when there is enough of water only for the deepest channel, and little even there. The floodwater stored during the spring flood could therefore be released during the low discharge period and water situation would thus be improved, in which case the benefit would also be channelled to the fishing economy.

Significance of the bifurcation for flood control

From west of Lake Jongunjärvi on the River Iijoki, floodtime bifurcation takes place into the River Nuorittajoki in the River Kiiminkijoki river system. Bifurcation waters gather into the food area which is 60 km^2, the volume being, by rough estimate, 58 million m^3.

From the technical point of view, floodtime bifurcation from Lake Jongunjärvi into the River Kiiminkijoki river system can be made more effective by constructing an additional channel (lateral canal). It is possible to reduce the discharge of the River Iijoki by 50 - 130 m^3/s, as compared to the natural state, during the highest probable flood, and thus lower the water level in Lake Jongunjärvi by 0,1 - 0,2 m. To exploit the massive floodwater basin in this bifurcation area and the process of bifurcation itself at the right time and capacity demands situation-specific calculation of a flood estimate. The size of the floodwater storage depends on the flood of the River Nuorittajoki, being thus no standard.

Making the bifurcation more effective would also increase, by a very high probability, floods in the River Nuorittajoki and thus also in the River Kiiminkijoki. There, ice barriers occur during spring flooding. The breaking up of the ice during the spring flood period, and formation of ice barriers depends on many factors, of which the kinetic energy of floodwater is of significance. Earlier timing of bifurcation, when theRiver Iijoki flood is at the stage of rising, the amount of kinetic energy will probably be increased. This means that the ice will start moving earlier, while harder than normal, in which case the development of ice barriers is more likely. As a result of the developing barriers the flood situation is aggravated. If the bifurcation is boosted during the flood peak of the River Nuorittajoki itself, the result is an increase in floodtime discharge in the rivers Nuorittajoki and Kiiminkijoki. With this increase, the flood will also get worse. Activating the bifurcation after the flood peak of the River Kiiminkijoki has already been passed does not ease the flood situation in the population centre of the village of Kurenalus, for then the cutting down of flood discharge takes place only after the flood peak in Kurenalus.

The watercource of the River Kiiminkijoki has been entered in the Project Aqua which is a list selected by the International Limnologist Association and which includes protection areas regarded because of their scientific significance. The River

Kiiminkijoki has been included in this list expressly because of its being a brown-watered, unregulated river where the Baltic salmon rises. The River Nuorittajoki is the largest tributary of the River Kiiminkijoki, 72 % of its catchment area consisting of bog land, whereas the corresponding figure for the River Kiiminkijoki is 58 %. The brown colour of the River Nuorittajoki is distinctly stronger than the colour of the River Kiiminkijoki. As a result of this, the humus content is clearly increased in the main river bed at the confluence of the River Nuorittajoki, which also clearly increases the percentage of phosphorus and nitrogen in the River Kiiminkijoki. More effective bifurcation will thus probably affect the quality of water in both the Nuorittajoki and Kiiminkijoki rivers. All chenges in the water quality are also reflected in the living organisms of the watercourse.

The technical arrangements in order to arrive at more effective bifurcation, as far as the channel and regulation structures are concerned, alter the bog landscape in the area of operation as well as on a small area of the Lake Jongunjärvi shore. The location of the large masses of soil from the channel excavation without disturbing the landscape is probably difficult. In addition to this, the channel itself changes the natural bog landscape to a considerable extent, and, what is more, the channel would be excavated in a bog land area. This furthers the draining of the bog and increases the amount of humus leaching from there. The effect would reach as far as the Nuorittajoki and Kiiminkijoki rivers. In addition to the above-mentioned points, the extension of the bifurcation area to the bog protection area has to be considered.

COST-BENEFIT ANALYSIS

As for benefit analyses, Fig. 2 shows the correlation between the flood damage and the recurrence of a spring flood in the planning area. It is based on damage caused to buildings and structures, and has been prepared in its time on the basis of the flood damage estimates calculated for the River Iijoki. By means of the graph, it is possible to determine the annual mathematical expectation value for the flood damage corresponding with a certain sizing of flood control. The graph in Fig. 2 reveals that floods recurring on average once every 5 years do not cause economic damage. At the upper limit of the graph, the damages caused by spring floods recurring once every 1000 years are 16 million Finn marks (price level in September 1986). Calculating the area left between the graph and the horizontal axis, from the recurrence of a situation where there is no flood damage (recurrence period on average once every 5 years) as far as the recurrence value corresponding with the sizing of the flood protection measures, gives as a result the annual mathematical expectation value for the spring flood damage. In the benefit analysis, the expectation value

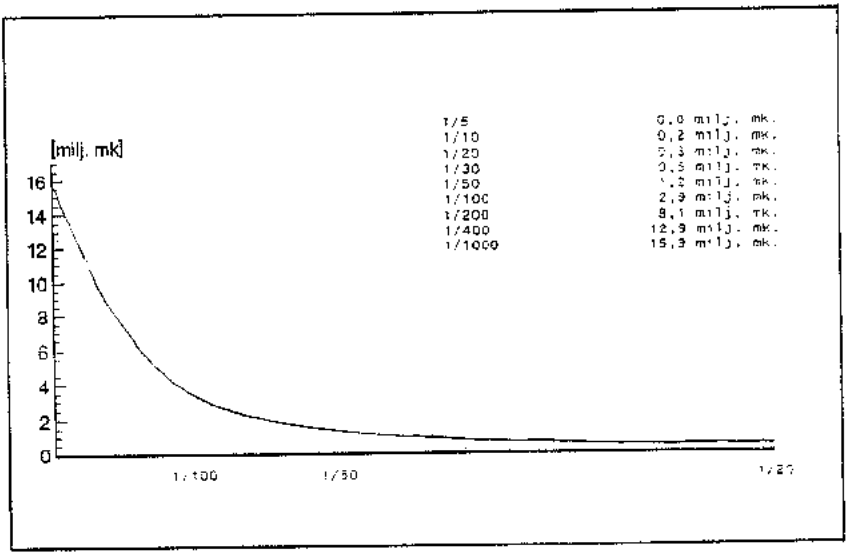

Figure 2. The correlation between the flood damage and the recurrence of a spring flood.

corresponds to the benefit to be achieved yearly by means of flood protection measures.

For the various alternatives, a recurrence value corresponding with the sizing of flood protection measures was determined and, on the basis of this, the flood control benefit was calculated by using the same principle. Additionally, in connection with the dredging operations, the benefit attained as a result of a decrease in flood damage was assessed. This means that cleaning can reduce flood damages even when the sizing of cleaning measures for the complete elimination of flood damages is insufficient.

The rise in the value of the shore areas which are released of the risk of flooding was taken into consideration in the case of two larger reservoir alternatives. Furthermore. the advantages of the alternatives from the point of view of water power economy were assessed on the basis of production costs for corresponding thermal power.

The count period for the investment estimates made was put at 50 years, because the lifetime of flood control structures can be assumed to be long. The computational interest used was the percentage of interest used normally in the cost-benefit calculations in the state administration, that is, 6 %.

CONCLUSION

As far as flood control security is concerned, the best alternative is the construction of a power economy reservoir, which in the Pudasjärvi lake group and Kurenalus population centre can help achieve security against floods recurring on average once every 200 years.

As far as the reservoir alternatives are concerned, there are no grounds to raise the flood control security higher than to the level against floods recurring on average once every 200 years. If this is exceeded, the power plant structures will suffer damages, compared to which the benefits achieved in the waters upstream are insignificant.

None of the alternatives discussed is, if measured by flood control benefits, economically profitable. The flood control benefits attained in connection with the reservoir alternatives are marginal if compared with other benefits of the project. The economically profitability of the alternative reservoir solutions is determined fully on grounds other than flood control benefits.

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FLÖDESDIMENSIONERING I LULEÄLVEN

Känslighetsanalys av de nya svenska riktlinjerna

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ABSTRACT

A sensitivity analysis of the new Swedish guidelines for spillway design in Luleälven in northern Sweden is presented. The simulations were made using a system based on the HBV-model. The 25 000 km^2 basin was divided into 35 subbasins with 16 calibration points. 5 of 16 dams in the river were analysed. The results showed that changes in the hydrological model had only minor effects on the design water stages. Of greater importance was changes in the prescribed precipitation and snow-pack, as well as spillway capacities. Alterations in the reservoir regulation strategies as regards initial water stage before snowmelt can be of importance in the largest reservoirs. The use of a hydrological model for design flood calculations seem adequate as the major factors of importance, in a developed river system, can be treated systematically.

INLEDNING

Nya riktlinjer för dimensionering av dammar och utskov är nyligen framtagna i Sverige (Flödeskommittén, 1990). Riktlinjerna stipulerar användandet av avrinningsmodeller med vilka olika klimathändelser, som hög nederbörd, kraftigt snötäcke, fyllda markvattenmagasin etc, kan kombineras. I praktiken är det HBV-modellen som kommer att utnyttjas även om det inte är ett krav enligt riktlinjerna. Jämfört med originalversionen av HBV-modellen, presenterad av Bergström 1976, har under de senaste åren rutiner för magasinshantering utvecklats, vilket gör det möjligt att simulera ett helt kraftverkssystem.

För att simulera dimensionerande flöden i ett flodsystem är det nödvändigt att kalibrera den hydrologiska modellen för olika delområden. Ett delområde görs för varje damm, för naturliga sjöar av betydelse ur magasineringssynpunkt samt där det eljest är påkallat ur hydrologisk synvinkel, t ex för större glaciärer med separat vattenbalans. Vid kalibreringen utnyttjas företrädesvis den lokala tillrinningen för resp delområde för en period av ca 10 år.

Vid simuleringen utnyttjas den kalibrerade modellen samt klimatdata (nederbörd och temperatur) för den senaste 10-årsperioden. Med tillämpning av riktlinjerna undersöks sedan hela denna period och sorteras fram det tillfälle som ger det högst beräknade vattenståndet i aktuellt magasin. Av detta följer att det dimensionerande vattenståndet beror dels av uppströms liggande kraftverk och deras avbördningsförmåga, och dels av vald regleringsstrategi.

I detta arbete har för fem dammar i Luleälven undersökts känsligheten i de dimensionerande vattenstånden med avseende på förändringar i modellkalibreringen, dimensionerande nederbörd och snötäcke, vald regleringsstrategi samt utskovskapaciteter. Beräkningarna utgår ifrån att samtliga av dessa dammar kommer att klassificeras som riskklass I dammar, vilket innebär högriskdammar. Metodiken är i huvudsak i överensstämmande med den av Lindström och Harlin utnyttjade i ett liknande arbete för Ljusnan (Harlin, 1992)

METODIK

Dimensioneringsförfarande

I Fig 1 visas arbetsgången vid en dimensioneringsberäkning. I riktlinjerna skiljs mellan riskklass I dammar, med en beräkningsgång enligt övre delen av bilden, och riskklass II dammar, enligt nedre delen. En komplett beskrivning ges i Flödeskommittén 1990.

Den mest betydelsefulla faktorn i dimensioneringen är nederbördssekvensen om 14 dagar. Olika sekvenser har tagits fram för olika regioner med hänsyn till skillnader i nederbördsklimatet. Sekvenserna, som ger arealnederbörden för ett område på 1 000 km^2, justeras med hänsyn till aktuellt tillrinningsområdes storlek samt medelhöjd över havet. Vidare görs en justering för skillnader i nederbördsintensiteten under året.

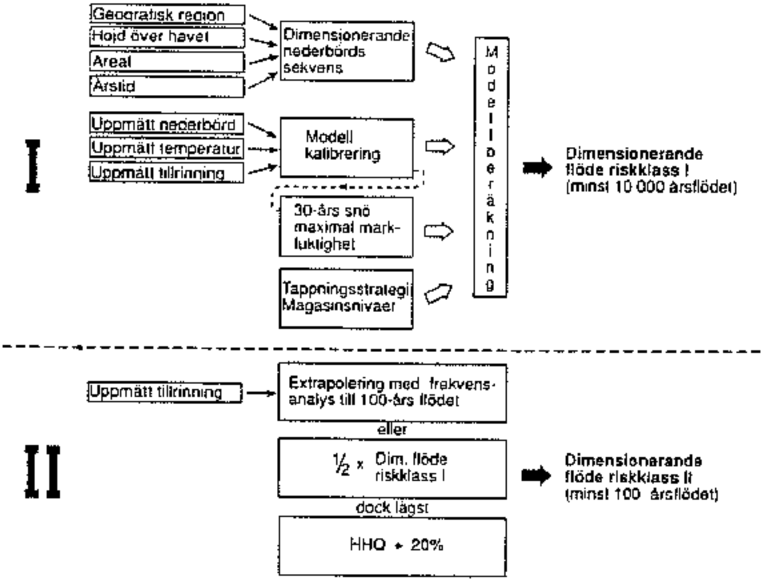

Fig 1. Arbetsgång vid dimensionering för riskklass I resp riskklass II dammar

Den hydrologiska modellen kalibreras utgående från uppmätta dygnsvärden på nederbörd, temperatur samt tillrinning. Därutöver utnyttjas också beräknade månadsmedelvärden på potentiell avdunstning. När modellen kalibrerats beräknas 30-årsvärdet av de av modellen beräknade årliga maxvärdena på snötäcket. Detta 30-årsvärde tillsammans med mättade markvattenmagasin utgör utgångspunkten inför vårfloden för de år som beräkningarna skall utföras.

En annan faktor av vikt är den regleringsstrategi som skall tillämpas. För de stora regleringsmagasinen väljs den startnivå som normalt föreligger då en kraftig vårflod förväntas. Vidare beskrivs i modellen den normala årsregleringen med hänsyn till de minimitappningsregler etc som gäller.

Med den upplagda modellen görs för en 10-årsperiod upprepade beräkningar då nederbördsekvensen får ersätta den uppmätta nederbörden i steg om ett dygn. Den härmed erhållna mest kritiska magasinsutvecklingen blir den dimensionerande.

Luleälven

Luleälven är ur energisynpunkt Sveriges viktigaste älv med en fjärdedel av vattenkraftproduktionen. I älven finns 16 kraftverk (Fig 2). Vattnet regleras i 6 större magasin belägna i älvens övre delar. Vid modellkalibreringen indelades älven i 35 delområden. Därvid utgicks från dammar, naturliga sjöar samt glaciärer. Modellen har kalibrerats i 16 punkter. Älven har två huvudgrenar, Stora resp Lilla Luleälven, med arealer på ca 11 300 resp 9 500 km^2. Vid mynningen i Östersjön är avrinningsområdet 24 490 km^2, sjöandelen 7.7 % och medelavrinningen ca 500 m^{3}s^{-1}.

I Tabell 1 anges data för de fem studerade dammarna. Tjaktjajaure och Suorva representerar regleringsmagasin i fjällområdet, Letsi och Messaure är exempel på kraftverk med begränsade magasin belägna i nedre delen av Lilla resp Stora Luleälv och Boden slutligen är ett typiskt strömkraftverk längst ned i älven.

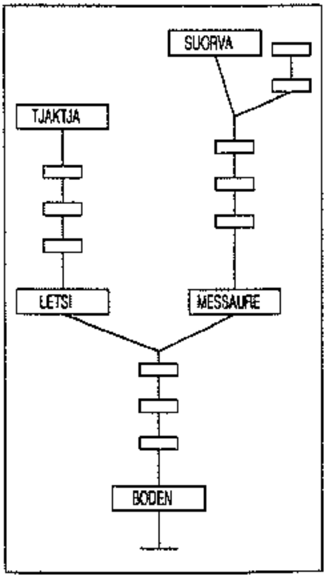

Fig 2. Skiss över dammarna i Luleälven

Tabell 1. Data för studerade dammar

	Tjaktjajaure	Letsi	Suorva	Messaure	Boden
Tillrinningsområde (km^2)	2 267	9 520	4 680	11 300	24 490
Magasinsvolym (Mm^3)	1 675	67	5 900	53	0.8
Magasinsareal (km^2)	81	18	270	23	2.8
Utskovkapacitet vid DG(m^3s^{-1})	9 00	1 560	1 260	1 800	2 820
Utskovstyp	Yt + botten	Yt	Botten	Yt	Yt
Utbyggnadsvattenföring (m^3s^{-1})	135	390	530	575	680

Till grund för analyserna ligger en inledande dimensioneringsberäkning för var och en av dammarna. Inför dessa referensberäkningar har modellkalibreringen slutförts samt har tagits fram en preliminär regleringsstrategi för älven som helhet. För att kunna ta hänsyn till hydrauliska effekter längs älven har en hydraulisk modell (DAMBRK) lagts upp för intressanta älvsträckor. Med denna beräknas, utöver dammbrottssimuleringar, dämpning i älven, ev motdämning vid dammarna samt vattenståndsprofiler längs älven.

Om inte annat anges så gäller för samtliga genomförda analyser att en faktor åt gången har analyserats och alla andra hållits konstanta i enlighet med referensberäkningen. I diagrammen redovisas vattenstånden som en avvikelse från en referenshöjd. Denna höjd utgörs av tätkärnans nivå. I en del fall når vattenytan upp över dammarnas faktiska krön. Beräkningarna har då utgått ifrån att dammarna varit tillräckligt höga föra att överrinning ej skall inträffa.

Känslighetsanalys

Känslighetsanalysen avser för det första några hydrologiska modellparametrar samt inverkan av den hydrauliska modellen. För det andra analyseras förändringar i den dimensionerande nederbörden och snötäcket, samt justeringar avseende startvattenstånd inför vårfloden och sänkning av dämningsgränsen. För det tredje görs beräkningar om utskovskapacitetens inverkan på det dimensionernade vattenståndet samt effekten av begränsningar i överdämningen i de olika magasinen.

Genom justeringar av några av den hydrologiska modellens parametrar erhålls en uppfattning om hur stabilt resultatet är med hänsyn till aktuell kalibrering. Av speciell vikt vid flödesdimensionering är den parameter som styr recessionen vid högflödesförloppen (K0). Känsligheten för K0 har studerats genom förändringar i steg om +/- 10 %. Denna förändring har gjorts för samtliga ingående delområden uppströms aktuell damm. Vidare har parametern MAXBAS, som beskriver dämpningen i ett område, studerats. MAXBAS anges i hela dygn och har dels ökats med ett dygn och dels minskats med ett dygn (där utgångs värdet överstigit 1 dygn). Härutöver redogörs något för den hydrauliska modellens inverkan på flödeshydrograferna vid Letsi och Boden (övriga dammar omfattas inte av den hydrauliska modellen).

Den dimensionerande nederbördssekvensen samt 30-årssnötäcket har ändrats i steg om +/- 10 % . Dessa förändringar har gjorts för samtliga ingående delområden uppströms aktuell damm. Känsligheten i den framtagna regleringsstrategin har studerats genom förändringar i startvattenstånd inför vårfloden samt antaganden om sänkt dämningsgräns . Vad gäller Tjaktjajaure och Suorva har ändringarna i startvattenstånd gjorts i 4-meters steg. För övriga anläggningar har endast mindre förändringar varit möjliga med anledning av den begränsade regleringshöjden. Vad gäller sänkningen av dämningsgräns har ändringarna gjorts i 0.5-meters steg.

Som en tredje punkt har undersökts hur känsligt resultatet är med hänsyn till dammarnas utskovskapacitet. Två typer av analyser har genomförts. Vid den första har utskovens kapacitet justerats i steg om +/- 10 % med syfte att se inverkan på det dimensionerande vattenståndet vid aktuell anläggning. Vid den andra analysen har förutsatts att utskoven är ombyggda för att kunna avbörda tillrinningen dels vid dämningsgräns och dels vid tätkärnan. Det senare har gjorts för att undersöka hur stor tillrinningen ned genom älven blir om ingen dämpning kan tillåtas i uppströms belägna magasin.

RESULTAT OCH DISKUSSION

Referensberäkningar

Känslighetsanalyserna relateras till de referensberäkningar som genomförts för resp damm. I Fig 3 redovisas beräkningen gällande för Boden. Diagrammen för övriga dammar hänför sig också till det dimensionerande tillfället för Boden. Nederbördssekvensen inleds den 5/8-81 och har sitt maxvärde med 93 mm den13/8. Flödet i Boden kulminerar den 17/8. 30-årssnöns vatteninnehåll uppgår för Bodens hela tillrinningsområde till drygt 400 mm. Tillrinningshydrograferna för Tjaktjajaure och Suorva är förhållandevis spetsiga, medan motsvarande längre ned i systemet är betydligt trubbigare med en längre varaktighet av de högsta flödena.

Känslighetsanalys

Den hydrauliska modellen fördröjer hydrograferna vid Letsi och Boden (Fig 4). Hydrografernas toppvärden är dock i stort sett lika. Här kan noteras att parametern BLAG i HBV-modellen, som beskriver tidsförskjutningen mellan två kalibreringspunkter, genomgående är noll i den dimensioneringsmodell som lagts upp för Luleälven. Därför torde den hydrauliska modellen, som matats med exakt samma tillrinningshydrografer som beräknats i den hydrologiska modellen, ge ett mer sannolikt flödesförlopp.

K0 för de studerade områdena har värden i intervallet 0.15-0.50 dygn^{-1} med de högsta

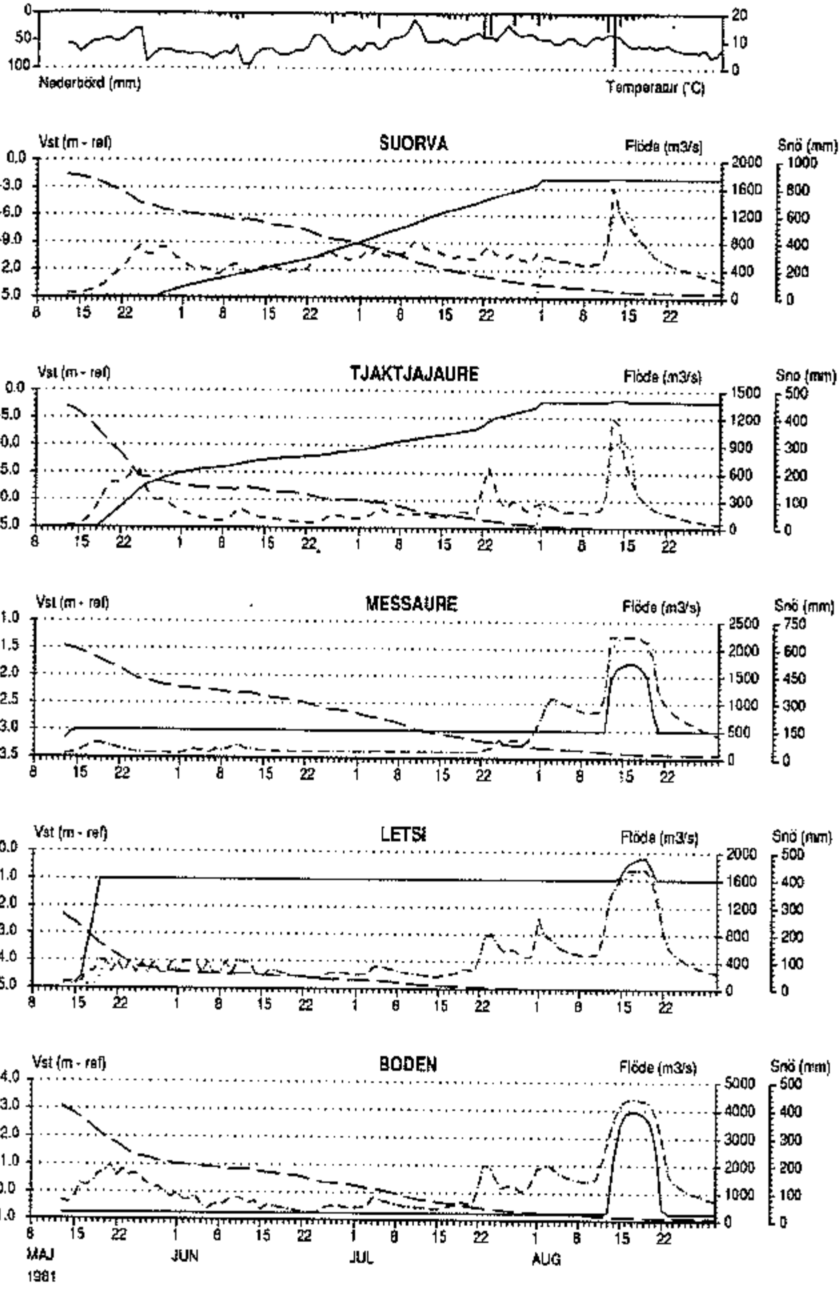

Fig 3. Flödes- och vattenståndsutvecklingen i de fem dammarna vid det dimensionerande tillfället för Boden

värdena i fjällområdet. Kalibreringsnoggrannheten torde rymmas i intervallet +/- 10 % och därför kan de genomförda justeringarna anses vara kraftiga. En förändring av K0 med 10 % påverkar vattenståndet med maximalt 0.2 m (Tjaktjajaure), vilket kan bedömas som relativt lite. En justering av MAXBAS med +/- 1 dygn har för alla dammar utom Tjaktjajaure en försumbar inverkan på vattenståndet (Fig 5). En orsak till att förändringen av de hydrologiska parametrarna K0 och MAXBAS endast leder till en begränsad påverkan på de dimensionerande vattenstånden är att tillrinningsområdena till dammarna består av flera delområden. Tillrinningen till magasinen är därför en blandning av flera hydrografer. I de fall dammen är beläget i ett randområde (ej flera delområden) blir effekten av motsvarande förändring tydligare (jfr Harlin, 1992).

De dimensionerande vattenstånden är känsliga för ändringar av nederbördssekvensens volym. Effekten är knappt 0.5 m per 10 % för Tjaktjajaure, Letsi och Boden, medan den är ca hälften för Suorva och Messaure. En procentuell justering av snötäcket får störst volymeffekt i fjällområdet, eftersom snötäcket normalt är högst där. 30-årsvärdet för Suorva är hela 1 034 mm, vilket förklarar den kraftiga effekten trots Suorvas stora magasin. För Suorva och Tjaktjajaure inträffar den dimensionerande situationen i samband med vårflodens kulmination. För de tre nedre dammarna inträffar den dimensionernade situationen på hösten vilket förklarar den minimala effekten. En sänkning av magasinens vattenstånd inför en förväntad kraftig vårflod kan leda till lägre dimensionerande vattenstånd i de stora magasinen. Det är dock sänkningar på åtskilliga meter som krävs. Om utskoven hålls öppna för fullt ett stycke under dämningsgränsen, erhålls lägre dimensionerande vattenstånd för både Suorva och Tjaktjajaure. Effekten är nästan 1 på 1, dvs full tappning 1 m under dämningsgränsen leder till knappt 1 m lägre vattenstånd. Här måste emellertid observeras vad som händer nedströms samt att produktionsbortfallet av en sådan åtgärd är mycket stor. I de små magasinen har förtappningen ingen som helst effekt (Fig 5).

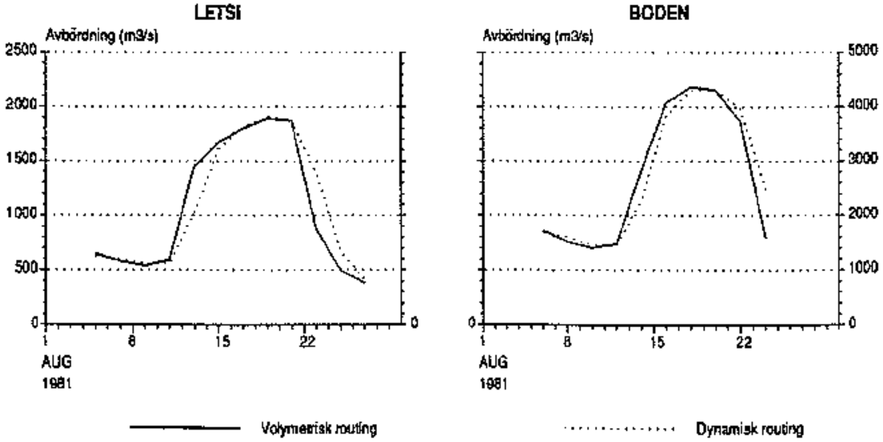

Fig 4. Den hydrologiska modellens volymetriska routing jämförd med den hydrauliska modellens dynamiska routing vid Letsi och Boden

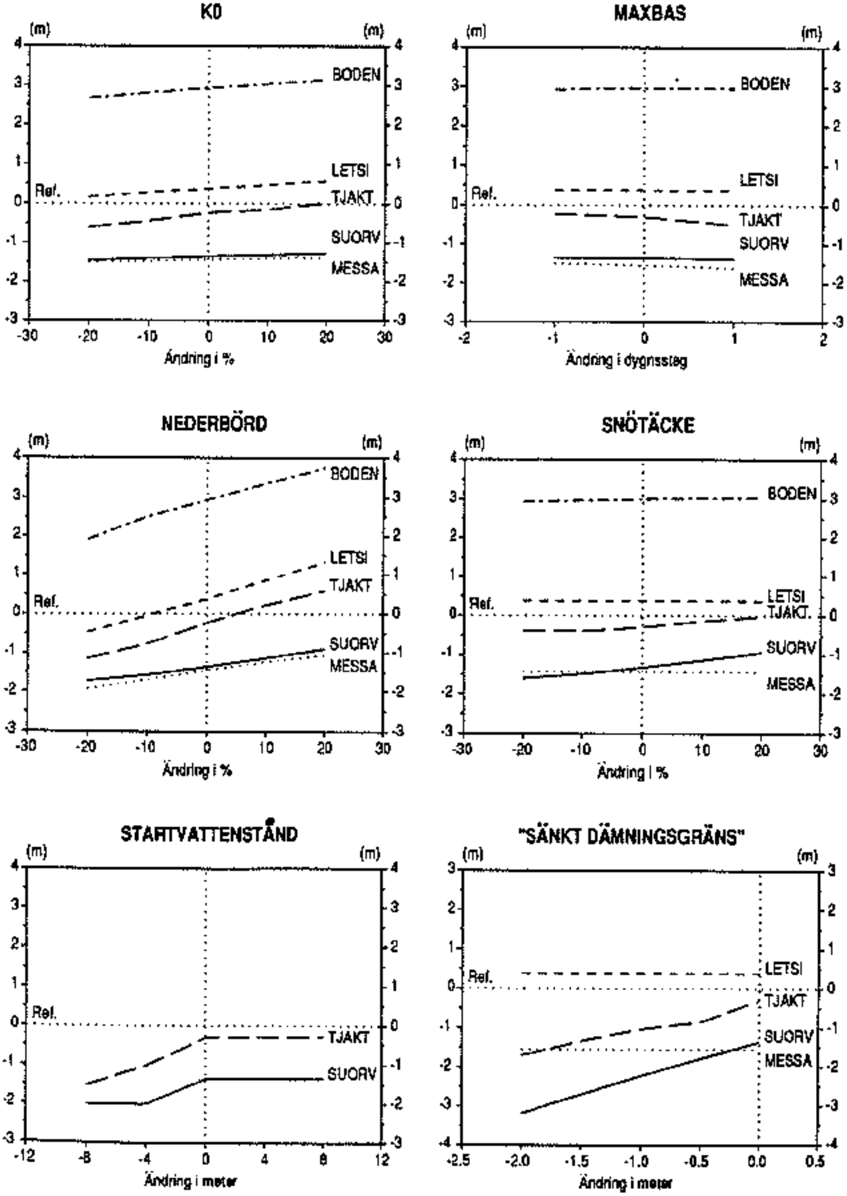

Fig 5. Det dimensionerande vattenståndets känslighet för förändringar av K0, MAXBAS, nederbörden, snötäcket, startvattenståndet samt sänkt dämningsgräns.

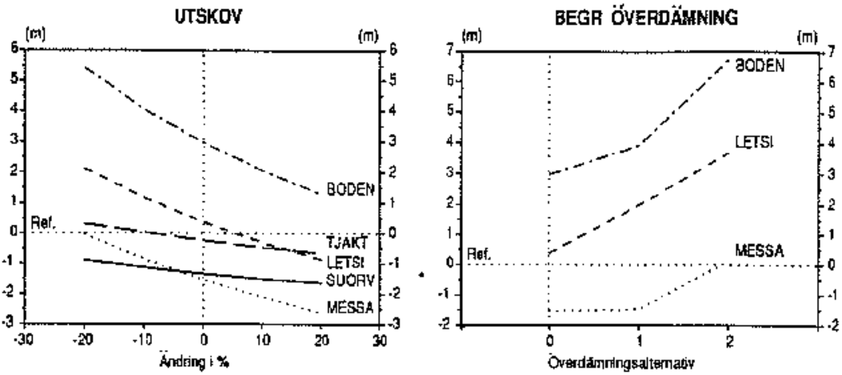

Fig 6. Det dimensionerande vattenståndets känslighet för förändringar av utskovskapacitet samt begränsningar av överdämningen i uppströms liggande magasin

Av stor vikt för de dimensionerande vattestånden är utskovens avbördningsförmåga (Fig 5). I de fall som avbördningsförmågan från början är relativt begränsad får en procentuell ökning en mindre effekt. Så är fallet med Tjaktjajaure och Suorva som delvis eller helt har bottenutskov. Ytterligare en variant på avbördningstemat är den figur som kallas begränsad överdämning. Här innebär 0 - referensberäkningen, 1 - att ingen överdämning görs över tätkärnan på uppströms liggande dammar och 2 - att ingen överdämning görs över dämningsgränsen. De flöden som erhålls vid Boden för dessa tre alternativ är ca 4 400, 4 800 resp 6 200 m^3s^{-1} . Som synes av resultaten så krävs en hel del magasinering över dämningsgränsen för att godtagbara nivåer skall nås i nedre delen av älven.

SLUTSATSER

För de högst belägna dammarna inträffar den dimensionerande situationen på våren, medan höstflödena blir mest kritiska längre ned i systemet. I huvudsak är det samma tillfällen som blir dimensionerande vid flertalet av dammarna.

Känslighetsanalyserna visar att de dimensionerande vattenstånden generellt är kraftigt beroende av den dimensionerande nederbördens storlek och utskovens kapacitet. För de största magasinen kan kraftigt sänkta startvattenstånd inför vårfloden leda till lägre dimensionerande vattenstånd. Justeringar av de hydrologiska modellparametrarna leder i ett komplext älvsytem endast till mindre förändringar av vattenstånden.

Användandet av en hydrologisk modell för flödesdimensionering synes vara ett lämpligt arbetssätt då de viktigaste faktorerna, såsom klimat, vald regleringsstrategi samt effekten av uppströms liggande dammar, kan behandlas på ett systematiskt sätt.

Detta arbete har finansierats av Vattenregleringsföretagens samarbetsorgan (VASO). Jag vill också rikta ett tack till mina kollegor Göran Sprinchorn och Pål Svendsen för värdefulla kommentarer på manuskriptet.

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FLOMVARSLING OG SNØKARTLEGGING MED SATELLITT

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ABSTRACT

The flood forecasting services of the Norwegian Water Resources and Energy Administration at it's present form has been operational since 1989. One of the problems experienced when updating the hydrological forecast models is the lack of information on the water equivalent and distribution of snow cover of the forecasted basins. Snow-monitoring by satellite is regarded to have potentials to partly solve this problem. The article describes the present status of the development of an operational snow monitoring service based on data from the NOAA-satellite and proposes a future Nordic co-operation in this field.

BAKGRUNN

Mye av det tidligere arbeidet på fjernanalyseområdet har hatt forskningsmessig preg og det har kun unntaksvis resultert i operative brukersystemer. Dette skyldes vesentlig at tiden fra nedlesing og frem til at bildematerialet har vært tilgjengelig for brukeren har vært for lang for de fleste operative formål. Den vanlige bruker har også som regel manglet utstyr for rasjonell billedanalyse og -presentasjon. Disse forholdene er vesentlig endret idag. Det er f.eks. nå mulig å overføre satellittbilder til ulike brukere over datanett i løpet av få timer etter nedlesing (Hamnes m.fl., 1989). Analyse og presentasjon av satellittbilder kan idag også utføres på en vanlig PC.

Bruk av satellittbilder kan gi verdifull informasjon i forbindelse med tilstandsovervåking og -varsling for våre vassdrag. Spesiell hydrologisk interesse knytter seg til bruk av slike bilder for snøkartlegging og det har vært utført flere studier på dette området (Andersen & Ødegaard, 1980; Andersen, Haakensen & Johnsrud, 1984; Østrem, 1985). Operative systemer er bl.a. tatt i bruk i forbindelse med værvarslingstjenestene i Sverige og Norge. I Norge har også Statkraft siden 1989 hatt et satellittbasert system for snøkartlegging i prøvedrift.

De viktigste brukergruppene vil være det enkelte lands værvarslingstjenester og flomvarslingstjenester (NVE i Norge) og vannkraftsektoren som bruker informasjon om snøforholdene til å prognosere smelte-tilsig til magasiner og kraftverker. En generell kartlegging av snøforholdene vil også ha en egenverdi.

Sluttbrukere vil være almenheten som ved sikrere vær- og flomvarsler vil få bedre forutsetninger til å sikre verdier (og liv) i bl.a. flomutsatte områder og lokale myndigheter som vil få et bedre grunnlag for iverksettelse av beredskapstiltak i forbindelse med flom. En bedre utnyttelse av snømagasinet i forbindelse med manøvrering av reguleringsmagasiner vil også føre til en effektivere kraftproduksjon.

SNØKARTLEGGING

Flomvarslingen (og værvarslingen) stiller spesielt store krav til sanntids databearbeidelse- og presentasjon, fordi varslingshorisonten som regel er kort, 1-7 dager. Av størst betydning for flomvarslingen er oversikter over snødekket areal (snødekningsgrad) fordi denne bestemmer smelteintensiteten på kort sikt. Det er jo vesentlig innkommende stråling over snødekket areal som kan brukes til å smelte snø. På lang sikt vil også oversikter over snømagasinets volum (vannekvivalent) ha betydning for kontroll og oppdatering av tilstandene i de simuleringsmodeller som benyttes i flomvarslingen.

Tilsigsprognosering i forbindelse med vannkraftproduksjon har som regel en noe lenger prognoseringshorisont og stiller derfor lavere krav til sanntids databearbeidelse. For denne typen av prognosering vil oversikter over vannekvivalenten i snømagasinet være av større interesse enn snødekningsgraden, fordi en er mer interessert i smeltevolumet enn i intensiteten.

Generell kartleggging av snøforhold stiller i utgangspunktet ingen krav til sanntids datainnsamling og -bearbeidelse. Derimot er muligheten for kartlegging av store områder ved bruk av satellittdata av stor interesse.

For disse formål ble tidligere vesentlig brukt tre ulike kartleggingsmetoder:

- Snømålinger i felt i punkter eller langs strekk (manuelle målinger med stikkstenger og snørør, registrerende snøputer, snøradar).
- Summering av all vinternedbør etter en gitt dato (teoretiske snøakkumulasjonskart).
- Modellberegninger basert på observert nedbør og temperatur ved f.eks. HBV-modellen.

Snømålinger i felt er ofte både tid- og kostnadskrevende og kan av praktiske grunner som regel ikke utføres etter at snøsmeltingen har kommet igang. Teoretiske akkumulasjonskart, som beregnes for ulike høydenivåer, har den vesentlige svakheten at de ikke tar hensyn til evt. smelting og avrenning under vintersesongen.

Modellberegningene har ingen av disse svakhetene, men avhenger i stor grad av antakelser om de benyttede nedbør- og temperaturstasjonenes representativitet for det aktuelle felt/område. Det er derfor vanlig at beregnet avløp fra disse modellene sammenlignes med observert avløp for på den måten å danne grunnlag for oppdatering av modellen, hvis denne ikke gir akseptable resultater. Modellene beregner som regel både snødekningsgrad og snømagasinets vannekvivalent. I snøsmelteperioden vil derfor opplysninger om begge disse variablene være verdifull tilleggsinformasjon ved oppdatering av modellene.

OPERASJONALISERING

Av ovenfor nevnte grunner ønsker NVE å utvikle et system for operativ bruk av satellittdata for snøkartlegging (Lundquist, 1991). I første omgang tar en sikte på å få til et opplegg for kartlegging av snødekningsgrad. På litt lenger sikt ønsker vi også å undersøke mulighetene for kartlegging av snødekkets vannekvivalent.

I Norge vil en ofte oppleve store lokale variasjoner i snødekningsgrad (snøflekker/barmarksflekker) som resultat av ujevn snøfordeling (fonndannelse pga. vind). Det vil derfor ikke være tilstrekkelig å kartlegge i bare to klasser, snødekket og ikke snødekket mark, men fortrinnsvis i intervaller (f.eks. 20%, 40%, osv. snødekke i et gitt område).

DATAKRAV

Ved vurdering av hvilke datakilder (satellitter) som er aktuelle ved operativ bruk av satellittdata for snøkartlegging må følgende egenskaper vurderes:

- Leveringsfrekvens (hvor ofte)
- Leveringstid (hvor raskt)
- Romlig oppløsning (hvor detaljert)
- Sensoregenskaper
- Pris

Det er pr. idag kun NOAA-satellitten som oppfyller tilstrekkelig mange av de aktuelle kravene.

DATAPROSESSERING

Utarbeidelse av et operativt opplegg for bruk av satellittdata for snøkartlegging forutsetter rutiner med flere av følgende funksjoner:

- Geometrisk korrigering av rådata fra satellitten
- Atmosfærekorrigering og korrigering for varierende solvinkel
- Avmasking av skydekkede områder
- Klassifisering av snøegenskaper
- Beregning av arealstatistikk
- Resultatpresentasjon

STATUS I NORDEN

I **Norge** utføres tilnærmet operativ snøkartlegging med satellitt siden 1989 av Statkraft i samarbeid med Norsk Regnesentral (Holbæk-Hansen, 1989). Formålet er sikrere tilsigsprognoser og derved effektivere kraftproduksjon. Data som brukes er NOAA/AVHRR kanal 2. NVE har i 1990 innledet et samarbeid med Statkraft for bruk av metoden ved flomvarsling.

Områder som representerer fullstendig snødekke resp. barmark utvelges i bildene og tilsvarende pixelverdier bestemmes. Det brukes utelukkende rådata uten noen form for konvertering til albedoverdier eller andre korreksjoner. Ved bruk av lineær interpolasjon mellom de to bestemte ytterverdiene beregnes snødekningsgraden i prosent (intervallbredde på 20%) for hver enkelt pixel på bildet. Resultatene presenteres både som oversikter for hele landsdeler og for predefinerte reguleringsområder, for hvilke det også beregnes midlere snødekningsgrad.

I tillegg til utviklingsarbeidet ved Statkraft og Norsk Regnesentral arbeides det også med metodestudier på snøsiden ved Norsk Hydroteknisk Laboratorium/NHL (Faanes, 1991 og 1992), og med meteorologiske applikasjoner ved Det Norske Meteorologiske Institutt/DNMI (Sunde & Haga, 1991).

I **Sverige** har Sveriges Meteorologiska og Hydrologiska Institut/SMHI videreutviklet et system for snøkartlegging ved satellitt (Brandt & Moberg, 1990) basert på et avansert opplegg for skyklassifisering, også utviklet ved SMHI (Karlsson & Liljas, 1990). Data som brukes er NOAA/AVHRR kanal 1-5.

All prosesering fra rådata til sluttprodukt skjer helt automatisk. Geometrisk korrigering av rådata utføres f.eks. kun på grunnlag av baneparametre. I klassifiseringen skilles kun mellom snødekket mark, snøfri mark og "vinter-skog" (representerer delvis snødekket mark).

I **Danmark** er det utviklet en metode for snøkartlegging med satellitt ved Geografisk Sentralinstitut, Københavns Universitet, for bruk bl.a. på Grønland (Søgaard & Thomsen, 1988). Data som brukes er NOAA/AVHRR kanal 1 (og evt. 4). Metoden er senere videreutviklet til også å omfatte skyklassifisering (Broge, Jørgensen & Scharling, 1991). Billedbehandlingssystemet som brukes er egenutviklet og kalles CHIPS. Dette er et PC-basert opplegg som kun krever investering i et grafikk-kort og en høyoppløselig skjerm i tillegg til en PC. Prinsippet som brukes ligner sterkt på det norske. Forskjellen er at istedenfor å bruke rådata direkte benyttes beregnede og korrigerte albedoverdier. Ved å anvende teoretiske albedoverdier for snø og barmark trenger en da ikke å bruke kjente referanseområder for kalibrering. Metoden tar hensyn til solvinkel og kan også foreta korrigeringer for terrengets helning.

I **Finland** er det utviklet en metode for snøkartlegging med satellitt basert på NOAA/AVHRR kanal 1 (Kuittinen, 1989). Der foreligger planer på å bruke metoden i operativ drift.

Metoden beregner snøens vannekvivalent ved regresjonslikninger etablert mellom satellittdata og målte snømengder i tre ulike terrengtyper; granskog, furuskog og åpne områder. Det foretas korreksjoner for varierende solvinkler. Metoden brukes sammen med tradisjonelle feltmålinger og gammamålinger for å gi verdier basert på et bredest mulig grunnlag.

BRUK AV MIKROBØLGESENSORER

Bruk av mikrobølgesensorer har to interessante aspekter i relasjon til snøkartlegging. De kan evt. brukes til å kartlegge kvalitative egenskaper ved snødekket (eks. vannekvivalenten) og de kan se gjennom skyer (aktive sensorer som SAR). En statusundersøkelse vedr. bruk av mikrobølge-data til snøkartlegging er nylig utført i Norge (Sand, 1991).

VIDERE ARBEID

Ved NVE satses det nå på en videre operasjonalisering av et opplegg for snøkartlegging med satellitt samtidig med at NHL arbeider med videreutvikling og verifisering av klassifikasjonsalgoritmer for snø. Av aktuelle problemstillinger i tiden fremover kan nevnes:

- Automatisering av den geometriske opprettingen av satellittbildene
- Innføring av atmosfærekorreksjoner og solvinkelkorreksjoner
- Automatisk skymasking/klassifisering basert på bruk av 2-3 kanaler
- Kobling mot GIS (Arcinfo) og utarbeidelse av snøstatistikk for predefinerte felter
- Uttesting av alternative algoritmer for klassifisering av snødekke

På sikt ønsker en også å se satellittbilder, GIS, en landsomfattende høydedatabase og enkle hydrologiske modeller (synoptiske vannbalansemodeller av typen HBV) som et utgangspunkt for samtidig beregning av snømagasin, markvannsdeficit, grunnvannsoppfylling og avløpsdannelse.

Viktig i årene som kommer vil være storskala verifisering av snødekningsalgoritmer og implementering av slike data som grunnlag for dagens varslingsmodeller, dvs. som inngangsdata til bl.a. HBV-modellen.

Utover de nevnte aktivitetene er det i Norge i 1992 også initiert et forsknings- og utviklingsprosjekt (SNØSAR) av NHL og FORUT i Tromsø vedr. bruk av SAR-data (radardata) fra den europeiske ERS1-satellitten. Resultatene fra dette prosjektet kan gi viktige bidrag til videreutviklingen av en operativ snøovervåking, bl.a. fordi slike radardata kan brukes også ved overskyet vær.

NORDISK SAMARBEID

Uansett om formålet med fjernalyseaktiviteten er flomvarsling, værvarsling, tilsigsprognosering eller bare snøkartlegging alene vil der være en rekke felles problemstillinger vedr. metodeutvikling etc. Det foreslås derfor nedsatt en nordisk arbeidsgruppe i regi av Nordisk Hydrologisk Forening/NHF for å følge opp og om mulig koordinere utviklingen på dette området i den neste toårsperioden 1992-94.

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INNVIRKNINGEN AV 1980 ÅRENES TILSIGSFORHOLD PÅ PRODUKSJONSPOTENSIALET I DET NORSKE KRAFTSYSTEMET

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ABSTRACT

Simulations of the power production potential in the norwegian hydro power system carried out by the Norwegian Power Pool (NPP) are normally refered to inflow statistics for the 50 years period from 1931 to 1980. The 1980's are especially characterized by high inflow. We therefore want to implement these years in the inflow statistics to visualize the influence of these years on mean- and firm power production. For several reasons it has been difficult to extend all 112 records up to 1990. Calculations are therefore carried out with a reduced numbers of records.

INNLEDNING

Tilsigsforholdene gjennom 1980 årene har vært preget av milde nedbørrike vintre og høye tilsig. Disse forhold har hatt stor innvirkning på produksjon av elektrisk kraft i det norske kraftsystemet som er tilnærmet 100% vannkraftbasert.

Beregninger av kraftsystemets produksjonspotensiale baserer seg på tilsigsserier for periodene 1931 - 60 og 1931 - 80. Med så stor vanntilgang som vi har hatt i perioden 1981 til 1990 får dette følger for middelproduksjonen i kraftsystemet, alt avhengig av hvilken tidsperiode vi velger som representativ for beregning av middeltilsig.

Det har i denne 10 års perioden vært svært nedbørrike vintre som igjen har ført til høye vintertilsig og store snømagasiner. Høsttilsiget har økt i forhold til sammenlignbare tiårsperioder. På denne bakgrunn er det foretatt beregninger av Norges kraftpotensiale i dagens kraftsystem der det i størst mulig grad er tatt hensyn til tilsigsforholdene i 1980 årene.

MODELLBESKRIVELSE.

I disse simuleringene er det benyttet en modell med ukesoppløsning, VANSIMTAP (1), som er utviklet ved Energiforsyningens Forskningsinstitutt A/S (EFI). VANSIMTAP er basert på vannverdimetoden og modellen består av to nivåer. Det første nivået er en aggregert modell av systemet, "Enmagasinmodellen", som beregner vannverdiene. Enmagasinmodellen er koblet til en tappefordelingsmodell (detaljdatamodell) der den detaljerte driften av produksjonssystemet simuleres.

Sumproduksjonen for en uke blir beregnet av enmagasinmodellen. Tappefordelingsmodellen foretar så en disponering av vann i enkeltmagasiner og en fordeling av produksjon på enkeltstasjoner. I enmagasinmodellen blir det ikke tatt hensyn til tappe- og magasinrestriksjoner til enkelt magasiner og kraftstasjoner (moduler). I tappefordelingsmodellen er det for den enkelte modul tatt hensyn til slike forhold i den grad de lar seg modellere.

I disse simuleringene er det benyttet en detaljdatamodell for hele Norge som består av 831 moduler, herav 21 pumper/pumpekraftverk (Norgesmodellen). Denne modellen, som omfatter nær 100% av alle kraftproduksjonsenheter i Norge, gir en god beskrivelse av det norske kraftsystemet og er fullstendig oppdatert pr mai 1991. De få varmekraftenhetene som finnes i det norske system er det også tatt hensyn til.

Norgesmodellen brukes for å foreta beregninger av den totale krafttilgang i det norske kraftsystemet under varierende forutsetninger. Det er i disse beregningene sett bort fra utveksling av kraft med utlandet.

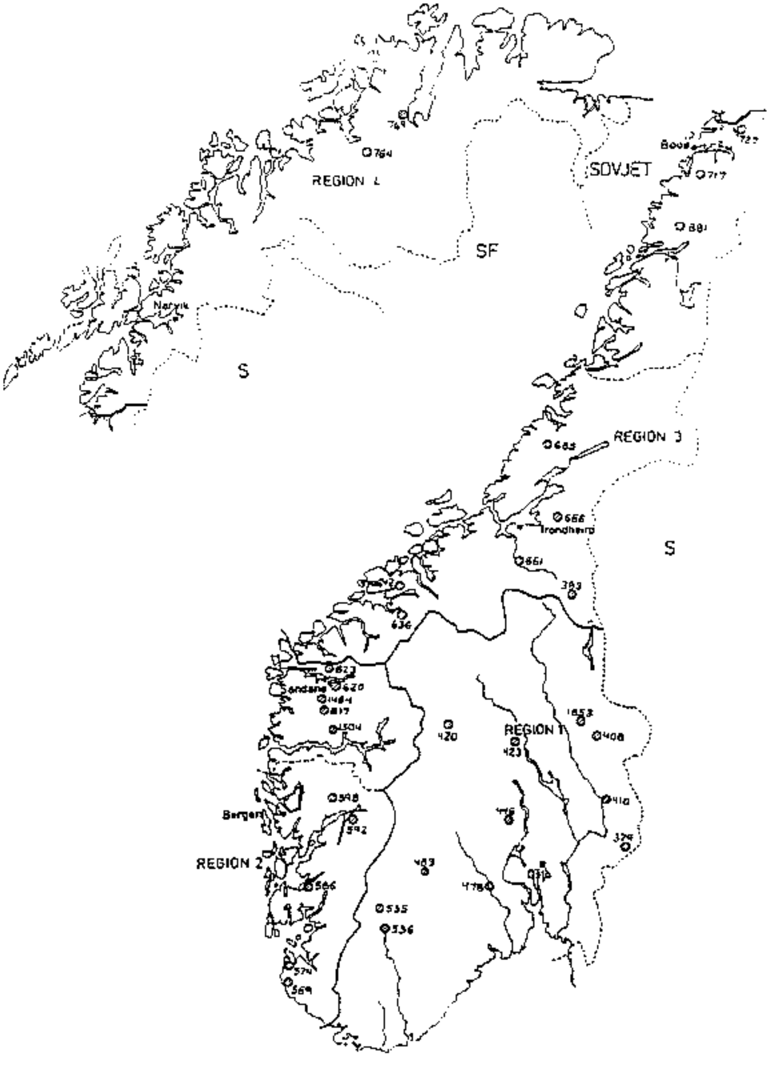
TILSIGSUNDERLAG.

Ved seriesimuleringer med Norgesmodellen for tilsigsperioden 1931 til 1980 har vi normalt anvendt 112 ulike tilsigsserier. Det er viktig at tilsigsunderlaget i detaljsimuleringen av produksjonssystemet skal være mest mulig representativt. De fleste seriene er beregnet av Norges Vassdrags og Energiverk (NVE) og bygger på vannstandsobservasjoner, men flere serier er innhentet direkte fra produksjonsverk og eventuelt utvidet ved hjelp av regresjonsanalyse hos Samkjøringen.

Det har ikke vært mulig å fremskaffe et like solid tilsigsunderlag når periode utvides med 10 år til også å omfatte 1980 årene. NVE har beregnet 33 tilsigsserier som er rimelig godt fordelt over hele landet og som dekker hele perioden 1931 til 1990 (figur 1).

I modellen er det knyttet et fast middeltilsig (en parameter) til hver enkelt modul som representerer en fast tidsperiode. Når tilsigsperioden forandres må dette middeltilsiget justeres slik at middeltilsiget er representativt for den nye tidsperioden. I disse beregningene er det gjort slik at middeltilsiget i alle moduler som er representert av et bestemt vannmerke er likt skalert.

Av de 33 tilsigsseriene har 30 et middeltilsig som er høyere for perioden 1931-1990 enn for 1931-1980. Av de øvrige har 2 tilnærmet samme middelverdi mens en serie har et lavere langtidsmiddel for den forlengede serie. Endringen av er fordelt på følgende måte:



Figur 1. Geografisk oversikt over tilsigsserier som inngår i beregningene.

I 3 serier øker middeltilsiget med over 5%.
I 17 serier øker middeltilsiget med mellom 2 og 5%.
I 10 serier øker middeltilsiget med mellom 0 og 2%.
I 2 serier er middeltilsiget uendret.
I 1 serie avtar middeltilsiget.

REPRESENTATIVITET I TILSIGSUNDERLAGET.

Et generelt problem ved detaljsimulering av det norske kraftsystem over en så lang tidsperiode er å finne fram til et tilstrekkelig antall representative tilsigsserier. Enkelte målestasjoner vil måtte representere "uforsvarlig" store geografiske områder. Enkeltserier representerer en middelproduksjon fra 0.1 til 15.0 TWh/år. Generelt kan man si at representativiteten i tilsigsunderlaget reduseres når antall serier reduseres.

De lange tilsigsseriene er ofte referert et punkt lokalisert i lavereliggende deler av vassdrag der observatører har vært tilgjengelig. Målestasjonene representerer derfor ofte lavereliggende områder i tillegg til fjellområder og ofte er også arealet i nedslagsfeltet stort. Det er imidlertid i fjellområdene de fleste inntaks- og reguleringsmagasiner er lokalisert.

Effekten av at lavlandsserier blir satt til å representere høyfjellsfelt i simuleringene er bl.a. tidligere vårflomstart, lang smelteperiode med utstrakt flomtopp, kortere lavvannsperiode og høyere vintertilsig. Ved at færre tilsigsserier benyttes forsterkes muligens denne effekten noe bl.a. ved at større andel av seriene hentes fra store nedslagsfelt.

RESULTATER OG DRØFTING.

Ved å ta tilsiget til hver modul og kjøre gjennom modellen uten hensyn til vanntap eller restriksjoner av noen art kommer man fram til "brutto energitilsig". Brutto energitilsig gir kun uttrykk for råenergitilgangen. Midlere brutto energitilsig øker fra 117 TWh/år for perioden 1931-80 til 121 TWh/år når perioden utvides med 10 år til 1931-90, en økning på 3.4 %.

Ved en ordinær kjøring av VANSIMTAP tas det hensyn til alle forhold som er modellert. Fordeling av elektrisitetsforbruk over året, mulighet for leveranser til prisavhengige markeder og magasinhåndtering påvirker produksjonsbehovet til enhver tid. Minstevannføringer og restriksjoner i magasinene overholdes. Tilsig som kraftsystemet ikke har kapasitet til å lagre eller utnytte direkte i produksjon blir registrert som flom. Man står igjen med det tilsiget som systemet har kapasitet til å utnytte; det "nyttbare tilsiget".

Det nyttbare energitilsiget gir uttrykk for kraftsystemets reelle produksjonsevne i en gitt tidsperiode. Det midlere nyttbare tilsig for perioden 1931-80 er beregnet til noe over 108 TWh/år, fullt overensstemmende med det vi pr idag regner som den midlere vannkraftproduksjon beregnet i modellen med 112 tilsigsserier. For perioden 1931 - 90 øker det midlere nyttbare tilsiget med over 2 TWh/år til nær 111 TWh/år.

30 års midler, "normalperioder".

Tilsigsperioden som er benyttet i disse simuleringene er så lang at den inneholder to meteorologiske normalperioder, 1931-60 og 1961-90. Se tabell 1.

Periode	Brutto energitilsig (TWh)	Nyttbart energitilsig (TWh)
1931-60	117.0	107.8
1961-90	124.2	113.2

Tabell 1. Midlere energitilsig for 30 årsperiodene 1931-60 og 1961-90. "Normalperiodene".

I figur 2 er løpende 30 års midler av brutto- og nyttbart tilsig framstilt. 30 års midlere energitilsiget har sin minimumsverdi i perioden 1931-60 og 1951-80. Fra 1980 har siste 30 års middel vist en jevn stigning med unntak av perioden 1958-87. Årene 1989 og 1990 har som det framgår av figur 2 hatt en dramatisk innvirkning på langtidsmiddel for energitilsiget.

Minimum 30 års middelverdi finner vi for perioden 1931-60 (den første "normalperioden"), mens maksimumsverdien for 30 års middel er for perioden 1961-90 (den siste normalperioden). Høyeste 30 års middel for nyttbart tilsig ligger 6 TWh eller 5 % over laveste 30 års middel.

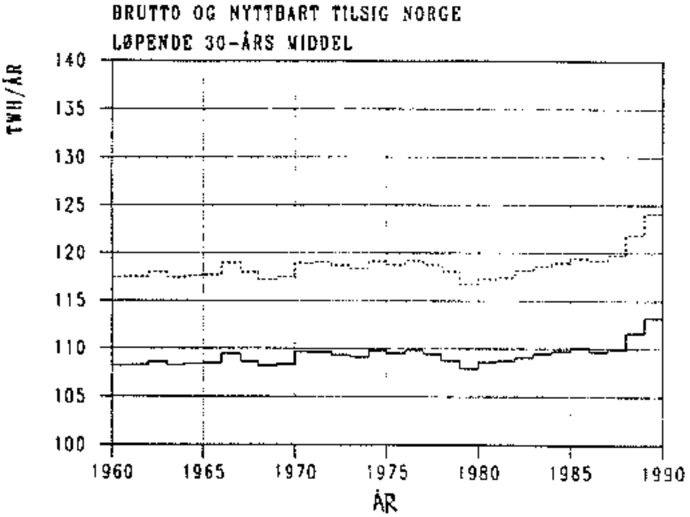
Blant de 10 laveste 30 års midler er 8 fra 60 åra, mens blant de 10 høyeste er 6 fra 80 åra.

10 års midler for energitilsig.

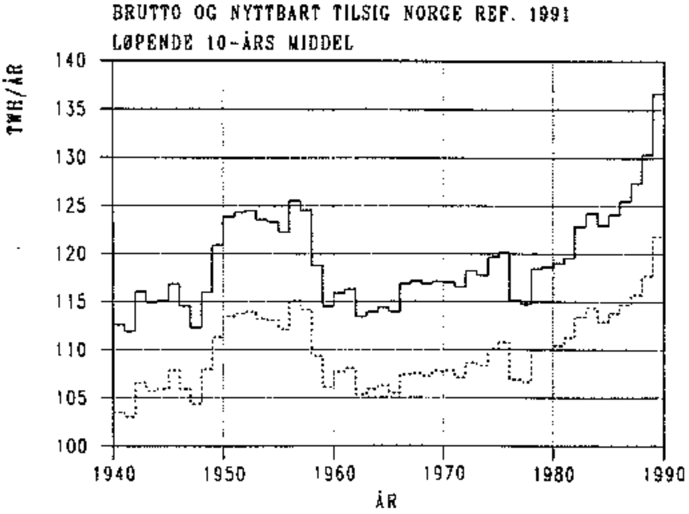
Tabell 2 og figur 3 viser 10 års middelverdier for brutto- og nyttbart tilsig.

Periode	Brutto energitilsig (TWh)	Nyttbart energitilsig (TWh)
1931-40	115.6	105.9
1941-50	120.9	111.3
1951-60	114.5	106.1
1961-70	117.1	107.7
1971-80	118.7	110.1
1981-90	136.7	121.8

Tabell 2. Midlere energitilsig for de hele 10 årsperiodene i perioden 1931 til 1990.



Figur 2. Løpende 30-års midler av brutto- og nyttbart tilsig for utbygd norsk kraftsystem pr 1/5 1991.



Figur 3. Løpende 10-års midler av brutto- og nyttbart tilsig for utbygd norsk kraftsystem pr 1/5 1991.

Samme tendens som framkom ved å betrakte 30 års midler vises ved å betrakte 10 års midler. Den siste hele 10 års perioden, 1981-90, har det største middeltilsiget og den første, 1931-40, har det laveste.

Det bør forøvrig bemerkes at midlere nyttbart tilsig for 1981-90 er vel 10 TWh høyere enn for noe tidligere decenium og 12.5% over middeltilsiget for perioden 1931 - 80.

Generelt

De tre enkeltår som har de høyeste nyttbare tilsig i hele 60 års perioden finner man også i den siste 10 årsperioden (1990,1983 og 1989). Kun 2 enkeltår (1985 og 87) fra tiårsperioden 1981-90 har lavere tilsig enn gjennomsnittet for hele 60 årsperioden. Figur 4 viser brutto- og nyttbart tilsig år for år.

En summasjonskurve som viser akkumulert avvik fra langtidsmiddel av brutto tilsig er vist i figur 5. I løpet av 80 årene innhentes hele det akkumulerte avviket.

USIKKERHET

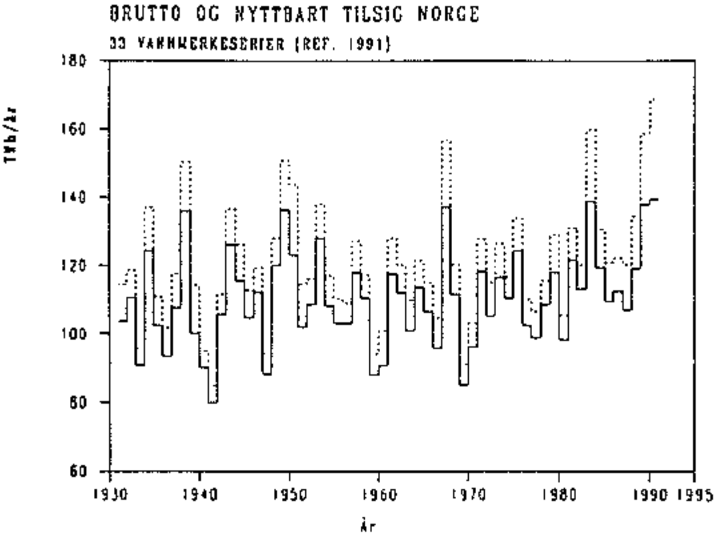
Usikkerheten i beregningene som er utført i denne undersøkelsen er noe større pga at antall tilsigsserier som er benyttet er adskillig lavere enn det som normalt benyttes av Samkjøringen ved sumberegninger for hele Norge (Norgesmodellen). Tidligere beregninger for totalsystemet for perioden 1931-89 (2), men med kun 16 serier, gir resultater som er helt i tråd med de resultatene som framkommer i disse beregningene. Når flere tilsigsserier blir tilgjengelig for denne perioden kan denne usikkerheten reduseres noe.

En kilde til usikkerhet ligger også i at det i modellen benyttes ukesoppløsning. I mindre nedslagsfelt og i dårlig regulerte magasiner blir det derfor ikke tatt hensyn til kortevarige flommer i tilstrekkelig grad.

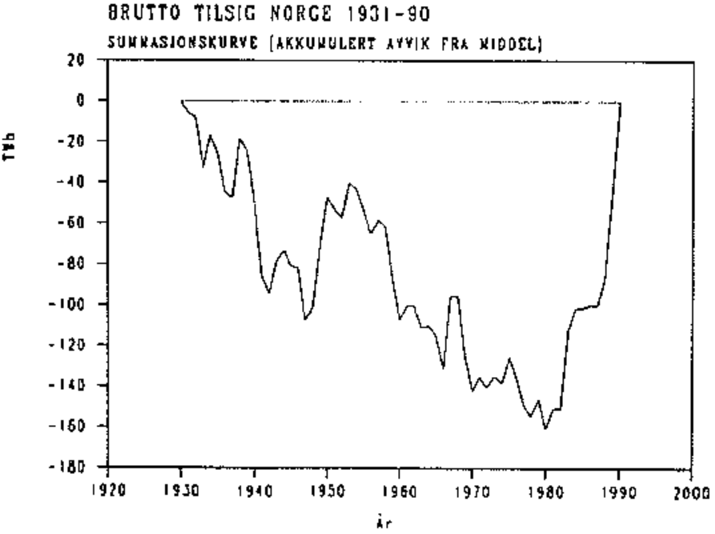
Det er også knyttet en usikkerhet til tilsigsnormalene til de enkelte moduler i modellen. Kvaliteten på disse data er varierende bl.a. fordi tilsigsunderlaget for beregning av tilsigsnormalene bygger på ulike observasjonsperioder, alt avhengig av når utbyggingen er foretatt og hva slags formål de er beregnet for. Mye av dette underlaget bygger på perioden 1931 - 60 eller deler av denne og er siden ikke korrigert.

Det ligger også en usikkerhet i selve modellverktøyet som er vanskelig å kvantifisere, men nøkternt vurdert antas denne å ligge i størrelsesorden 1-2 %.

Vannkraftproduksjonen blir liggende på et jevnt nivå selv om systemet presses. Den vesentligste usikkerhet ligger i beskrivelsen av kraftmarkedet som modellen ser. Slik disse beregningene er utført blir det ikke tatt hensyn til nordisk samkjøringsgevinst i og med at det er sett bort fra utveksling av kraft med utlandet.



Figur 4. Brutto- og nyttbart tilsig år for år gjennom hele simuleringsperioden. Kraftsystemet ref. 1/5 1991.



Figur 5. Akkumulerte avvik fra middeltilsig år for år gjennom hele simuleringsperioden. Kraftsystemet ref. 1/5 1991.

KONKLUSJONER

Beregning av vannkraftpotensialet i det norske kraftsystemet er sterkt avhengig av hvilken tilsigsperiode som blir benyttet. Den sterke økningen i midlere energitilsig som framkommer ved å øke simuleringsperioden fra 50 til 60 år må betraktes som dramatisk og bekrefter denne påstanden.

Valg av tilsigsperiode bør avhenge av formål med simuleringen. Ved utbyggingsplanlegging for vannkraftverk som har en levetid i størrelsesorden 60 år bør det legges andre vurderinger til grunn enn når man foretar en driftssimulering med et 3 års perspektiv.

Tilsiget i det siste tiåret sett under ett er ekstremt mye høyere enn i tidligere tiårsperioder vi har landsdekkende data for.

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VIRKNINGER AV ALTAUTBYGGINGEN PÅ ISFORHOLDENE

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ABSTRACT

During the planning stage of the Alta power plant great attention was given to environmental investigations. The influences on the environment downstream the power plant are caused bye the changes in water discharge, of which fish conditions and ice conditions were the most important.

To reduce possible conflicts the plant has very strict flow regulations, and due to uncertainties about the magnitude of the changes caused by regulated flow, a temporary water scheme was given. The trial period was set to 5 years.

During this period the fish- and ice-conditions have been studied closely, and the influence of various water schemes have been evaluated. Based on this the manouvering regulations are now being reconsidered. In this paper only the ice conditions are described.

KORT OVERSIKT OVER VASSDRAGET OG UTBYGGINGEN

Altavassdraget har sitt utspring på Finmarksvidda og renner nordover mot Altafjorden. Vassdraget kan deles i en øvre og nedre del ved innsjøen Vir'dnejav'ri. Den øvre del ligger på Finmarksvidda mellom ca 360 moh og ca 260 moh. Hovedelva, som her kalles Kautokeinoelva, har her lite fall og består delvis av lange, smale innsjøliknende elvepartier.

Fra det naturlige utløpet av Vir'dnejav'ri (normalvannstand 250 moh) falt elva nesten 200 m på ca 7 km og gikk delvis i en trang kløft og delvis i et bratt gjel. Nedenfor Vir'dnejav'ri heter elva Altaelva.

Vir'dnejav'ri er kraftverkets eneste magasin. Omtrent 5 km nedenfor det naturlige utløpet er det bygd en 110 m høy dam, og magasinet har en høyeste regulert vannstand på 265 m. Laveste regulerte vannstand er 245 m ovenfor det naturlige utløpet av Vir'dnejav'ri og 200 m i det kunstige delmagasinet nedenfor. Magasinvolumet er 135 mill m^3, og magasinprosenten er ca 6, det er altså et meget lite magasin.

Kraftverket utnytter fallet mellom magasinet og dalbunnen, Savco, ca 80 moh og ca 2 km nedenfor dammen. Det er 2 turbiner

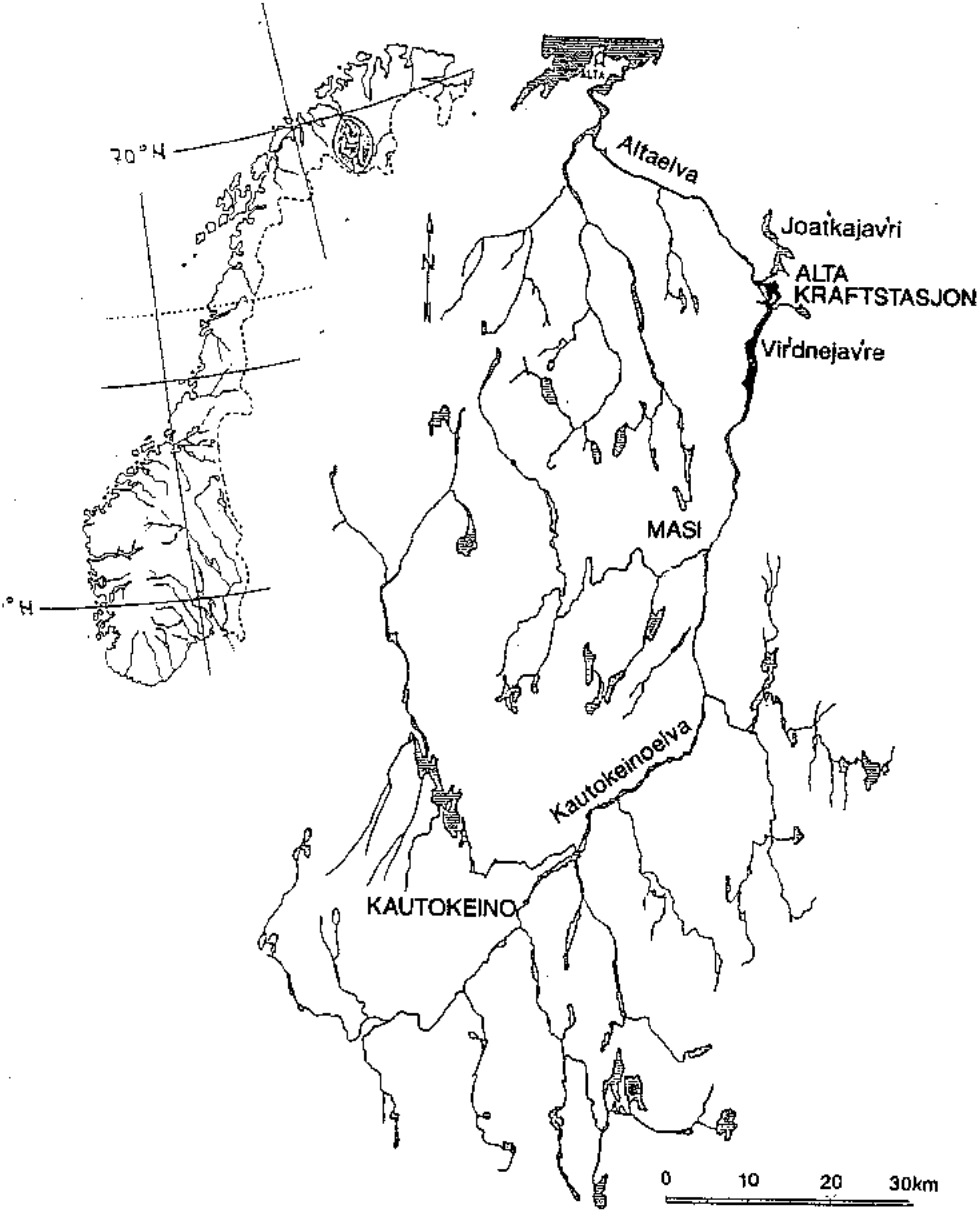

Fig 1. Oversikt over Alta-vassdraget, beliggenheten av Virdnejavvre og Alta kraftstasjon

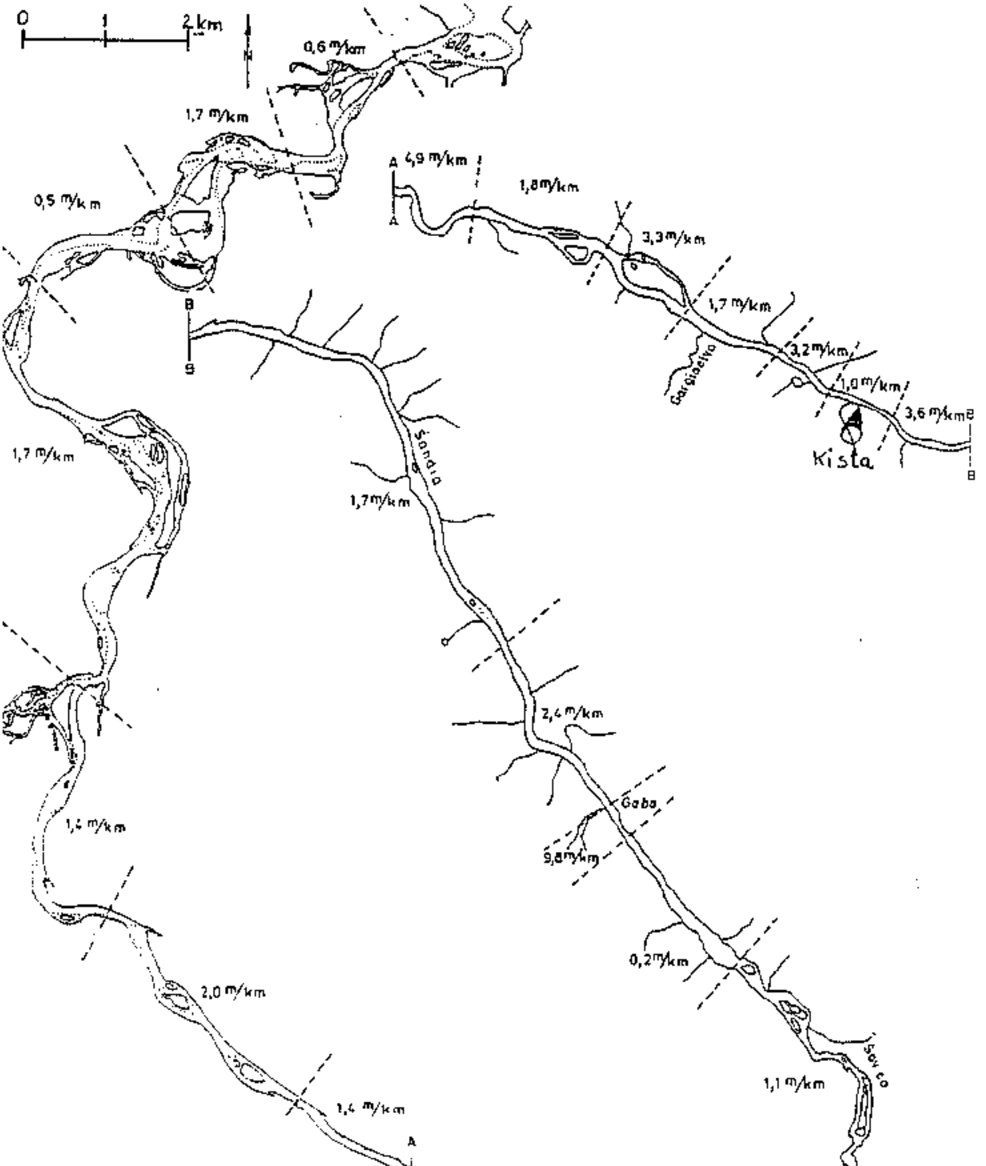

Fig 2. Skisse over Altaelva fra utløpet av kraftstasjonen til havet. Fallforholdene, utløpet av kraftstasjonen og Kista vannmerke er avmerket.

i kraftstasjonen med slukeevne på 33 m³/s og 63 m³/s. Fra utløpet av kraftstasjonen renner Altaelva først ca 5 km, delvis i stryk og så gjennom en mindre innsjø, Savco-vannet, gjennom den karakteristiske Alta canyon, skiftevis i roligere partier og stryk gjennom Altadalen og ut i Altafjorden ved Alta. Det er ca 45 km fra utløpet av kraftstasjonen til fjorden (fig 2).

MANØVRERINGSREGLEMENTET

Manøvreringsreglementet for Alta kraftverk er fastsatt for en prøveperiode på 5 år. Dette skyldes bl a usikkerhet ved kvantifisering av virkningene på isforholdene ved økt vintervassføring i elva nedstrøms utløpet av kraftstasjonen. Her behandles bare den del av reglementet som har betydning for vurdering av virkningene på isforholdene, altså høst- og vinterperioden.

Ved planleggingen av utbyggingen ble mulige virkninger på isforholdene vurdert. Med utgangspunkt i dette ble det foreslått et midlertidig manøvreringsreglement som senere ble vedtatt.

Pentademidler for vinteravløpet i perioden 1915-74 viste store variasjoner fra år til år (fig 3). Ved fastsettelsen av mulige vintervannføringer tok en utgangspunkt i en regulert vassføring i isleggings-tiden tilsvarende øvre kvartil i den historiske serien, slik at vassføringen gradvis ble redusert til 30 m³/s i midten av desember. På dette tidspunkt var elva stort sett islagt de fleste år.

Denne vassføringen ble anbefalt som regulert vintervassføring. Døgn- og ukereguleringer ble frarådet. Med stigende vassføring i isleggingstiden ville faren for oppbryting av isen, sammenskyvninger av ismasser og eventuelt isganger øke. En anbefalte derfor å sørge for at det ikke forekom økninger i vassføringen under isleggingen, og helst slik at også naturlige vassføringsøkninger i denne perioden ble holdt tilbake.

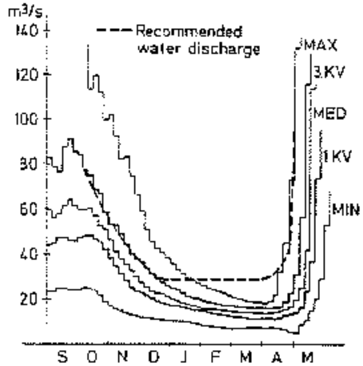

Fig 3. Karakteristiske verdier av vintervannføringer i Altaelva i perioden 1915-74. Anbefalt driftsvannføring er angitt.

Om våren etter at elva var åpen i strømdraget kunne vassføringen gradvis økes, for eventuell uttømming av restmagasin.

Et slikt reglement ble vurdert å gi en tilfredsstillende utnyttelse av magasinet de aller fleste år. De aller siste år har imidlertid både hydrologisk og klimatisk vært meget forskjellige fra den perioden som ble benyttet som grunnlag. Dette vil en komme tilbake til.

ISFORHOLDENE FØR UTBYGGING

Det har vært foretatt ismålinger og isforholdene i elva har blitt kartlagt siden 1962. De første årene dekket iskartene den midtre del av elva, i de senere år har hele strekningen fra utløpet av kraftstasjonen til fjorden blitt kartlagt. Utløpet av kraftstasjonen ligger 80 moh. På den ca 46 km lange strekningen til utløpet i Altafjorden går elva skiftevis i stryk og roligere langsomtflytende partier, ca 5 km nedenfor utløpet ligger Savco-vannet som er ca 2 km langt.

Isleggingen begynte normalt i november, og de stilleflytende partier ble islagt først, aller først området ved Alta bru helt nederst i elva. Ved holmer og øyrområder der elvetversnittet innsnevres og vannhastigheten øker går elva lenger åpen. I kaldt vær blir det stor sarrproduksjon i de åpne områdene, og det blir isoppstuvinger og oppbygging av isdammer i elveløpet. Dette medfører at elveløpet avtrappes, vannhastigheten avtar og elva islegges etter hvert. Før utbygging sank vassføringen relativt raskt utover høsten og vinteren, og det var stort sett bare få og små råker i elva midtvinters bortsett fra i noen få brattere stryk de fleste år. Isleggingen foregikk til noe forskjellig tid fra år til år, mønsteret for isleggingen var imidlertid relativt ensartet. Fra omkring årsskiftet eller i første del av januar var det vanligvis bare små endringer i isforholdene.

På noen strekninger er det relativt store grunnvannstilsig som resulterer i årvisse råker. Ellers var det før utbyggingen bare små strømråker i vassdragets nedre del. I den øvre del er fallet gjennomgående større og i strykpartiene følgelig en del råker.

Det var betydelig isoppstuving i vassdraget, og median isoppstuving i perioden 1916-1969 er beregnet til 0.8-1.0 m ved målestedet Stengelsen i januar-mars.

I forbindelse med ismålingene er det også utført sarrmålinger. Det var til dels betydelige sarrmengder i vassdraget, de aller fleste år mest i begynnelsen av vinteren.

Det er registrert bare et fåtall vinterisganger i vassdraget, men sarransamlinger og mindre sammenskyvninger av ismasser har forekommet uten at dette er registrert som isgang.

Vanligvis begynte isløsningen i slutten av april eller begynnelsen av mai. Elva åpnes først i fosser og stryk i den øvre del. Vassføringen stiger raskt, og isløsingen går fort. Elva ble før regulering av og til rensket ved at det gikk vårisganger, men disse medførte bare sjelden skader eller ulemper, og er vanligvis ikke notert.

DRIFT AV KRAFTVERKET OM VINTEREN I PRØVEPERIODEN

Kraftverket ble startet høsten 1987, og vassføringer nedstrøms utløpet er gjengitt på fig 4. Variasjonene i vassføring gjenspeiler de varierende hydrologiske forhold i disse årene. Vassføringen nedstrøms kraftverket er beregnet på grunnlag av produksjonsmålinger og forbitapping. Vintrene 87-88 og 90-91 var vassføringen omkring 26 m^3, vintrene 88-89 og 90-91 var vassføringen ca 30 m^3/s, som var høyeste vintervassføring i prøvereglementet. Vinteren 91-92 ble det bevisst kjørt på høyere vassføringer som en del av prøveprogrammet, da isforhold og tilsigsforhold gav mulighet til dette.

Noen dager vinteren 1988-89 og en lengre periode vinteren 1989-90 ble det kjørt døgnregulering. Dette kommer en tilbake til i forbindelse med vurdering av isforholdene etter regulering.

ISFORHOLD ETTER REGULERING

Generelt

Isforholdene nedstrøms kraftstasjonen endres med værforholdene og vassføringen. Milde vintre vil forsinke isleggingen samtidig som større råker gir grunnlag for økt sarrdannelse i kuldeperioder. Økt vassføring forsinker også isleggingen og vil derfor også medføre økt sarrdannelse i kuldeperioder.

Variasjoner i værforhold og vassføring, spesielt i isleggingstiden, vil kunne forstyrre isleggingen ved at isdammer brytes ned og isleggingsprosessen må begynne på nytt. Stor sarrproduksjon vil kunne medføre at elveleiet mer eller mindre fylles opp av sarr- og ismasser og avløpsforholdene forstyrres. Dette kan videre medføre oversvømmelser og utløsing av isganger.

I ett og samme vassdrag er det et samspill mellom værforholdene og vassføringen som bestemmer hvordan isforholdene vil bli. Det er foreløpig vanskelig å kvantifisere virkningen av de enkelte parametre uten ved direkte erfaringer. I prøveperioden er forholdene overvåket for å gi grunnlag for å fastsette optimale driftsvassføringer innenfor tålegrensene for vassdraget.

Som underlag for vurdering av værforholdene er her benyttet døgnmiddeltemperaturer for Alta lufthavn de aktuelle år sett i relasjon til midlet for perioden 1971-1991. Temperaturene langs elva vil være en del lavere, men dette antas bare i liten grad å påvirke avviket fra midlet over en årrekke.

På grunn av relativt stor gjennomstrømning i magasinet også om vinteren blir driftsvannets temperatur bare 0,3 - 0,5 °C.

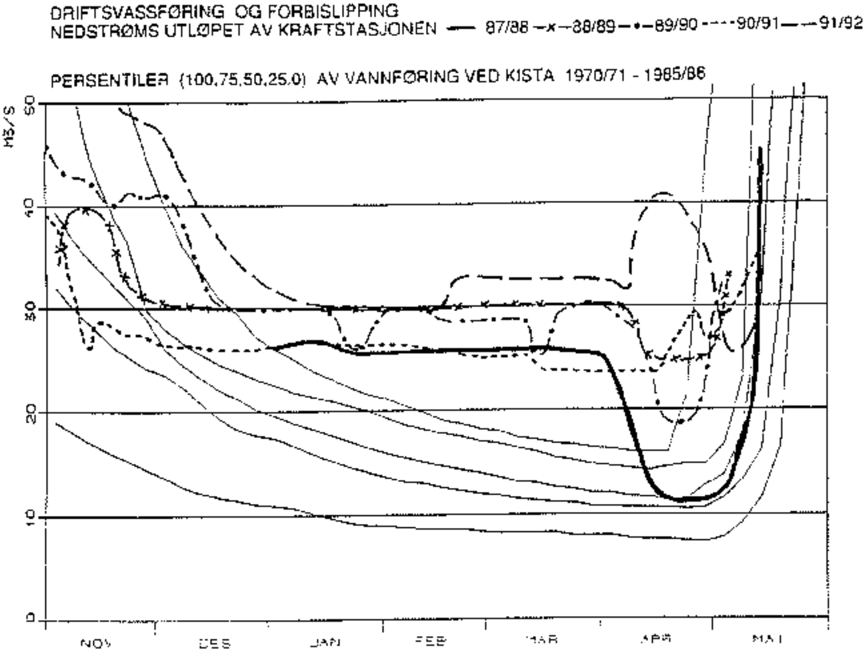

Fig 4. Karakteristiske verdier av vannføringen om vinteren før regulering sammenstilt med vannføring nedstrøms utløpet av kraftverket i årene etter regulering.

Dette medfører at Altaelva etter regulering går åpen ned til Savcovannet.

De enkelte år

I oktober 1987 var lufttemperaturen betydelig høyere enn normalt (fig 5) og dette har forsinket isleggingen i elva. Driftsvannets overtemperatur medførte som ventet råk fra utløpet til Savcovannet. Forøvrig var det ikke merkbare virkninger på isforholdene som følge av reguleringen. Driftsvassføringen var relativt jevn og generelt synkende fra ca 26 til ca 23 m3/s.

Noe høye lufttemperaturer i oktober 1988 sammen med betydelige høyere vassføringer medførte betydelig forsinkelse av isleggingen. Normale lufttemperaturforhold frem til midten av januar medførte at isforholdene da var omtrent som før reguleringen bortsett fra den helt øvre del som alltid vil være åpen. Driftsvassføringen var omkring 30 m^3/s hele vinteren. Det var relativt skiftende værforhold videre utover vinteren uten at dette påvirket isforholdene i uheldig retning. Dette viste at driftsvassføringer i denne størrelsesorden kan tåles i vassdraget.

Høsten 1989 var nær gjennomsnittet med hensyn til lufttemperaturen. Det var imidlertid stort tilsig også dette

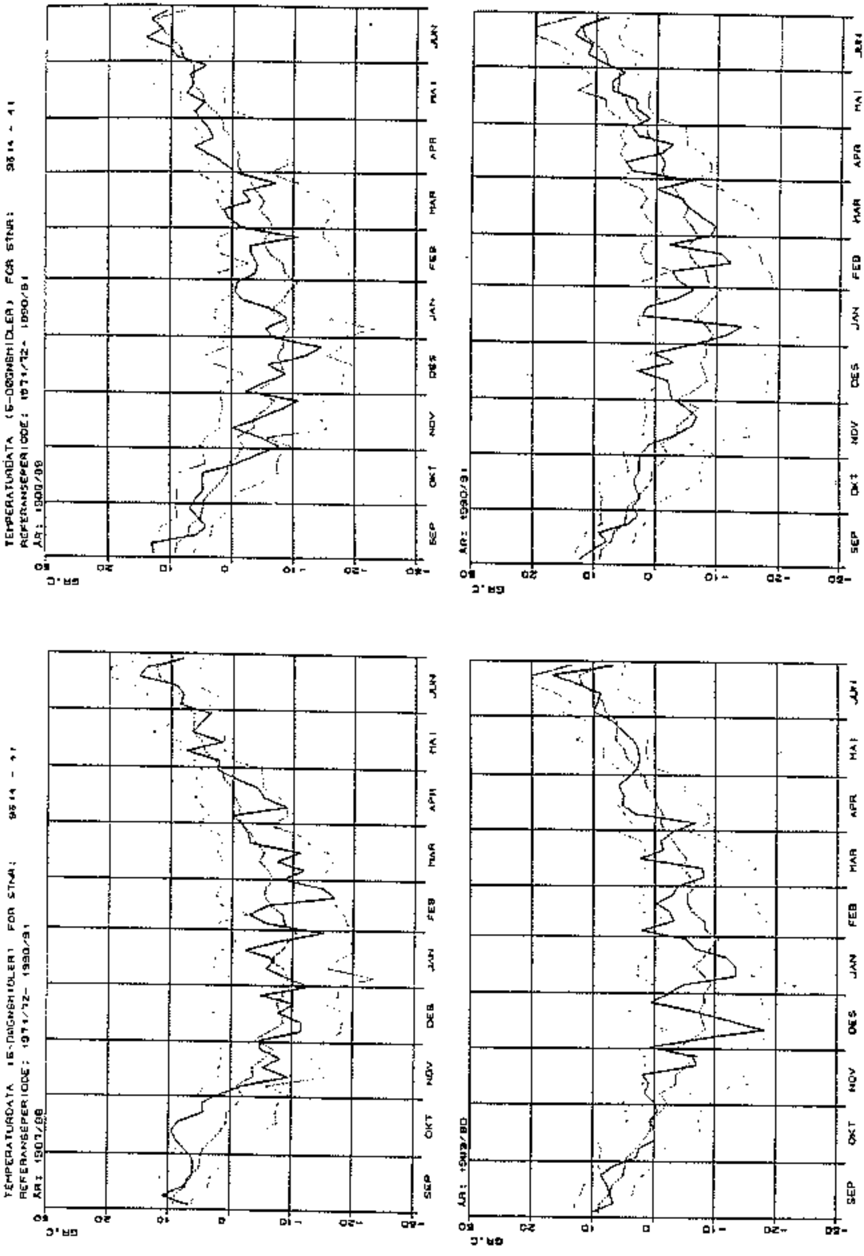

Fig 5. Lufttemperatur vintrene 87-88 til 90-91 sammenstilt med midlet for perioden 71-71 til 90-91.

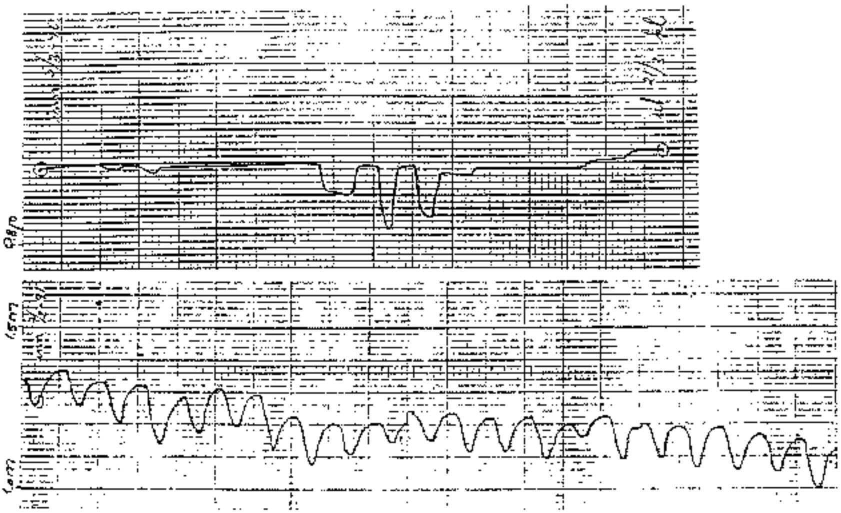

Fig 6. Utsnitt av limnigram fra Kista som viser vannstandsvariasjonene under døgnreguleringen mars 1990 og februar 1991.

året, og driftsvannføringen var omkring 30 m³/s hele vinteren. Vinteren var generelt mild, og det var ofte lufttemperaturer omkring 0°C. Dette medførte meget sen islegging. Først i slutten av januar var isforholdene omtrent som før regulering i elvas nedre del, i den øvre del var det betydelig mindre is enn noe tidligere år. Bare en meget kort periode var de større råkene delvis gjenfrosset.

Det var imidlertid ingen isproblemer i vassdraget. Driftsvassføringen var alle år så langt forsøkt holdt så jevn som mulig. En forsøkte da forsiktig med døgnregulering i en kort periode. Vassføringen ble redusert først med 5 m³/s, økt igjen og deretter variert tilsvarende med amplityde på 8 m³/s. Vannstandsvariasjonene ved Kista var 10-20 cm (fig 6). Dette gav en del overvann men førte ikke til oppbryting av isdekket. På grunn av vannsituasjonen ønsket ikke utbygger å fortsette prøven i lenger tid, men resultatene gav signaler om at moderat døgnregulering kunne være mulig i Altaelva.

Høsten 1990 var lufttemperaturen noe høyere enn et middelår, men det var bare korte kuldeperioder resten av vinteren. Tilsiget var lavere enn de to foregående år. Driftsvassføringen var i middel omkring 25 m³/s denne vinteren. Først og fremst værforholdene førte til betydelig forsinkelse av isleggingen, og bare en kort periode var det tilnærmet gjenfrosset i den øvre del nedstrøms Savcovannet.

En ønsket nå å undersøke virkningene av lengre tids døgnregulering på isforholdene, og det ble i februar og mars kjørt døgnvariasjoner med amplityder på 5 og til dels 8 m³/s. Dette gav tidvis noe overvann som tørket opp relativt fort.

kjørt døgnvariasjoner med amplityder på 5 og til dels 8 m^3/s. Dette gav tidvis noe overvann som tørket opp relativt fort. Det var ikke oppbryting av isdekket. Driftsvassføringen varierte i lenger tid mellom 22 m^3/s om natten og 27 m^3/s om dagen. Ved Kista var amplitydene i vannstand 10-12 cm (fig 6). Den isoppstuvede vannstanden viste en synkende tendens, som viser at sarr ble vasket ut i elveleiet. I forbindelse med isløsingen var det mindre sammenskyvninger av ismasser i vassdragets nedre del.

Høsten 1991 var mild og tilsiget var uvanlig høyt. Dette medførte at isleggingen bare såvidt hadde startet i midten av desember, isleggingen begynte for alvor først mot slutten av januar, og spesielt i den øvre delen av elva var det hele vinteren uvanlig mye åpent dette året.

Tilsiget var uvanlig høyt hele vinteren, og driftsvassføringen ble økt til 33 m^3/s i midten av mars og ytterligere til 40 m^3/s i begynnelsen av april. Dette førte til noe overvann i forbindelse med økningene, men forøvrig ikke merkbare endringer i isforholdene.

Sarr-og istykkelser har blitt målt også etter regulering. Både is- og sarrmengder målt etter reguleringen ligger innenfor de verdier som ble målt i perioden 1964-75 før reguleringen.

KONKLUSJONER

Etter reguleringen har det vært varierende tilsigsforhold med moderate og til dels store tilsig, det har ikke vært spesielt kalde år. Det har vært holdt en mest mulig jevn driftsvassføring i isleggingsperioden og isleggingen har foregått på relativt høye vannstander. Under de værforhold som har vært disse årene har driftsvassføringer på i overkant av 30 m3/s ikke gitt antydning til isproblemer. Det ser ut til at elva tåler ytterligere økninger i driftsvannføringen.

Når det gjelder døgnregulering er dette forsøkt bare etter at et stabilt isdekke er etablert i den nedre del av elva. Også i øvre del har isdekket vært stabilt på de rolige partiene, men det har vært til dels lange åpne strekninger.

Ved døgnreguleringen har vassføringen først blitt redusert og deretter økt til det opprinnelige nivå. Dette har medført overvann, men ellers har ikke isdekket blitt påvirket merkbart. Svingningene i vannstand har vært 10-15 cm ved Kista hvor elveleiet er relativt trangt. Dette tilsvarer døgnvariasjoner på 5 m^3/s. Isdekket er stabilt og synes å tåle enda større døgnvariasjoner under tilsvarende værforhold som en har hatt. En må regne med at tålegrensen blir lavere ved strengere værforhold. Dette har sammenheng med at sarr-produksjonen da vil kunne øke betydelig i de åpne områdene og kunne gi avløpsproblemer.

ALTA PROSJEKTET - VANNOPTIMALISERING

Programvare for beslutningsstøtte

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ABSTRACT

A complete system for optimal utilisation of available water resources for hydro electric power plants is described. The system is automatically or manually collecting information from the Norwegian Meteorological Institute (DNMI), field measurement stations and the general power control system. These informations give the operator the following decision support:

- optimal total discharge for turbines,
- optimal total discharge for escape valves,
- optimal setpoint distribution on turbines,
- optimal discharge distribution on escape valves and
- trend forecasts of reservoir level.

INNLEDNING

Mye vann renner utenom turbinene i norske vannkraftverk. Ved enkelte verk er tapene store. Disse tapene skal en nå kunne minimalisere ved å benytte beslutningsstøtte verktøy for driftsoptimalisering av kraftverk. En har idag utstyr som kan samle inn meteorologiske og hydrologiske data og bearbeide disse i en modell slik at en kan få informasjon om forventede vanntilsig til magasin(er). Ut fra tilgjengelige informasjoner gis det beslutningsstøtte for å kunne utnytte de tilgjengelige vannressurser på best mulig måte.

Siemens har i samarbeid med Statkraft Alta-verkene utviklet et beslutningsstøtte verktøy for Alta Kraftverk. Idag renner opptil 20 prosent av vannet utenom turbinene i Alta Kraftverk. Noe vann må renne forbi uansett, men det er beregnet at utstyret skal gjøre Alta-verkene i stand til å redusere vanntapet med 2-3 prosent. Spesielt om sommeren går det mye vann forbi, fordi vannmassene kommer overraskende på driftspersonellet.

Dette systemet er tilpasset Alta Kraftverk, men er laget så generelt at det skal kunne modifiseres og tilpasses andre kraftverk.

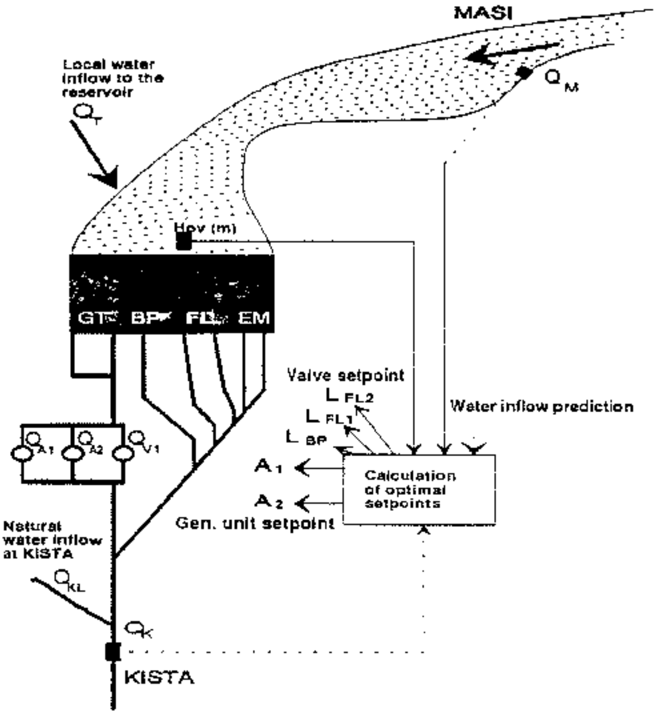


Fig. 1. Alta Kraftverk. Demningen har flere luker og ventiler. GT er luker for tunell systemet til turbinene, BP er omløpsventil, FL er flomluker og EM er nødsflomluker.

FUNKSJONER

Funksjoner som inngår i beslutningsstøtte verktøy for drift av kraftverk er som følger:

- Feltmålinger
- Data innsamling
- Innsamling og lagring av virkelige prosess data fra driftssentral
- Kontroll og retting av inndata
- Datalager for lagring av data fra innsamlingssystemet, statistikk og prognose data fra DNMI
- Tilsigsmodell for hvert nedslagsfelt i systemet
- Setting av systemets konsesjonskrav
- Beregning av optimal vannføring gjennom turbiner og luker over kort tid (1 uke, korttidsoptimalisering)

- Beregning av optimal vannføring gjennom turbiner og luker over lang tid (26 uker, langtidsoptimalisering)
- Optimal fordeling av vannet på turbinene
- Fordeling av vannet på lukene etter vedlikeholdskrav
- Prosess-simulator
- Generering av vannhusholds rapporter
- Operatør kommunikasjon

Noen av disse funksjonene er beskrevet i avsnittene som følger.

TOTALT SYSTEM

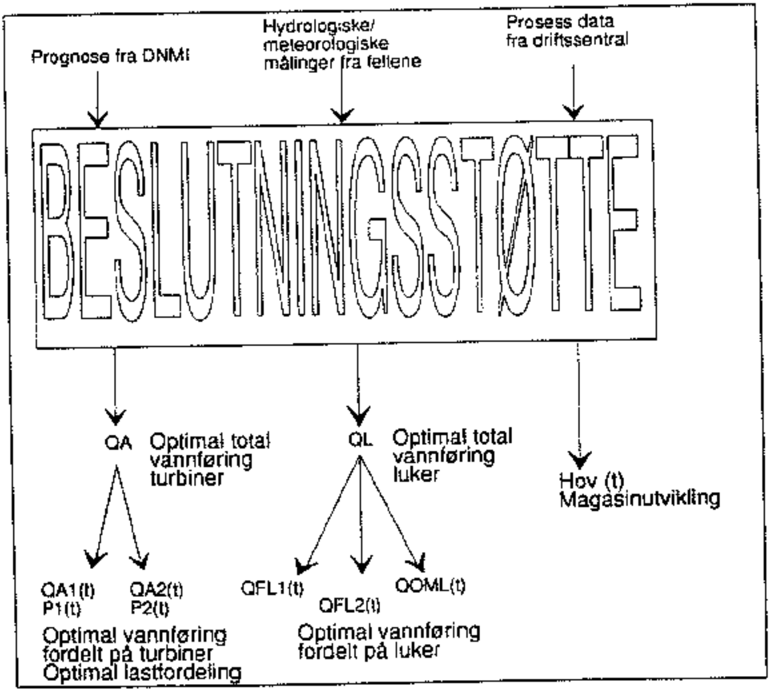


Fig.2. Total system beslutningsstøtte

Figur 2 viser hvilke data en må ha inn i systemet for bearbeiding og hvilke resultat data som kommer ut av systemet. Følgende data vil flyte inn i total systemet:

- Nedbør og temperatur prognose fra DNMI
- Meteorologiske og hydrologiske data fra feltene til systemet
- Prosess data fra driftssentral

Etter bearbeiding av disse dataene vil en få ut følgende data som skal brukes til beslutningsstøtte:

- beregnet optimal total vannføring turbin (QA),
- optimal total vannføring luker (QL),
- optimal vannføring fordelt turbiner (QA1 og QA2) med tilhørende lastfordeling (P1 og P2),
- optimal vannføring fordelt luker (QFL1, QFL2 og QOML) og
- magasinutvikling (Hov).

IMPLEMENTERING

Beslutningsstøtte system for optimal utnyttelse av vann ressursene er delt i to hoveddeler, HYDRO PRED og HYDRO OPT. Disse beskrives kort i de neste to kapitlene.

HYDRO PRED

HYDRO PRED (Hydro Prediction System) er et hydrologisk/ meteorologisk system for beregning av prognose for vanntilsig. Figur 3 viser hvilke programmer/systemer HYDRO PRED består av.

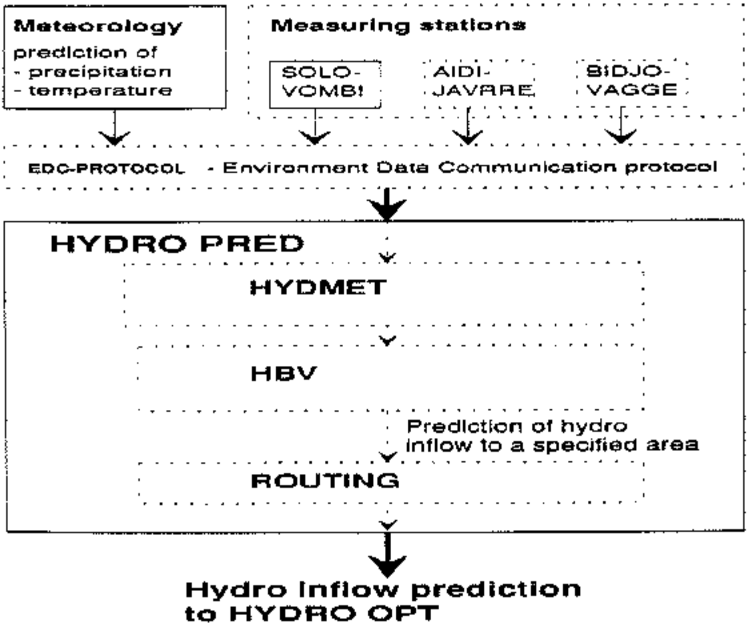


Fig. 3. Tilsigs prognose system (HYDRO PRED)

HYDRO OPT

HYDRO OPT (Hydro optimalization system) er et system for optimal utnyttelse av tilgjengelig vannressurser for vannkraftverk. Dette skal oppnås gjennom maksimering av energiproduksjon på både timebasis og ukebasis, samtidig som konsesjonsbestemmelser skal overholdes. Optimal total vannføring gjennom kraftverk og optimal lastfordeling mellom aggregater velges ved bruk av prediktert tilsig og estimerte virkningsgrader samt estimerte størrelser som vannstand og vannføringer. Figur 4 viser moduler i HYDRO OPT.

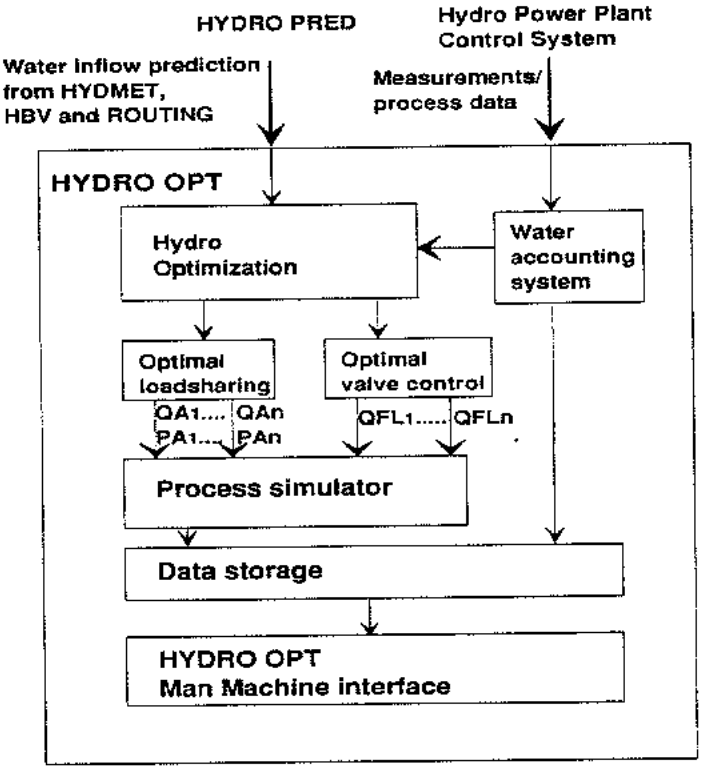


Fig. 4. HYDRO OPT

KONSESJONSKRAV

De fleste vassdrag i Norge har strenge konsesjonskrav for vannføringene. Disse kravene må legges inn for hvert enkelt vassdrag.
I Altavassdraget fremstår f.eks. manuvreringsreglementet med en rekke konkrete begrensninger angående den regulering som kan foregå i Altaelva. Disse kan summeres opp som følger:

1. 15.12. - 31.03.: Maksimal vannslipping begrenset til 30 m3/s.
2. 01.04. - 25.04.: Maksimal vannslipping gradvis økende fra 30 m3/s til 50 m3/s.
3. 26.04. - 30.04.: Maksimal vannslipping gradvis økende fra 50 m3/s til full driftsvannføring (i beregningene som følger er den satt til 96 m3/s.)
4. 01.05 - til tilsiget er større enn slukeevnen (96 m3/s): Full driftsvannføring.
5. Fullt magasin - 31.09: Vannføringen skal ligge innenfor +/- 10 % av naturlig vannføring målt ved Kista.
6. 01.10. - 15.12.: Maksimal vannslipping må ikke overstige en jevnt avtagende vannføring fra 85 m3/s til 30 m3/s.

EKSEMPEL PÅ BESLUTNINGSSTØTTE FOR OPTIMALISERING MED EN TEST TILSIGSPROGNOSE

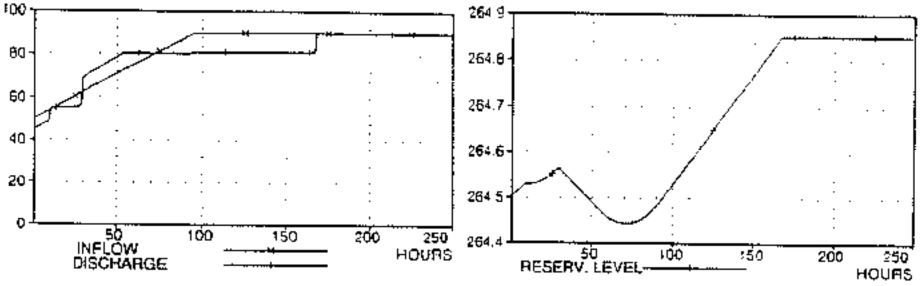


Fig. 5. Tilsig (m3/s, inflow), total vannføring gjennom turbiner (m3/s, discharge) og magasin nivå i simulerings eksemplet (m, reserv.level).

Figur 5 viser tilsigsprognose og forslag til optimal kjøring. Testkjøringen bruker en tilsigsprognose som starter med 50 m3/s og øker lineært til 90 m3/s over 4 døgn. Deretter er tilsiget konstant 90 m3/s. Vi ser også at start høyden på magasinet er satt til 264.5 moh.

Beslutningsstøtten gies her i form av forslag til total vannføring gjennom turbinene og dertilhørende magasinutvikling. Effekten av +/- 10% begrensningen er tydelig vist i forskjellen mellom tilsig og vannføring gjennom turbinene. Samtidig kan en se av magasinutviklingen hvordan systemet prøver å spare vann (fra ca. time 75 til 165). Dermed økes den totale vannutnyttelse.

KONKLUSJON

Vi har beskrevet et system for besluttningsstøtte ved Alta Kraftverk. Vi tror at den viktigste egenskapen ved systemet er integrasjonen av målingene og matematiske modeller.

Den vanskeligste delen ved optimalisering av vannføringen er sannsynligvis valg av framtidig magasin tilstand. En spesiell modell har blitt utviklet for å ta seg av dette problemet.

Simulerings studier, utført før prosjektstart, viste en mulig økning av produsert effekt på 2-3%.

INNGREP I VASSDRAG - FoU-PROGRAMMET "ETTERUNDERSØKELSER"

Per Einar Faugli   Norges vassdrags- og energiverk   Norge

ABSTRACT

The Norwegian Water Resources and Energy Administration (NVE) is carrying out an R. & D. programme encompassing the effects of hydropower schemes on the environment.

The main disciplines being studies are flora and vegetation, freshwater biology, ornthology, fluvial geomorphology, glaciology and outdoor recreation. Most of the studies are being carried out in the following watercourses: Ekso, Aurland, Fortun, Dokka (with emphasis on the delta), Orkla and Skjoma. In addition particular topics have been studies, such as "Changes in the transport of suspended material after hydropower development". The significiant of varius encroachements for the total landscape has also been considered.

So far, the results indicate that conditions in the river channel are modified in line with the degree of change in discharge, while on a large scale there is considerably less change.

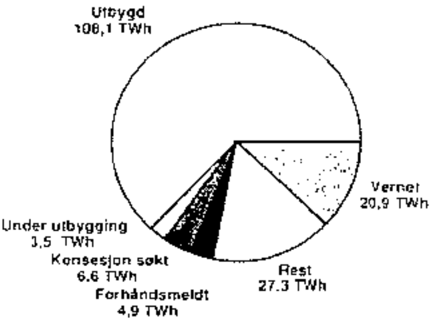
The work is aimed at finding ways of improving the predictability of environmental impact assement. The increased knowledge will also prowide the basis for habitat modification and other remedial measures.

INNLEDNING

Vann er en viktig naturressurs i Norge. Landets relieff gjør at elvene er egnet til produksjon av elektrisitet. Vannkraften er en fornybar ressurs og således svært attraktiv. Men inngrep i vassdrag forårsaker konseskvenser på naturmiljøet og landskapet. Kunnskap om konsekvensene av de ulike inngrep er varierende. FoU-programmet "Etterundersøkelser" ble igangsatt for å bøte på dette.

FORVALTNING

Forvaltningen av vassdragsressursene i Norge når det gjelder å gi konsesjon for kraftutbygging, bygger i hovedsak på Verneplanene for vassdrag og Samlet plan for vassdrag. Annen bruk av vassdragene er ikke underlagt noen hovedplan, men ulike lover gir visse restriksjoner. Verdt å merke seg er at Verneplanene for vassdrag bare omfatter vern mot kraftutbygging (NOU 1992:12A). Dette har skapt forvaltningsmessige problemer.



NYTTBAR VANNKRAFT PR. 31.12.1990
(midlere årsproduksjon)

Samkjøringens statistikk viser følgende tall for 1991. Prosentvis endring i forhold til 1990 er angitt til høyre

Alminnelig forbruk	71,5 TWh	4,1 %
Alminnelig forbruk, temperaturkorrigert	72,7 TWh	1,0 %
Kraftintensiv industri	28,6 TWh	÷ 3,4 %
Pumpekraft	0,6 TWh	
Elektrokjeler	5,9 TWh	22,9 %
Tap i nettet	1,7 TWh	
Samlet innenlands forbruk	108,3 TWh	2,6 %
Netto eksport	3,0 TWh	+ 81,4 %
Samlet norsk kraftproduksjon	111,3 TWh	÷ 8,5 %

Alminnelig forbruk er referert kraftverk.
Alt annet forbruk er referert forbruker.
Eksport er referert grensen.

Fig. 1. Oversikt over nyttbar vannkraft i Norge pr.31.12.1990 og samlet norsk kraftproduksjon for 1991.

Norges vassdrags- og energiverk (NVE) arbeider nå med å utvikle differensierte forvaltningsregler for de vernede vassdragene.

Elektrisitetsproduksjonen i Norge var i 1991 på 111,3 TWh mot 121,6 TWh året før. Maksimalbelastningen er anslått til ca. 17 200 MW. Vernet potensiale er beregnet til 20,9 TWh (Fig. 1).

Vassdragene brukes i dag til en rekke ulike formål. Intensiteten av inngrep er stadig økende også, i de vernede vassdragene. Sett i relasjon til økt fokusering på hensynet til miljø, og behovet for en bærekraftig utviklintg ved bruk av naturressursene, setter dette store faglige krav til sektorforvaltningen (Brundtland 1987, Mellquist 1992). Siden mange utfordringer har sin hovedårsak i samfunnsutviklingen, er det en utfordring for forskningen å skaffe oversikt over de ulike prosesser som virker inn, og å utvikle egnete planleggings- og styringsverktøy. Utviklingen av vassdragssimulatoren er et ledd i dette (Killingtveit & Fossdal 1992). Helhetsanalyser og konsekvensvurderinger tillegges nå mer og mer vekt.

Forskningsbehovet innen vassdragssektoren er avhengig av bl.a. samfunnsutviklingen generelt, brukernes krav til vannkvalitet og vannmengde, utviklingen av inngrepstype og påvirkning og

endringer i vannforvaltningens struktur og praksis. Det er nødvendig å styrke forskningsinnsatsen for at forvaltningen skal få den forventede kompetanse for å kunne utføre sin oppgave.

Videre vil lovverket måtte utvikles, slik at det er i pakt med en moderne forvaltningsstrategi av naturressursene. De to mest aktuelle lovene, vassdragsloven og vassdragsreguleringsloven, er for tiden under revisjon (Ot. prp. nr. 50 1991-92).

"ETTERUNDERSØKELSER"

I 1988 la NVE frem sin FoU-plan for perioden 1988-1992 (Faugli 1988). Programmet "Etterundersøkelser" ble startet opp i 1988. Programmet første fase avsluttes i år. Bakgrunnen for programmet var at man hadde liten kunnskap om konsekvensene av inngrep på natur og miljø. Det var også et faktum at en rekke av de utførte forundersøkelsene var rene registreringer fremfor konsekvensanalyser.

Mål

Hensikten er å;
- klarlegge om konsekvensanalysene holdt mål, faktisk og metodisk og forbedre forutsigelsesmetodene
- gi økt viten om inngrepenes innvirkning på natursystemene (prosessene)
- gi grunnlag for biotopjusterende tiltak

NVE har den overordnede styring, og det er et nært samarbeid med andre involverte forvaltningsorgan, utbyggere og kommuner. Det er hittil bevilget ca. 9 mill. kr. til programmet, og landets ledende fagmiljøer står for forskningsinnsatsen.

Programmet har lagt til grunn foreliggende materiale innen problemområdet, som "Terskelprosjektet" (Mellquist 1985) og NTNFs program "Miljøvirkninger av vassdragsutbygging" (NTNF 1989). Videre er det, med ulike arrangører, gjennomført en rekke kunnskapsoppsummerende seminarer innen relevante fagfelt som lokalklima, isforhold, grunnvann, vannkvalitet m.v.

Innen dette programmet inngår de tradisjonelle naturvitenskapelige fagfelt som geofag, hydrologi, ferskvannsøkologi, botanikk og ornitologi. Men også friluftslivs- og landsskapsproblematikk er trukket inn. Videre er det lagt vekt på å få frem tverrfaglige problemstillinger, fordi de geo-økologiske prosessene må sees som en enhet for å forstå inngrepenes virkelige konsekvenser. Det er lagt opp til prosjekter hvor resultatene forventes å ha overføringsverdi. Et vanskelig tema, fordi elvene er av så ulik type.

Sentrale faglige problemstillinger er:

- endringer på delta
- etablering av magsiners virkninger
- endringer i elveløpet
- konsekvenser av at vassdrag endrer karakter fra brevassdrag til lavlandsvassdrag
- konsekvenser av endret vanntemperatur
- inngrep i naturlige prosesser
- skille naturlige endringer fra konsekvenser av inngrep
- analyser av vassdrag hvor likevekten forstyrres

Referansevassdrag

Det er mange måter å klassifisere et vassdrags ulike egenskaper på. Et opplegg er forsøkt i det vernede vassdraget Atna, som er utpekt som referansevassdrag. Ni parametre ble lagt til grunn; årsmiddelvannføring, hydrologisk regime, høyde over havet, gradient, profil, bunnsubstrat, løpsform, strandvegetasjon og arealbruk. For denne 97 km lange elven med et nedbørfelt på 1300 km2 ble det konkludert med at det var nødvendig med tre undersøkelsesstasjoner for å kunne få frem vassdragets karakteristika. (Faugli & Lundquist 1988). Dette viser hvor ressurskrevende vassdragsforskning er.

Skal effektene av inngrep klarlegges, er det nødvendig å ha naturlige elvesystemer som referanse. Effekter som skyldes naturlige svingninger og påvirkninger av miljøet pga. lufttransporterte forurensninger (f.eks. sur nedbør) må skilles ut. En oversikt over det faglige behov for referansevassdrag er gitt av Eie et. al. (under bearb.) i forbindelse med verneplanarbeidet. Atna inngår i denne oversikten som det vassdrag som er best undersøkt, og her bygges det opp hydrologiske og biologiske måleserier.

Andre momenter kommer også forstyrrende inn når inngrepenes konsekvenser skal klarlegges. Bruken av arealene har endret seg i raskt tempo. På Vestlandet har f.eks. beitemønsteret i fjellområdene endret seg, og heilandskapet vårt holdes i hevd pga. beiting (Dahl 1987). Omlegging av driften innen jord- og skogbruk forårsaker vesentlige endringer. Alt dette påvirker igjen avrenningsforholdene.

Forventede klimaendringer vil kunne få betydning for vassdragene. Avløppsregimet endres, og alle parametre avhengig av denne. Spesielt sesongfordelingen av tilsiget kan bli endret kraftig (Sælthun et. al 1990).

Aktuelle vassdrag

Sentrale vassdrag innen Etterundersøkelsesprogrammet er (Fig. 2.): Ekso, Aurlandsvassdraget, Jostedøla, Fortunelv, Dokka, Glåma, Orkla, Nea og Skjoma. Inngrepenes art er forskjellige og tiden siden de ble utført varierer.

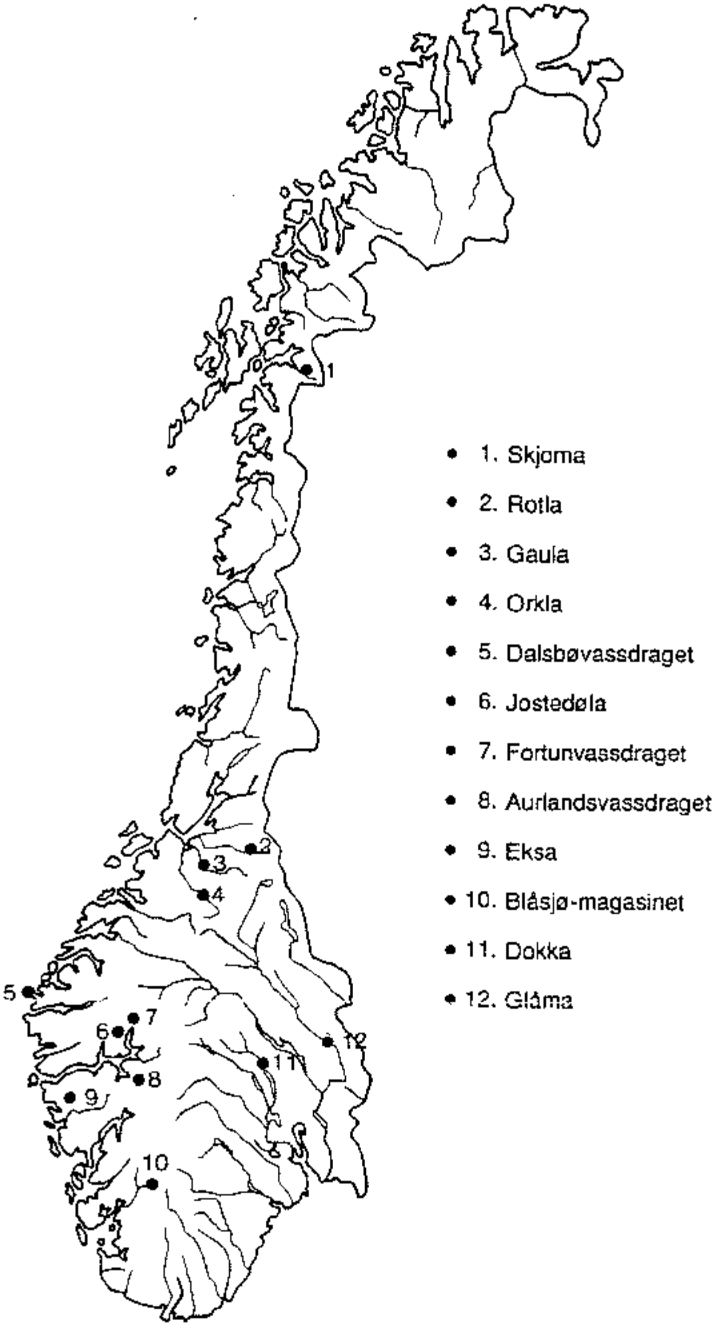


Fig. 2. Oversikt over sentrale vassdrag/lokaliteter som

Det er for tidlig å gi noen oppsummerende resultater fra programmet, men følgende kan trekkes ut av årsrapporten for 1991 (Eikenæs & Faugli 1992):

- bresmeltingen har generelt gitt økt tilsig, men forholdne varierer veldig lokalt
- i løp hvor vannføringen er sterkt redusert er ikke de vegetasjonsmessige endringene så store som forventet. Hvis flommene uteblir, overtar vegetasjonen og skaper problemer for løpets avløpskapasitet
- elvestrekninger hvor vanntemperaturen har økt og flommene sterkt redusert, gir økt produksjon av ulike bunndyr
- i magsinomåder påvirkes lokalklima i sonene nær høyeste regulerte vannstand, slik at habitatene blir kvalitetsforringet

- deltaene har komlekse prosesser, kan være vanskelig å skille ut de enkelte faktorer
- kjennskap til vannkvaliteten er fundamental der nye magasiner etableres og overføringer foretas
- når elveløps likevekt forstyrres kan det skje store endringer i de fluviale prosesser
- langtidseffekter kan vise seg å opptre totalt forskjellig fra korttidsvirkninger. Et eks. på virkningene ved endring av materialtransporten studeres bl.a. i Fortunvassdraget (Fergus 1992).

Et problem ved å gjennomføre sammenlignende undersøkelser før og etter inngrepet fant sted, er at metodene nå ofte er betydelig videreutviklet. Dagens data er langt sikrere.

Resultatene fra en rekke undersøkelser viser at tiltak vil kunne bedre forholdene i vassdraget. Utviklingen av ulike tiltak studeres innen FoU-program "Biotopjustering" (Brittain & Eie 1991).

For å få frem mangfoldet også i konsekvenser av et inngrep, nevnes to konklusjoner ad vegetasjonsforhold i Aurlandsvassdraget på Vestlandet (Odland 1990 s. 56 og 57):
" Fossestrykpåvirkete biotoper er i stor grad blitt ødelagt på Vestlandet som følge av vannkraftutbyggingen, og de er svært lite undersøkt. En vet derfor lite om hvordan slike biotoper er sammensatt og hvor mange som fortsatt finnes intakt. --- Hvilker endringer som vil skje i et område som blir regulert ved vannkraftutbygging, avhenger av mange faktorer. Mest avgjørende er selvsagt de utbygnisktekniske inngrepene, men topografiske forhold innen nedbørfeltet er også av betydning. I et vestlandsvassdrag som Aurland, renner elvene for det meste bratt og dypt nedskåret i berggrunnen, og det er som regel lite vegetasjon i og langs elveløpet. I slike områder vil en minskning i vannføringen oftest få liten virkning da vegetasjonen får sin vanntilgang fra dalsidene ovenfor. I flatere områder kan imidlertid en minskning av vannstanden i elva føre til lavere grunnvannstand med påfølgende endringer i flora og vegetasjon."

Landskapet

Landskapsbildet endres. Landskapet spenner over et bredt aspekt, fra det naturdominerte til det industri- og urbandominerte. Kraftutbyggingen er også en del av landets utvikling som også påvirker kulturlandskapets utvikling. Noen av de eldste anleggene er verneverdige som kulturminner. NVE har i sin forvaltning lagt vekt på at de vedtatte utbyggingene skal resultere i levende kulturlandskap i fremtiden - ikke ruiner, altså en bærekraftig utvikling (Hillestad 1989).

Det er et faktum at: "Mennesker har alltid preget natur og landskap gjennom bruk og aktivitet. Den store forskjellen ligger først og fremst i at dagens mennesker ut fra kunnskap og teknikk har så mye større muligheter for påvirkninger og omforming både i positiv og negativ retning." (Hillestad 1992 s. 7).

Innen forskning om kulturlandskap er vassdragets betydning for dets utvikling dessverre blitt neglisjert.

Tverrfaglighet

For å forstå de mange relasjoner og bindinger, er tverrfaglig samarbeid og forskning ofte nødvendig. Viktigheten av dette blir stadig større, et forhold som også nylig er påpekt av miljø- vernminster Berntsen (1992).

Forskningsmessig er tverrfaglig samarbeid vanskelig å få til av ulike årsaker. Forskerne arbeider lett i nisjer. Ofte blir det en flerfaglig syntese i stedet. Dette setter krav til de involverte. Jeg tror ikke vi har lykkes på dette felt innen programmet, men vi har kommet et lite skritt videre. Sanduren Fåbergstølsgrandane er et egnet område for slike studier (Rye 1987, Faugli et. al. 1991) samt Aurlandsvassdraget (Faugli 1991). Det stiller krav alt i planleggingsfasen, slik at det blir fokusert på de tverrfaglige problemstillingene når feltopplegget fastsettes.

I Ekso er det gjort forsøk i et terskelbasseng hvor det er lagt opp til alt fra innsamling av feltdata fra lokalklimatiske parametre, til fiskenes lengde og vekst i bassenget. I opplegget inngår også etableringen av en feltstasjon i samarbeid mellom Universitetet i Bergen, NVE, utbyggeren Bergenshalvøens kommunale kraftselskap, Vaksdal kommune og det lokale grendalaget.

Informasjon

Regjeringen legger vekt på at det fra FoU-programmer skal gis informasjon og publisering av resultater, når slike foreligger (St. meld. nr. 28 1988-89, Berntsen 1992).

I dette programmet er en rekke opplegg forsøkt.

Kunnskapsformidling og informasjon består bl.a. av:

- delmålrapporter/årsrapporter
- sluttrapport fra delprosjekt
- programmets sluttrapport
- vitenskapelig publiserte artikler
- popularisert stoff
- andre informative tiltak for ulike grupper
    - * brosjyrer
    - * tematurer

Sluttrapporter fra delprosjekter vil komme i stor grad utover dette året. Som et ledd i utarbeidelsen av sluttrapporten (her programmets 1. fase) arrangerer NVE og Vassdragsregulantenes forening en større konferanse "Inngrep i vassdrag; konsekvenser og tiltak" 2.-4.febr. 1993. De involverte forskere er også anmodet om å bearbeide materialet videre for internasjonal publisering som f.eks Odland et.al 1991. Innlegg på internasjonale fagkonferanser oppfordres det også til.

Erfaringen har også vist at ofte pågår en rekke andre faglige undersøkelser i det relevante vassdrag med andre oppdragsgivere. I tillegg hender det at forskning pågår utfra egeninteresser. Vi har derfor i noen vassdrag avviklet seminarer hvor de ulike aktørene har presentert sine undersøkelser og resultater. Seminarer er arrangert om Ekso (Eie & Brittain 1989), Aurlandsvassdraget (Faugli 1991), Jostedøla (Faugli 1987), Dokka (Kroken & Faugli 1990), Orkla (Berg & Faugli 1992) og Skjoma (Kroken & Faugli 1992).

Den populærfaglige delen er tillagt stor vekt av NVE (Faugli 1992). Diskusjonen om utbyggingen av Aurlandsvassdraget var spesiell, og det ble fokusert på en rekke forhold som bl.a. bruken av dalens nedre del, veiutbygginger, fotturistenes bruk av området m.v. Resulatene herfra er derfor blitt viet spesiell oppmerksomhet. De er tilkjennegjort gjennom egen brosjyre for vassdraget og årlige tematurer. I år inngår også det vernede Flåmvassdraget i tematur-opplegget.

Jostedalsvassdraget er faglig og forvaltningsmessig interessant. Vassdraget har vært besøkt av forskere fra hele verden i mer enn 250 år. De har kommet, og kommer, for å studere naturforholdene. Jostedalen, med Jostedalsbreen og dens sidearmer og utløpere, sammen med Fåbergstølsgrandane utgjør et landskaps- område med instruktive og varierte naturfaglige elementer. Dette representerer en naturfaglig helhet av meget stor verdi, både nasjonalt og internasjonalt.

Avveiningene om vern og/eller utbygging krever et solid faglig fundament før de kan sluttføres. Utbyggeren måtte derfor finansiere omfattende naturfaglige undersøkelser. Spørsmålet om opprettelse av Jostedalsbreen nasjonalpark hadde også innvirkning på forvaltningsvedtaket for vassdraget. Resultatet ble et både/og, noe jeg tror de involverte parter er fornøyd med. Resultatene fra de nevnte undersøkelsene, sammen med foreliggende forskningsresulater er, popularisert i en publikasjon utgitt i et samarbeid mellom Universitetet i Bergen, Statkraft og NVE (Faugli et. al. 1991)

Fjorder

Et eget program har tatt opp etterundersøkelser i fjorder. NVE har hatt ansvaret for bevilgningene, og Universitetet i Bergen har stått for prosjektgjennomføringen. Undersøkelsene er lagt til Ryfylkefjordene. Både biologiske og fysiske forhold inngår, og det er lagt vekt på utvikling av egnede modeller (Lie et.al. i trykk.)

Programforskning - FoU eller ?

Dette forskningsprogrammet er initiert av forvaltningen og har som mål å gi svar på problemstillinger den arbeider med. Er så dette FoU ? Hva er FoU ? Det er forvaltningsrettet forskning og utvikling det her er behov for. Denne er i sin art hverken grunnforskning eller anvendt forskning, men har elementer av begge i seg. Dens tyngde ligger innen utvikling, men har tidvis karakter av utredningsarbeid. Dette FoU-arbeidet bør skje i kontakt med utdanningsinstitusjonene, slik at det samtidig foregår kompetanseutvikling.

Grunnforskning eller anvendt FoU må ikke neglisjeres. De danner basis for den forvaltningsrettede FoU. Samarbeid og forståelse for hverandre blir fundamentalt. Jeg ser det slik at skal en få løst de kortsiktige FoU-behov forvaltningen har, må dette skje i nær kontakt med den langsiktige, grunnleggende forskningen.

I Norge er det dessverre ikke så lett å få gehør for at sektorforvaltningen selv har behov for FoU-arbeid. Men innen miljøvernforskningen, og denne angår oss alle, er kursen lagt om. Det poengteres at sektorforvaltningen selv har ansvar for miljøforskningen, og samarbeid må til for å få løst de problemer en står ovenfor (Berntsen 1992).

Konklusjon

De faglige resultater som fremkommer vil få betydning for å forbedre konsekvensanalysenes opplegg i fremtiden. Der hvor det er behov for å arbeide videre med avbøtende tiltak, tas dette opp med "Biotopjusteringsprogrammet" for videreutvikling.

Resultatene fra programmet vil være viktige når vurderingen av nye manøvreringsreglement skal vurderes. Dette er et viktig moment i arbeidet for å etablere fleksibel manøvrering som er under vurdering i en rekke utbygde vassdrag. Revisjonen av vassdragsreguleringsloven gir lettere adgang til å foreta nyvurderinger av et vassdrags tilstand etter reguleringen.

Det forventes at den nye viten som innhentes vil føre til en mer samfunnsriktig forvaltning av vassdragene. Vedtakene vil bygge på bedre faglig grunnlag når vurderingene foretas.

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VERKNAD AV VASSDRAGSREGULERING PÅ LOKALKLIMAET

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ABSTRACT

Water power plant development has existed in Norway since the turn of the century. Particularly during the last decades one has been concerned with their impact on the local climate. Because of water release from power plants during winter the regulated rivers may not freeze even in cold winters. This results in the formation of steam fog over the river and the adjacent banks.

If the water is released into a fjord, either directly or via a river, a shallow layer of fresh water forms on the fjord surface. This layer freezes readily, thereby eliminating the contact between the air and water. The transfer of energy from the water to the air thus becomes greatly reduced, resulting in lower air temperature locally.

The height of Norwegian dams may reach 100 m or more. They are often situated in deep valleys and may effect the drainage flow of cold air through the valleys. This happens over the reservoir of the Alta river. The drainage flow at the village Máze situated upstream of the reservoir, however, is not affected according to a model calculation.

INNLEIING.

Vassdragsutbygging kan verke på lokalklimaet ved tørrlegging eller oppdemming. Dette fører til endra fysiske tilhøve i grenseflata mellom bakken og lufta. Dei viktigaste vêrelementa blir vind, temperatur og råme. I denne artikkelen vil det bli gjeve spesielt rom for klimakonsekvensar ved Alta-reguleringa. Plassen vil ikkje tillate at alle sider ved emnet blir drøfta.

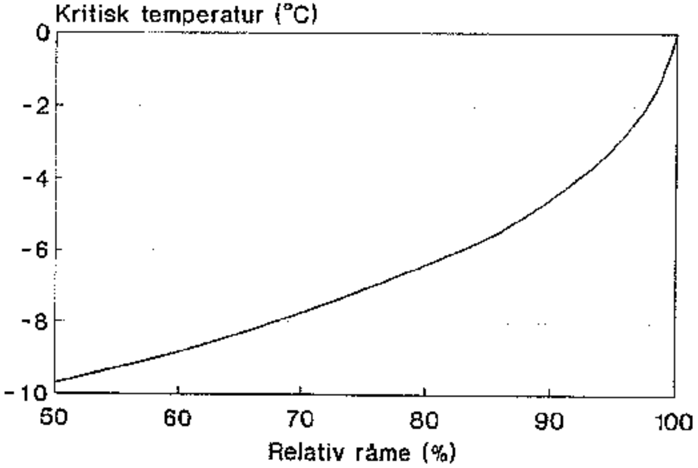
FROSTRØYKPRODUKSJON OVER OPE VATN.

Generelt om frostrøyk.

I Noreg finn ein frostrøyk over fjordar der kald luft frå innlandet strøymer ut over vatnet. Det skjer ofte i Finnmarksfjordane og i Oslofjorden. I innlandet er frostrøyk vanleg om hausten over elvar og vatn og om vinteren over elvar som held seg isfrie, gjerne i samband med tapping av varmt vatn frå eit kraftverksmagasin.

Frostrøyk kan berre koma i stand når den isfrie vassflata er varmare enn den omgjevande lufta. Lufta over vassflata tek til å stige og luft som før låg over land, sig utover vatnet slik at ei sirkulasjonscelle blir danna. Når lufta kjem i kontakt med vatnet, tek ho opp vassdamp og kan bli overmetta i det ho skal til å stige slik at frostrøyk kan observerast.

Teoretisk er det mogleg å finne eit naudsynt kriterium for frostrøyk. Dersom det rår "fri konveksjon" over ei varm vassflate, dvs. vind ≤ 3 m/s, kan ein kritisk temperatur, T_k, finnast som ein funksjon av temperaturdifferensen mellom vassflata og kaldlufta over land (Golytsyn, Grasjov, 1986). Dersom temperaturen i lufta er lågare enn T_k, er altså frostrøyk mogleg, figur 1. Ein kritisk temperatur kan også finnast ved at frostrøykdanninga blir sett på som ein blandingsprosess mellom to luftmassar, ei som er metta med vassdamp og har same temperatur som vatnet, og ei som har temperatur og relativ råme som den lufta som skal til å strøyme utover vatnet frå land, (Saunders, 1964). Båe metodane fører til nesten samanfallande resultat.



Figur 1 Kritisk temperatur, T_k, som funksjon av relativ råme, U, ved vasstemperatur 0°C.

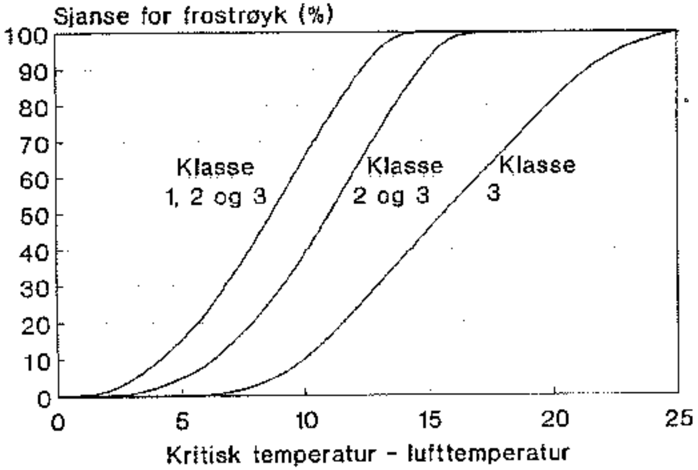
Praktisk utrekning av sannsynet for frostrøyk.

I samband med vassdragsreguleringar er det teke ei mengd frostrøykobservasjonar over opne elvar. Her skal eg avgrense meg til å nemne ein serie frå osen av Vågåvatnet som held seg ope heile vinteren. Materialet er heilt komplett for alle dei 14 vintrane granskinga vara og merkjer seg ut med å vera særs litande. Frostrøyken er delt inn i klassar som vist i tabell 1.

Di større differensen er mellom den kritiske temperaturen og lufttemperaturen, di større sjanse vil det vera for frostrøyk, figur 2. I samsvar med teorien viser også observasjonane at lufta må vera under den kritiske temperaturen for at frostrøyk skal kunne bli danna. Derimot syner det seg at den kritiske temperaturen langt frå er noko tilstrekkeleg vilkår for frostrøyk av ein slik styrke at han kan observerast. Sjølv den svakaste frostrøyken har ikkje nokon gong vorte observert nærare den kritiske temperaturen enn om lag 1°C og ved 50 % sjanse for frostrøyk var lufttemperaturen 8°C under den kritiske. Stiller ein krav til at frostrøyken skal ha ein viss tettleik, må lufttemperaturen vera enda meir under den kritiske og det same gjeld også om ein stiller krav til at frostrøyken skal vera såpass persistent at han kan breie seg ut frå det isfrie området, jamfør klasse 3 i tabell 1. Dette er da også avhengig av det lokale klimaet på noko større skala enn det som skjer i grenseflata mellom isfritt vatn og kald luft.

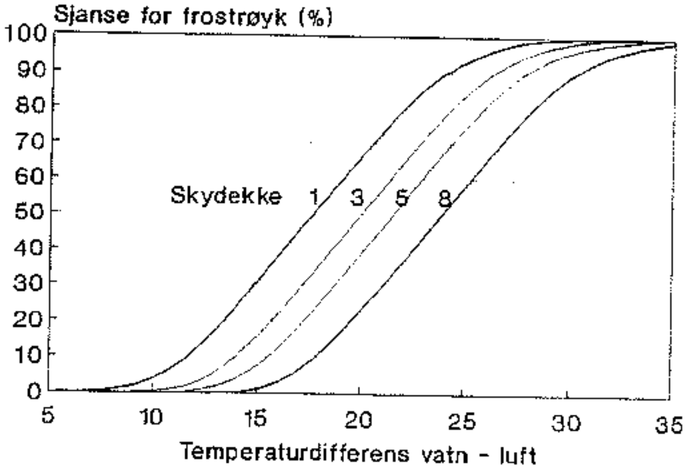
Tabell 1 Kriterium for klasseinndeling av frostrøyk.

Klasse	Kriterium
1	Så vidt synleg frostrøyk over ope vatn
2	Velutvikla frostrøyk som ikkje når utanom isfri vassflate
3	Frostrøyk, delvis tett som breier seg utanom isfritt vatn. Sterk riming på tre, glas og metall ute i det fri



Figur 2 Sjansen for frostrøyk (kumulativ) som funksjon av differensen mellom kritisk temperatur og lufttemperatur.

Av lokalmeteorologiske faktorar er det skydekket som i praksis viser seg å vera det vêrelementet som i størst grad etter temperaturen påverkar sjansen for frostrøyk, figur 3. Er temperaturdifferensen mellom vatn og luft 20°C er sjansen for frostrøyk berre vel 20 % i heilt overskya vêr, men nesten 70 % i klårvêr.



Figur 3 Sjansen for frostrøyk (kumulativ) som funksjon av differensen mellom vasstemperatur og lufttemperatur for frostrøykklasse 3. Skydekket (oktas) er brukt som parameter.

Særleg i samband med kraftutbygging har ein vore interessert i å finne meir realistiske kriterium enn den teoretiske, kritiske temperaturen for dermed å kunne varsle mogleg framtidig ulempe før eit eventuelt inngrepet. Til hjelp har ein ved DNMI utvikla frostrøykindeksar der vêrparametrar som blir observerte på ordinære meteorologiske stasjonar er inngangsdata. Det er temperatur i luft og vatn, skydekke og relativ råme.

Resultata frå Vågåmo viser at frostrøyken har ein dagleg gang i takt med lufttemperaturen. Klokka 07 er det 43 tilfelle av frostrøyk i gjennomsnitt pr. år, medan det berre er 32 kl 15. Reknar ein berre frostrøyk av ein slik styrke at han kan koma inn over land (klasse 3), er tilsvarande tal 18 og 13.

Frostrøyk på grunn av reguleringa av Altaelva.

Også føre reguleringa gjekk Altaelva open på somme strekningar. Over råkene kunne det danne seg frostrøyk, men frostrøyken breidde seg ikkje inn over land i særleg grad, truleg fordi kulden i Alta viste seg samstundes med drenasjevinden frå vidda. Luft som hadde vore i kontakt med ope vatn og dermed kunne innehalde frostrøyk, vart raskt blanda med større mengder frostrøykfri luft.

Isdekket er ikkje endra i særleg monn i dei delane av elva som i dag har busetjing og dermed heller ikkje sjansen for frostrøyk. Men like etter utlaupet frå kraftverket i Šávžu renn elva isfri og her har det vorte meir frostrøyk og riming etter reguleringa.

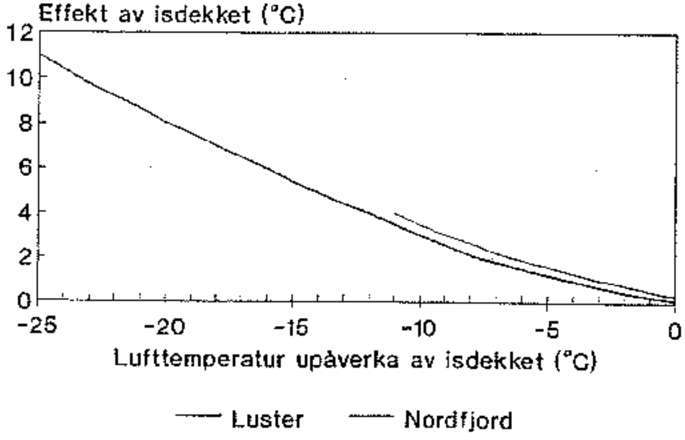
TEMPERATURENDRING PÅ GRUNN AV ENDRA ISLEGGING AV FJORDAR.

Mange av dei norske kraftverka har utslepp mot fjordane på Vestlandet eller i Nord-Noreg. Føre reguleringane gjekk elvane ofte med lita vintervassføring. Etter reguleringane vart vintervassføringa auka nedafor kraftverka og dermed også ferskvasstilførsla til fjordane. Dermed kan reguleringane vera med på å skape eit brakkvasslag i overflata, som igjen fører til auka vertikalstabilitet i fjorden og dermed lettare frysing.

I kaldvêrsbolkane om vinteren har vatnet i fjordane ein høgare temperatur enn lufta langs strendene. Vatnet verkar da som ei varmekjelde og lufta over fjordane tek til å sirkulere. Kaldluft vil gli nedover dalsidene og ut over fjordane. Der vil ho få tilført varme frå vatnet og dessutan vassdamp som kan frigjera varme ved seinare kondensasjon. Etter turbulensteorien kan transporten av følbar varme skrivast:

$$H = -\rho c_p K_H \left(\frac{\partial T}{\partial z} - \Gamma\right) \qquad (1)$$

Her er $\partial T/\partial z$ den vertikale temperatur-gradienten. At diffusjonskoeffisienten, K_H, er avhengig av temperaturgradienten, kompliserer likninga.



Figur 4 Utjamna effekt av isdekket i strandkanten langs Sognefjorden og Nordfjord (etter Hammer, 1986).

Inne i fjordane på Vestlandet er temperaturen om vinteren rett ofte mellom 0°C og -10°C og i Nord-Noreg ned mot -20°C og i sjeldne tilfelle enda lågare. Temperaturen i fjordoverflata når fjorden held seg isfri om vinteren, vil vera nær 0°C. Di kaldare luft som kjem inn over fjorden di større vil K_H og også talverdet av $\partial T/\partial z$ vera. Dermed ser vi av likninga at di kaldare vêrtypen er, di større blir transporten av varme oppover. Dersom vassflata er dekt av eit islag, vil islaget hindre noko av transporten av energi frå vatnet til lufta. Di tjukkare isen er, di meir blir energigjennomgangen hindra. Skulle det falle snø oppå isen, vil snøen isolere særs godt og såleis reduserer han varmetilførsla til luft sterkt. Lufta kan såleis bli kaldare over snø/islagde fjordar enn over fjordar med isfritt vatn.

Både i Nordfjord (Nordli, 1981) og i Sognefjorden (Hammer, 1986) har det vore gjort granskingar av verknader av isen på lufttemperaturen. Dei to granskingane viser bra samsvar, figur 4.

Figuren viser den utjamna effekten, dvs. at effekten ikkje berre varierer med temperaturen, men også med lendet. Såleis kan effekten på utstikkande nes t.d. vera større enn i vikar. Der sidedalar munnar ut i fjorden, kan effekten vera nær null. Slike dalar kan vera føringar for eit sig av kaldluft frå innland til fjord. Den lufta har ikkje vore i kontakt med fjordoverflata og er difor ikkje påverka av isdekket.

I Luster i Sogn har fleire reguleringar ført med seg at isen har lagt seg over større område og over lengre tid enn om området hadde vore uregulert (Boe, Roen, 1991). Storleiken på endringane varierte frå vinter til vinter. Dette har i sin tur ført til ein høgre frekvens av låge temperaturar og i fleire vintrar har den absolutte minimumstemperaturen også vorte lågare, (Gjessing, Nordli, 1991). I ekstreme tilfelle kan temperaturnedgangen bli 8-10°C, jamfør figur 4.

Temperaturendring på grunn av endra islegging av Altafjorden.

Før og etter reguleringa av Altaelva har det vore sett i gang temperaturmælingar, iskartlegging og frostrøykfotografering av den inste delen av Altafjorden. Spørsmålet om eventuelle temperaturendringar på grunn av reguleringa kjem venteleg opp i eit klimaskjønn i 1993. Enno ligg ikkje noko resultat føre.

TEMPERATURENDRING RUNDT MAGASIN.

Ved oppdemming av elvar til kunstige magasin aukar varmekapasiteten i overflata. Om våren vil den nye overflata i middel bli kaldare enn før, om hausten vil ho bli varmare. Difor vil vi dele inn verknaden av oppdemmingane etter årstid. Vi gjev eksempel frå Granasjøen på Nerskogen i Reinbuene (Rennebu) som er den oppdemminga i Noreg som er best granska, (Skaar, 1986). Sjøen er 6,9 km^2 og varierer mellom nivåa 610 - 650 m o.h.

Vår. Det kalde vatnet i overflata på magasinet kan føre med seg at temperaturoppgangen om våren blir seinka etter reguleringa. Særleg sterk blir nedgangen i maksimums-temperaturane og også middel-temperaturen kan bli lågare.

I Nerskogen vart det i juni funne ein nedgang av dei høgste maksimumstemperaturane på heile 5°C - 6°C like ved stranda på lesida av magasinet, men allereie 300 m frå stranda var denne endringa redusert til 0,5°C - 1°C. I middel for månaden vart det registrert ein signifikant nedgang i maksimumstemperaturane om enn langt mindre enn i dømet ovafor.

Sommar. Etter som vassflata blir varma opp, vil endringane i middeltemperaturen ikkje bli merkbare, men temperaturamplituden vil kunne bli mindre.

I Nerskogen vart i middel maksimumstemperaturane reduserte med 0,5°C i august opp til ei høgd over magasinet på 10-20 m.

Haust. Magasineringa av varme gjennom sommaren kan føre til ein auke av middeltemperaturen og særleg minimumstemperaturane. Spesielt store endringar kan det bli i perioden like før islegging av magasinet. Lendet som gjerne var snødekt føre reguleringa er nå erstatta av ei ope vassflate. Effekten av dette kan i storleik jamførast med effekten av open fjord kontra islagd fjord, sjå førre emne.

I Nerskogen vart det i middel funne ein signifikant auke av minimumstemperaturane på 1,0°C opp til nivået 30 m over sjøen.

Vinter. Norske vasskraftmagasin er stort sett dekte av snø slik at reguleringa ikkje endrar konsistensen i overflata, men sperringa av dalane som dammane representerer, kan likevel gje lokale klimaendringar. Etter som magasina blir tappa ned, blir inversjonslaget tjukkare (Andersen, Skaar, 1987). Den kalde botnlufta får vanskelegare vilkår for å bli drenert ut og temperaturen over isen bli lågare enn før.

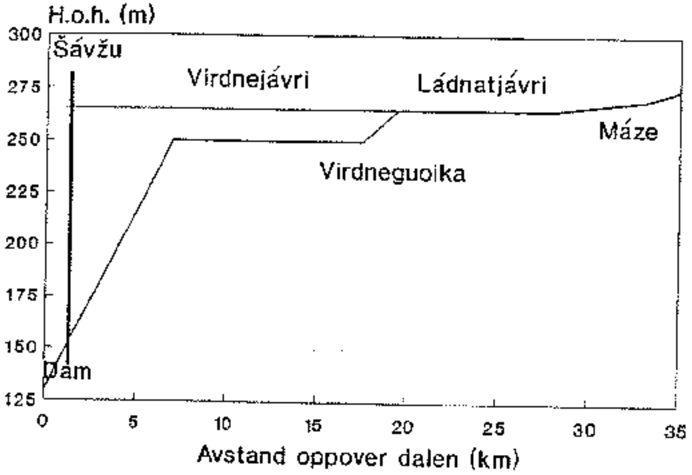
Temperaturendring rundt Virdnejávri, Altareguleringa.

Den nordlegaste delen av magasinet var før elv medan den sørlege delen var sjø. I utgreiinga for konsesjonssøknaden (Nordli, 1975) er endringane på grunn av reguleringa estimerte til å vera av om lag same storleik som ved Granasjøen på Nerskogen.

KALDLUFTSDRENERING LANGS ALTAELVA.

Mange demningar ved større norske kraftanlegg når opp i høgder på 100 m eller meir. Ein skulle da vente at innverknaden av slike inngrep på kaldluftsdreneringa var nøye granska. Det er likevel ikkje tilfelle, truleg fordi dei aller fleste av dei ikkje har noka busetjing der inngrepa har skjedd. Unntaket er Nerskogen (Andersen, Skaar, 1987) og dessutan Alta der konsekvensane av endra kaldluftsdrenering nedetter dalen var mykje debattert i fagmiljø. Spørsmålet vart reist om endra drenering kunne påverke klimaet i Máze som ligg om lag 35 km ovafor demninga. Ei oppsummering av denne diskusjonen er gjort for Alta heradsrett, (Gotaas, Nordli, 1990).

Det vesentlegaste bidraget til analysen av kaldluftsdrenering nedover Altavassdraget er gjort ved Universitetet i Bergen (UiB). Lengdesnitt av dalen nedafor Máze er vist på figur 5, frå dammen ved det smale partiet ved Šávžu over den regulerte sjøen Virdnejávri, gjennom det tronge gjelet Virdneguoika, langsetter sjøen Ládnatjávri opp til Máze som ligg i sørenden av denne sjøen. Sluttrapporten frå UiB gjev resultata frå ein halvempirisk modell (Hanssen-Bauer, 1989).



Figur 5 Lengdesnitt av dalbotnen langs Altavassdraget frå Šávžu til Máze. (Etter Hanssen-Bauer, 1989).

Modellen reknar farten på luftstraumen langs vassdraget i to daltverrsnitt, det eine ligg 1 km nedafor dammen, det andre er gjelet Virdneguoika mellom dei to sjøane, figur 5.

Ved tverrsnittet nedafor demninga vart det funne signifikant sterkare vind etter utbygginga enn før utbygginga ved elles like tilhøve i situasjonar med vind nedover vassdraget. Lågare verdi av ruheitsparameteren i magasinområdet etter neddemminga vart funne å vera ei rimeleg forklaring på det. Modellresultata gav ein reduksjon i ruheitsparameteren som tilsvara 13 % sterkare vindfart ved rein drenasjevind etter utbygginga. Ein hypotese om at høgre vindfart etter utbygginga kunne finne si årsak i større middel-helling av dalbotnen på lokal skala vart testa og forkasta.

Granskinga gav ikkje noko indikasjonar på at utbygginga av Altavassdraget har ført til lågare vindfart langs vassdraget i drenasjesituasjonar. Dermed kan heller ikkje reguleringa ha ført til auka oppstuving av kaldluft i dei øvre delane av vassdraget.

Volumtransporten gjennom det nedre gjelet hadde som nemnt auka utan at ein finn ein tilsvarande auke gjennom det øvre tverrsnittet. Denne skilnaden kan forklarast ved at reguleringa har ført til auka medriving av luft i overkant av drenasjestraumen (entrainment).

Klimaskjønnet i Máze skal setjast i 1993. Innan den tid vil det også bli gjort ei statistisk gransking av temperaturen i Máze bygd på mælingar føre og etter reguleringa. Desse resultata vil bli sett i samanheng med modellresultata. Endeleg konklusjon vil bli gjeve av dei klimasakkunnige for Alta Heradsrett i laupet av 1993.

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GEOMORPHOLOGICAL CHANGES IN THE FORTUN RIVER: AN ASSESSMENT OF THE IMPACT OF THE ALTERED FLUVIAL PROCESSES AFTER RIVER REGULATION FOR HYDROPOWER.

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ABSTRACT

This paper describes the altered sediment budget and fluvial processes after regulation for hydropower in the Fortun river. It particularly describes the changes in channel size and pattern of the river downstream of the regulated area, as a response to the altered fluvial processes. The Fortun is situated in south-western Norway. The hydropower scheme is Norway's 10th largest and was completed in 1959. The study was initiated by complaints from local farmers of an increase in the flooding of adjoining farm land after regulation. Cross profiles of the river measured in 1973 and 1989, along a 2 km reach, have been used to quantify aggradation and erosion in the reach and changes in channel geometry. The profiles show a reduction in channel size and capacity, with a net aggradation of approx. 7 800 m^3. Vegetation enroachment in combination with a reduction in channel size and capacity does increase the adverse effects of large magnitude flood events that do occasionaly occur in regulated basins. This paper shows that river regulation does initiate a slow, but gradual reduction of channel size in active, mass-transporting rivers with unregulated tributaries. It also adresses the need for these long term effects to be included in future studies of the consequences of river regulation.

INTRODUCTION

The fluvial geomorphological adjustments of river channels due to the abstraction of water for hydropower has been studied in countries such as Canada (Kellerhals, 1982) and Switzerland (Gurnell et. al., 1990). Petts (1984) has compiled the results of a number of similar studies. Despite the large scale and long term utilisation of water for hydropower in Norway, few studies on the subject have been made in this country. In a study of the Hallingdal river Nordseth & Svantesvold (1980) concluded that geomorphological adjustments such as a narrower channel and vegetation enroachment in the channel was the result of the altered fluvial regime, and especially the reducion in frequency of floods. Vegetation enroachment and channel adjustment due to the stabilisation of bed material in the Skjoma after regulation has been described by Faugli (1987).

This paper considers the adjustment of a river channel as a long term response to the altered fluvial regime after regulation for hydropower. Discharge and sediment load are considered as the primary independent variables influencing channel morphology (Schumm, 1977). The influence of discharge reduction, sediment supply and vegetation enroachment is evaluated comparing profile data and aerial photographs.

LOCATION AND HYDROPOWER SCHEME

The Fortun river is situated in the county of Sogn and Fjordane in the west of Norway. It runs into the Lusterfjord, one of the inner arms of Sognefjord. Due to the valley's inland situation the climate can be characterised as continental. Most of the river's catchment lies on the Sognefjell massife, 1000 to 1300 m.a.s.l., with peaks up to 2025 m.a.s.l.. There are a number of small glaciers in the catchment, amounting to 10 % of the catchment area (Østrem & Ziegler, 1969). The size of the catchment measured from Yttri (NVE St. no. 611-0) is 367 km^2. The studied reach lies 2 km upstream of Yttri and is 1700 m long. It lies approximately 40 m.a.s.l., and is bordered by floodplains used as agricultural land. The reach was channelized and the left bank armoured for flood protection in 1914. The Fortun was regulated for hydropower in the late 50's with the three power stations Fortun, Fivla and Herva starting succesively between 1959 and 1963. The hydropower scheme drains 73% of the catchment area upstream of Yttri. The regulated watershed lies in the northern and eastern parts of the catchment, draining the area above 1000 m.a.s.l.

There are three river intakes upstream of Yttri affecting the major tributaries Midtdøla, Vetledøla and Grandfasta. Minor tributaries and streams entering the main river are not affected by regulation. 90% of the glaciers in the catchment drain to the regulated area.

The power scheme has an annual production of 1375 GW. The scheme was the 3rd largest in Norway when it was completed in 1959. It is today the 10th largest power scheme in the country.

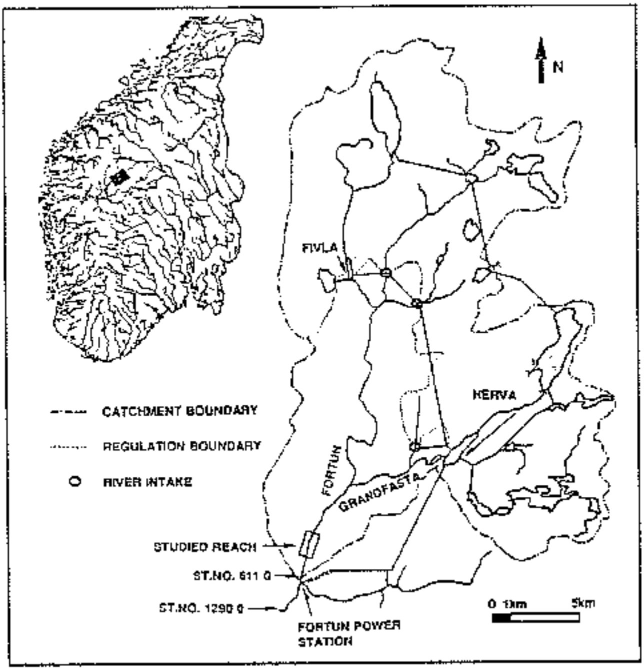

Figure 1. Location. Fortun river catchment.

HYDROLOGY OF THE FORTUN RIVER

The discharge has been monitored in the Fortun river since 1918 at NVE gauging st. 611-0. The series between 1918 - 1955 has been used in the analysis of the pre-regulation discharge. In 1956 a change in the measuring profile occured. Although discharge was measured until 1980, the series contains a number of major gaps. In 1960 a new gauging station (1290-0) was set up, but unfortunatly for this study, downstream of the power station outlet. A discharge series for the post-regulation period was therefore constructed using the discharge series from the neighbouring catchment, Mørkri (1404-0), and overflow data for the regulation dams. The series has been constructed for the years 1973 -1991 due to the availabilty of overflow data. The Fortun river catchment recieves approximately 800 mm of precipitation annually. Most of this falls as snow in August through January, due to the high elevation of the catchment. The pre-regulation annual hydrograph reflects the glacial/alpine discharge regime. Winter flows are low and the hydrograph is dominated by snowmelt and glacial runoff which peaks in mid- July. Glacial runoff ensures a high discharge through the summer months until the end of September. Autumn floods are caused by heavy precipitation in combination with glacial runoff. The post-regulation hydrograph is plotted together with the pre-regulation hydrograph in Figure 2, and illustrates the reduction in discharge after regulation.

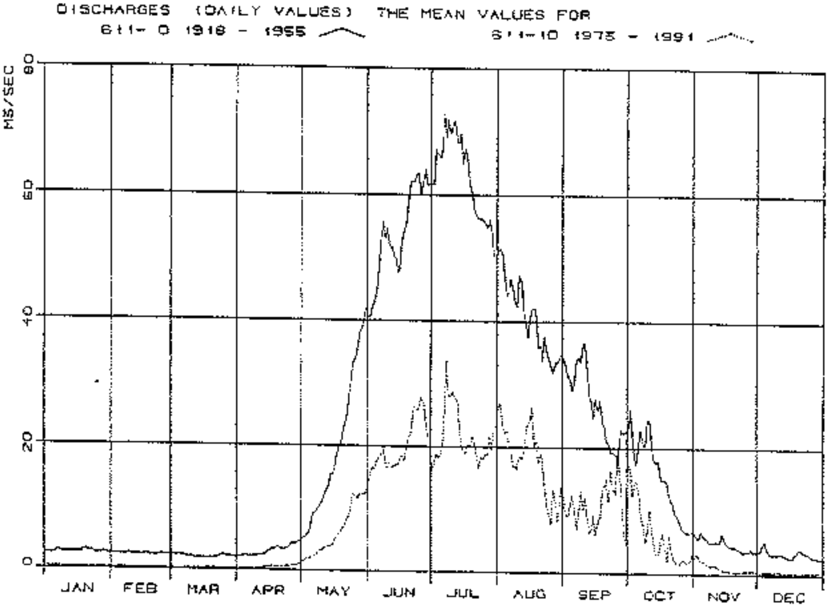

Figure 2. Pre- (611-0) and post- regulation annual hydrograph.

Discharge has been reduced to approximately 35 % of the pre-regulation disharge. The reduction in autumn flows (August, September, October) is slightly lower than that of spring and summer flows (May, June, July). Overflow from regulation dams accounts for 35 % of the discharge from May through October. 63 % of the overflow discharge occurs in August through October. Discharges for flows of specific return periods and the mean annual flow and flood are listed in Table 1. The annual maximum series was used for the analysis of flood frequency before and after regulation. As can be seen from Table 1 a pre-regulation flood with a return perion of 2 years has had its return period increased to 11 years after regulation, and a flood with a 10 year period has after regulation a return period of 33 years.

Table 1. Return period of pre- and post-regulation floods.

Pre-regulation discharge m^3/s	Return period (years)	Post-reg. return period (years)	Post-regulation discharge m^3/s	Return period (years)
140	2	11	78	2
163	5	23	113	5
174	10	33	136	10
180	15	40	149	15
183	20	44	158	20
189	30	50	171	30
192	50	59	187	50
140	Mean annual flood	11.5	86	Mean annual flood
20	Mean annual flow		7	Mean annual flow

The difference in return period before and after regulation decreases with the increase in discharge. The magnitude of post-regulation floods is to a great extent dependent on reservoir conditions before the onset of the flood event. If the flood event occurs at a time when reservoirs are full the catchment will approximate pre-regulation conditions. A situation with full reservoirs will generally occur in the autumn months. 16% of pre- regulation annual flood events occur after the 1st of August, while 63% of post-regulation events occur after the 1st of August. The difference in the mean date of occurance of the annual flood event before and after regulation was found significant at the 99% level.

SEDIMENT SUPPLY AND CHANNEL FORM CHANGES

Sediment supply to the main channel has been assessed qualititavely while 42 cross profiles of the river measured by the Water Resources Dep. of NVE in 1973 and 1989, have been used to quantify channel changes in the reach. The profiles in 1989 were measured at the same locations as in 1973 with a distance of 40 m between each profile. They do therefore provide a direct measurement of channel changes during the time period. The profiles were also used as input for the HEC-2 model for calculating the water level at different discharges. Aerial photographs from 1964 and 1984 were used to map vegetation enroachment in the channel.

Sediment supply.

Sediment entering the main channel is supplied by various processes, such as rapid mass movement (snow avalanches, debris flows and rockfall), flooding in tributaries, channel and glacial erosion. Snow avalanches in the winter and flash floods in the spring melting season occur annually at Øyaskredane ("island avalanches") on the western side of the valley. The road through this area has to be cleared of flood debris every spring often uncovering 2-3 m of deposited material across the flooded areas (pers. comm. Nyland. N. Hydro, Fortun). No minor tributaries entering the main valley have been affected by regulation and do therefore display the same discharge and sediment regime as in the pre-regulation period. Two of the tributaries (Holmastadgrovi & Smøla) have been channelized after regulation due to the adverse effects of flash flooding (deposition of large amounts of course material on grazing land) (archives, Water Resouces Dep. NVE). Channelization of these tributaries may have increased the direct sediment input to the main river. Tributary degradation after regulation due to flooding tributaries while the water level in the main river is lower than it's former level has been observed in Canada (Kellerhals, 1982). Tributaries in the Fortun do flood during the spring thaw when the main river water level is low, and tributary degradation may have occured, increasing sediment input. Due to the lack of pre-regulation data this cannot be confirmed. As a curiousity it can be mentioned that the word "grovi" which ends the names of a number of minor tributaries in both the Fortun and other valleys in the west of Norway is derived from the word "grave" meaning "dig", indicating that these tributaries geomorphological role was well known in the past. As a glacial catchment the Fortun can be compared to Mørkri, the neighbouring catchment with 13% of it's area covered by glaciers (Østrem & Ziegler, 1969). The Mørkri has a moderate sediment input from glaciers and they contribute mainly to suspended transport (Bogen, 1982). The glaciers that drain to the regulated area in the Fortun all drained to lakes or sedimentation basins prior to regulation and the input of course material is not considered to have been greatly altered due to regulation.

The total sediment input to the channel has therefore not been reduced to the same extent as discharge after regulation although sediment input from major regulated tributaries has been reduced.

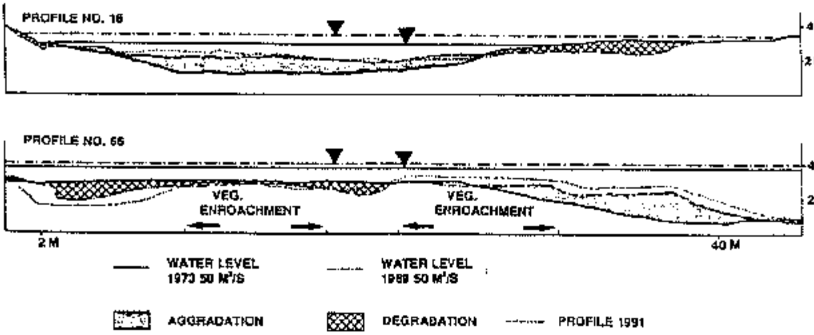

Figure 3. Profile no. 16 & 66. 1973, 1989 & 1991.

Channel adjustment and water level adjustment after regulation.

The adjustment in channel size and form has been established by comparing the two profile sets and calculating total aggradation and degradation since 1973, as well as the water level at different discharges. The total volume of aggradation along the channel reach was found to be 13 400 m^3 while total degradation was found to be 5 600 m^3, with a net aggradation of 7 800 m3. Practically all of the profiles show the same tendency of aggradation to the middle or one side of the profile, and lateral or vertical erosion, either on both sides or the opposite side of the aggrading side (Figure 3). Channel erosion does therefore also supply material to the channel. Lateral erosion has occured mainly on the right channel bank which is not protected by armouring, while vertical erosion mainly occurs where the banks are protected by armouring. The increase in channel slope since 1973 from 0.0016 to 0.0023 strengthens the impression of an aggrading channel (Figure 4).

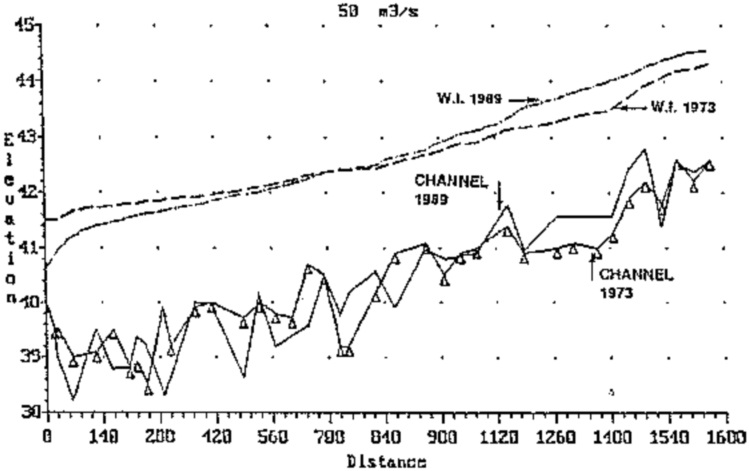

Figure 4. Length profile. Water level 1973 & 1989.

According to Petts (1984) channel changes in an aggrading reach will proceed until the flow characteristics (depth and velocity) are so adjusted that the flow competence and capacity are capable of transporting all the sediments that are supplied. An adjustment to a wider shallower channel and steeper slope will facilitate the transport of the supplied sediment load. Profiles measured in 1991 (Figure 3) and painted stones (med. diam. 8 cm) set across 4 profiles demonstrated clearly that the existing flows do have the competance to erode and move the river's bed and bank materials. The largest movement recorded was 113 m in 5 months with flows of up to 81 m^3/s. All of the stones recovered (70 %) were well imbricated and in some cases partially buried, showing that the bed material is mobile at existing flow conditions. The water level has been raised 0.2 m to 0.6 m in the upper parts of the reach (prof. 0 to 66), while it has been lowered 0.1 m to 0.8 m in the lower parts due to bank failure and erosion. The water level of a discharge of 25 m^3/s (equalled or exceeded 106 days

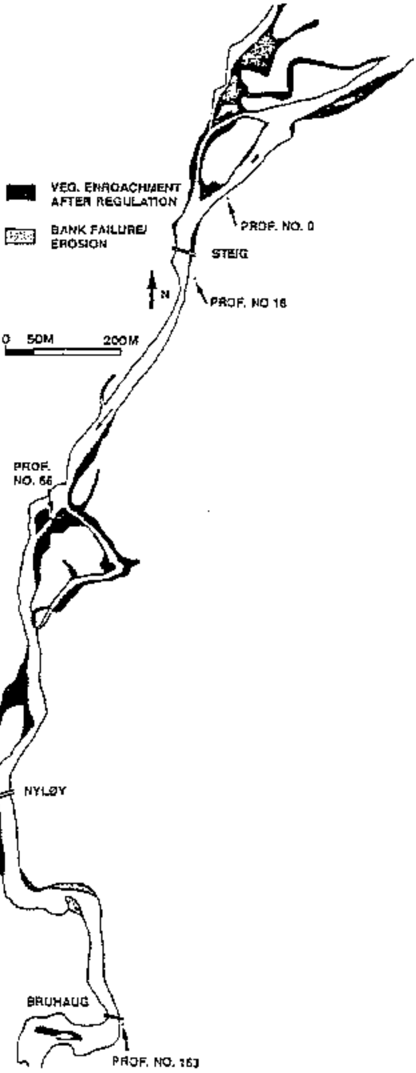

Figure 5. Vegetation enroachment.

annualy pre-reg. 29 days post-reg.) does now approximate the former water level of a discharge of 50 m^3/s (equalled or exceeded 51 days annualy pre-reg. 9 post-reg.) at Steig (Figure 4). The water level of 50 m^3/s now approximates the former water level of 85 m^3/s (eqalled or exceeded 11 days annualy pre-reg. 3 post-reg.). The difference between the water level of 1973 profiles and 1989 profiles decreases with the increase in discharge due to overbank flow. There is a close correlation between the river and groundwater level at Steig (Mylhr, 1971). A rise in the water level at in the river will be accompanied by a rise of the groundwater level affecting agriculture.

Vegetation enroachment

Figure 5 shows vegetation enroachment in the channel since 1964. Former flood channels and gravel bars along the channel margin are now vegetated, narrowing the channel. Species of salix (willows) dominate the margins while inner areas are dominated by alders and more mature forest. Salix is a pioneer species on coarse substrate (Fremstad, 1986), and flow velocities are extremely low in vegetational sones of salix (Beheim, 1991). Vegetation will stabilize sediments in the channel and induce further deposition due to reduced flow velocities (Petts, 1984).

Vegetation will also introduce debris to the channel that will in turn be trapped by vegetation downstream and build dams that may contribute to sedimentation and backwater effects. Dams of vegetational debris up to 2 m high were observed in the channel, as well as fine sediments deposited well into dense vegetation on former bars.

CONCLUSIONS AND IMPLICATIONS

The morphological changes of the channel described in this paper are a response to the imposed discharge conditions after regulation. Regulation in the Fortun has greatly reduced spring and summer flows as well as the magnitude of flood events. Sediment supply to the channel has not been subject to the same reduction, although supply from major regulated tributaries has been somewhat reduced. Vegetation enroachment of formerly "clean" gravel bars and flood channels has been possible due to the reduction in spring/summer flows and large abrasive flood events. Aggradation, steepening of the slope and the resulting instability of the channel is a result of the river's reduced ability to transport the supplied sediment load. Vegetation enroachment will enchance aggradation by stabilizing bed material supplied and by reducing flow velocities. Aggradation has in some parts of the studied reach raised the water level while it has been lowered in others. The overbank flow frequency is however not considered to have exceeded pre-regulation levels. This being due to the reduction in the frequency of large magnitude flood events. The shift in the onset of the annual flood event may have had a negative effect on agriculture by raising the groundwater level at harvesting time. More study into this effect is however nessecary to determine if the present situation is aggravated compared to post-regulation conditions.

Kellerhals (1982) has pointed out that the hydraulics of sediment transport provide the driving mechanism for morphological change. Several authors (Ergenzinger, 1988, Pitlick & Thorne, 1987, Klingeman & Emmett, 1984) have indicated that the bedload of gravel-bed channels is to a large extent supply dependent. Bogen (1986) has stressed the importance of studies of erosion processes and sediment transport and that investigations be done in such a way that the prediction of the effects of various activities can be made. The present studies of sediment transport and fluvial geomorphology in the Jostedøla (Husebye & Faugli, 1986. Husebye, 1987) will hopefully contribute to a better understanding of the processes governing, and the effects of morphological change after river regulation. The time scale and processes involving morphological change must be acknowledged. The provision of pre-regulation data such as discharge, profile data and sediment data must be made so as to enable future study and prediction of morphological change and the effects of these changes.

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KRAFTUTBYGGINGENS VIRKNING PÅ VANNFØRINGSFORHOLDENE I ALTAELVA

Jan-Petter Magnell   Statkraft   Norge

ABSTRACT

The Alta power station was set into operation in May 1987. General rules for running the power station were given by the authorities. In addition to these, to avoid difficulties like increased river bank erosion, ice-runs and death of fish due to sudden decreases in discharge, it has been necessary to work out a special strategy for running the power station.

Discharge values from 1988 to 1990 in the Alta river downstream the power station is compared to simulated unregulated discharge values. It can be seen that todays regulated conditions differ very little from the natural situation.

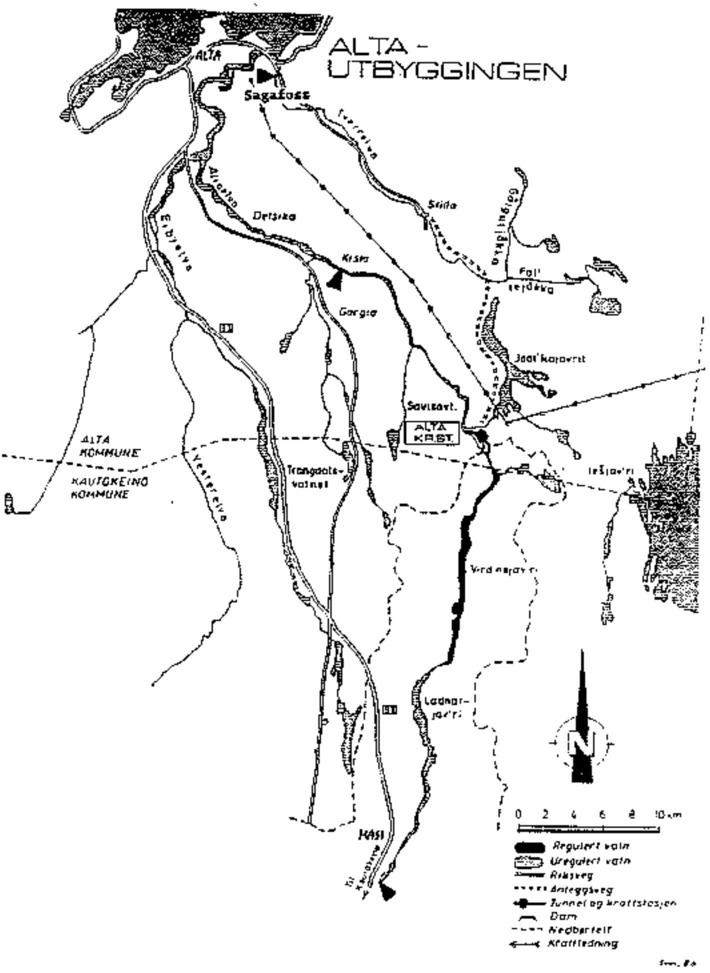
INNLEDNING

Alta kraftverk ble satt i drift i mai 1987. Denne artikkelen tar for seg manøvreringsreglementet og den kjørestrategien som har vært fulgt i de fem årene kraftverket har vært i drift. Videre er vannføringen i Altaelva etter regulering beskrevet og sammenlignet med beregnet regulert og beregnet naturlig vannføring.

KORT OM ALTAUTBYGGINGEN

Kraftstasjonen ligger ca 40 km opp i elva fra Alta tettsted (se fig. 1). Inntaksmagasin og eneste magasin i utbyggingen er Virdnejavri. Nedenfor er det satt opp noen sentrale hoveddata for utbyggingen.

Nedbørfelt	5946 km²
Midlere tilsig (1930-60)	2101 mill.m³
Virdnejavri	
magasinvolum	135 mill.m³
HRV	265 m o.h.
LRV	200 m o.h.
midlere fallhøyde	175 m



Figur 1 Kartskisse over deler av Altavassdraget der Alta-utbyggingen og avløpsstasjoner (▼) omtalt i teksten er vist.

Installasjon		
	1. aggregat	50 MW
	2. aggregat	100 MW
Maksimal driftsvannføring		
	1. aggregat	32 m^3/s
	2. aggregat	64 m^3/s
Beregnet middelproduksjon		
	vinter	240 GWh
	sommer	385 GWh

MANØVRERINGSREGLEMENTET

Manøvreringsreglementet skal ivareta ulike interesser knyttet til elva på en best mulig måte. Helt sentralt i Altaelva har vært hensynet til fisket og isforholdene. Disse faktorene ble vurdert å være så vesentlige at en fikk et manøvreringsreglement med svært snevre reguleringsmuligheter i forhold til elvas naturlige hydrologi.

Reglementet har en rekke konkrete begrensninger på den regulerte vannføringen. Disse kan summeres opp som følger:

I	15.12 - 31.03	Maksimal vannslipping begrenset til 30 m^3/s.
II	01.04 - 25.04	Maksimal vannslipping gradvis økende fra 30 m^3/s til 50 m^3/s.
III	26.04 - 30.04	Maksimal vannslipping gradvis økende fra 50 m^3/s til full driftsvannføring på 96 m^3/s.
IV	01.05 - tilsiget er større enn full driftsvannf.	Full driftsvannføring
V	Fullt magasin - 31.08	Vannføringen skal ligge innenfor ± 10% av naturlig vannføring målt ved Kista avløpsstasjon.
VI	01.09 - 30.09	Ingen restriksjoner
VII	01.10 - 15.12	Maksimal vannslipping må ikke overstige en jevnt avtagende vannføring fra 85 m^3/s til 30 m^3/s.

Videre gjelder det at en ved manøvreringen skal ha for øye at de naturlige flomvannføringer så vidt mulig ikke forøkes.

Alle vannføringsrestriksjonene er referert til avløpsstasjonen ved Kista ca 20 km nedstrøms kraftstasjonsutløpet (se fig. 1).

I tilknytning til reglementet har myndighetene oppnevnt to fagkyndige "medregulanter" på feltene is og fiske for å sikre at kjøringen ikke kommer i konflikt med hensynet til fisket og isforholdene.

KJØRESTRATEGIEN

For å unngå uheldige virkninger på isdekket, for fisken og på erosjonen i elva var det nødvendig med en strategi for kjøringen av kraftverket i en "normalsituasjon" selv med det strenge manøvreringsreglementet en har. Nedenfor er det gitt en kort beskrivelse av denne kjørestrategien som en har fulgt siden 1987:

Ca 31.10 ligger Virdnejavrimagasinet mellom kote 264 (HRV-1) og 265 (HRV).

Fra 1.11 og fram mot islegging (ofte omkring 15.12) kjøres det på tilsiget ± 10% samtidig som en passer på at vannføringen avtar slik at isen legges på ca 30 m^3/s.

Antatt vintertilsig beregnes på grunnlag av høst og vintertilsigsverdier fra en rekke tidligere år. I tillegg til vintertilsiget skal magasinet kjøres ut i løpet av vinteren. Det legges opp til en jevn, eventuelt noe avtagende, vannføring gjennom hele vinteren fram til antatt vårflomstart, og det legges inn sikkerhetsmarginer p.g.a. usikkerhet i beregningen av vintertilsiget.

Oppkjøringen om våren har vært utført i samarbeid med "medregulantene". Tilsiget kjøres til vårflommen kommer, og øker til ca 96 m^3/s uten noe særlig fylling i magasinet.

Under oppfyllingen av magasinet har en fulgt følgende fyllingsprosedyre:

Oppfyllingen skjer gradvis. Det forbitappes stadig mer vann for at overgangen til vårflommen ikke skal bli for brå. Forbitappingen bestemmes hver dag utfra magasinets fyllingsgrad og tilsiget samme dag.

$$\text{Tapping} = \frac{\text{Magasin}}{135} * \text{Tilsig} * 0.9$$

Faktoren 0.9 er introdusert for å gi fullt magasin på et rimelig tidspunkt.

Etter at magasinet er fullt kjøres det slik at vannføringen ved Kista ligger innenfor ±10% av naturlig vannføring. I denne perioden fram mot 1.11 varierer magasinvannstanden mellom HRV og 1 m under HRV.

VANNFØRINGSFORHOLDENE ETTER REGULERING

I de første årene med drift har magasinet blitt tappet ned noe raskere enn forutsatt i kjørestrategien grunnet revisjoner. Dette har ført til at det i den siste tiden før vårflommen begynner bare er tilsiget som har blitt sluppet forbi dammen.

Det gjeldende manøvreringsreglementet er gitt midlertidig for 5 år og skal deretter tas opp til vurdering. Eventuelle endringer i reglementet vil bli vurdert ut fra bl.a. de driftserfaringer en har etter 5 års drift. I den forbindelse har Alta kraftverk sammen med NVE-Iskontoret utført forsøk med opp og ned reguleringer om vinteren bl.a. for å undersøke mulighetene for døgnregulering vinterstid. Forsøkene har vært utført i forståelse med "medregulantene" på is og fisk.

En vil alltid kunne få en viss døgnfluktuasjon i driftsvannføringen fordi maskinene reagerer automatisk på svingninger i nettfrekvensen. Turbinene skal være med og stabilisere frekvensen og av den grunn varierer pådraget med endringer i frekvensen. Om vinteren med bare et aggregat i drift vil dette kunne gi maksimale variasjoner i driftsvannføringen på 2 m^3/s. Om sommeren med kjøring på begge maskinene kan variasjonene bli opptil 7 m^3/s.

Observerte og simulerte verdier

Vannføringsforholdene ved avløpsstasjonen Kista (se fig. 1) for årene 1988-1990 er vist på døgn- og månedsbasis og sammenlignet med beregnet naturlig uregulert vannføring samme sted.

Det naturlige avløpet ved Kista er beregnet som en sum av registrert avløp ved Masi og lokaltilsiget fra feltene mellom Masi og Kista. Den uregulerte avløpsstasjonen Sagafoss i nabovassdraget Tverrelva er brukt til å beregne lokaltilsiget nedenfor Masi. Det er i beregningene tatt hensyn til den naturlige selvreguleringen i sjøene Ladnatjavri og Virdnejavri.

Observert og beregnet naturlig vannføring ved Kista på månedsbasis er satt opp i tabell 1. Døgnverdiene er vist i figurene 2 til 4, en for hvert av årene 1988 til 1990.

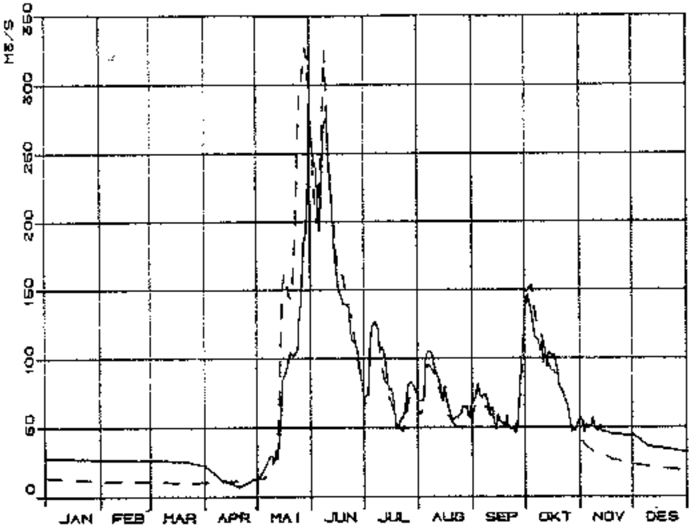
Årene 1972 til 1982 ble brukt til simuleringer i forbindelse med planleggingen av kraftverket. I tabell 2 er observerte månedsmiddelverdier sammenlignet med beregnete regulerte månedsverdier. Sammenligner en med tabell 1 ser en bl.a. at vinterverdiene i 1988 til 1990 har vært høyere enn antatt i simuleringene fra planleggingstiden. Dette har dels sin årsak i nødvendige arbeider i april, som har krevet utkjøring av magasinet noe raskere enn forutsatt i et vanlig år, og dels i de store vintertilsigene en har hatt.

Tabell 1 Altaelva ved Kista
Midlere månedsavløp i m^3/s for 1988 til 1990
Beregnet naturlig og observert vannføring

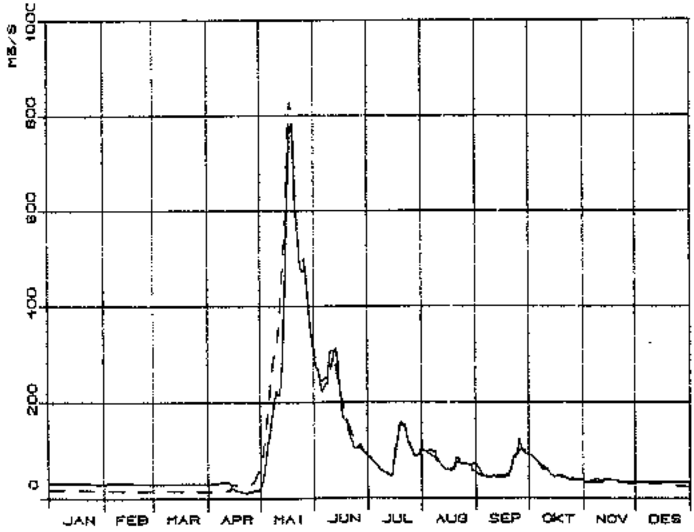
Måned	Beregnet naturlig			Observert		
	1988	1989	1990	1988	1989	1990
Januar	12.7	17.1	22.7	27.7	32.1	33.4
Februar	11.0	15.3	20.9	26.7	31.4	31.9
Mars	10.3	14.5	20.5	25.4	30.1	29.9
April	11.4	26.2	29.3	12.5	22.6	27.5
Mai	135.9	425.5	139.5	85.3	362.3	103.1
Juni	183.9	200.7	193.9	176.5	194.6	165.8
Juli	77.9	88.7	100.1	84.7	89.3	102.9
August	67.1	73.5	50.4	73.9	77.9	53.9
September	61.8	61.4	38.9	65.4	64.7	41.0
Oktober	94.2	55.0	40.0	92.6	53.7	42.7
November	30.0	34.0	31.9	47.6	37.2	35.6
Desember	20.8	29.6	26.6	36.0	34.2	40.5
Året	60.0	87.5	59.7	63.0	86.4	59.1

Tabell 2 Altaelva ved Kista
Midlere månedsavløp før og etter regulering
Datagrunnlag årene 1972-82

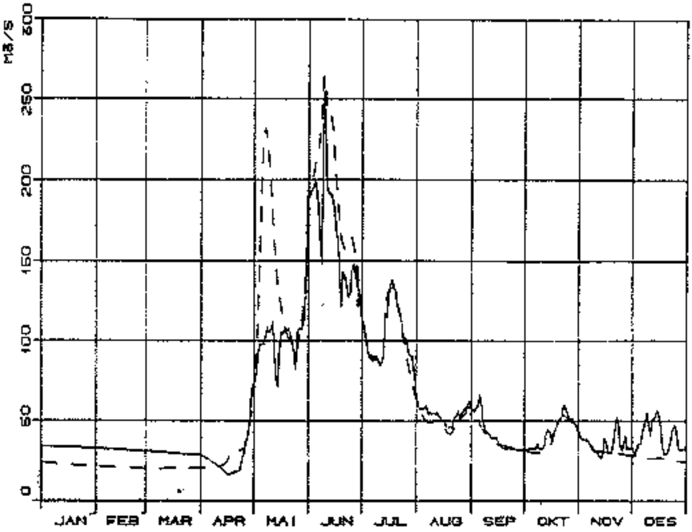
Måned	Før regulering			Etter regulering		
	Middel	Maks.	Min.	Middel	Maks.	Min.
Januar	16.3	21.8	9.9	23.1	28.7	16.8
Februar	13.6	18.5	8.7	21.7	26.6	17.0
Mars	12.1	16.6	8.2	21.4	25.9	17.7
April	11.3	15.7	7.7	22.0	26.3	18.3
Mai	188.8	312.4	55.5	160.6	276.3	53.4
Juni	271.7	466.4	120.9	262.0	429.9	118.3
Juli	97.3	229.4	37.9	97.0	228.1	37.2
August	77.9	250.9	28.1	77.4	247.1	27.8
September	70.8	177.8	29.2	71.1	177.7	29.5
Oktober	65.4	155.1	25.2	64.5	153.6	24.6
November	33.5	45.2	16.6	34.2	45.9	17.8
Desember	22.5	34.5	12.2	26.4	32.5	16.8
Året	73.7	98.4	53.6	73.6	98.4	53.6



Figur 2 Døgnvannføring ved Kista i 1988
Observert —— Beregnet naturlig - - -



Figur 3 Døgnvannføring ved Kista i 1989
Observert —— Beregnet naturlig - - -



Figur 4 Døgnvannføring ved Kista i 1990
Observert—— Beregnet naturlig- - -

I perioden fra magasinet er fylt opp og fram mot vinteren skal kraftverket kjøres slik at vannføringen ved Kista ligger innenfor ± 10% av naturlig vannføring. Dette er et strengt krav som i praksis nærmest vil si at det er tilsiget som til enhver tid skal slippes videre i elva. Av figurene 2 til 4 ser en at vannføringen i denne perioden omtrent er sammenfallende med beregnet naturlig vannføring.

Hittil har driftspersonalet bare hatt vannstandsavlesningene i magasinet og vannføringen observert ved Masi å bygge på når de har bestemt kjøringen av kraftverket. For lettere å kunne overholde manøvreringsreglementet og samtidig få en best mulig utnyttelse av vannet har et styringssystem for optimal kjøring av turbiner og luker blitt utviklet og installert på driftssentralen. Ved hjelp av HBV-modellen beregnes tilsiget til magasinet og til det uregulerte feltet mellom kraftstasjonen og målepunktet Kista. Modellen beregner også uregulert vannføring ved Kista, slik at en hele tiden kan sjekke at en kjører innenfor reglementet.

GRUNNVANNSUNDERSØKELSER LANGS ALTAELVA

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ABSTRACT

Groundwater observations along the Alta River started in 1972 at four different cross-sections downstream from the dam-site. Hydro-power production started in 1987 and data for the period after the regulation are compared to data for the period before. Correlations between water levels in the river, air temperature, amount precipitation and groundwater are discussed and conclusions on the effects of the regulation are drawn. In addition a general description of the groundwater regime is given.

INNLEDNING

Statskraftverkene startet planleggingen av Altautbyggingen i 1970. En del av planleggingen var diverse konsekvensundersøkelser. I 1972 startet NVE-Hydrologisk avdeling grunnvannsmålinger langs vassdraget. Målet med datainnsamlingen var å finne ut i hvilken grad grunnvannstanden påvirkes av vannstanden i elva.

Dette manuskriptet omhandler undersøkelsene og tar sikte på en presentasjon av noen av de innsamlede data samt enkelte analyser av disse. Grunnvannsobservasjonene fra et av våre undersøkelsesområder er sammenlignet med observasjoner av vannstand i elva, nedbør og lufttemperatur.

KRAFTVERKS HYDROLOGI

Altaelva er ca. 170 km lang med utløp i Altafjorden. Kraftverket ligger ca. 40 km oppe i elva. Innsjøen Virdnejavri er kraftverkets magasin. Vannet tas inn like ovenfor betongdammen og slippes ut 2 km lenger ned hvor Joatajohka og Altaelva renner sammen. I området med sterkt redusert vannføring er det lite løsmasser og forholdsvis bratte dalsider. Det er derfor lite interesant med tanke på grunnvannsundersøkelser.

Under vårflommen skal vannføringen økes i takt med tilsiget samtidig som magasinet fylles opp. Vannføringen er pålagt å ikke endres mer enn 10% i forhold til uregulert vannføring etter at magasinet er fullt (ca. juni). Endringene lenger ned i elva er relativt små (fig.nr. 1).
Kraftverket ble satt i drift 18. mai 1987.

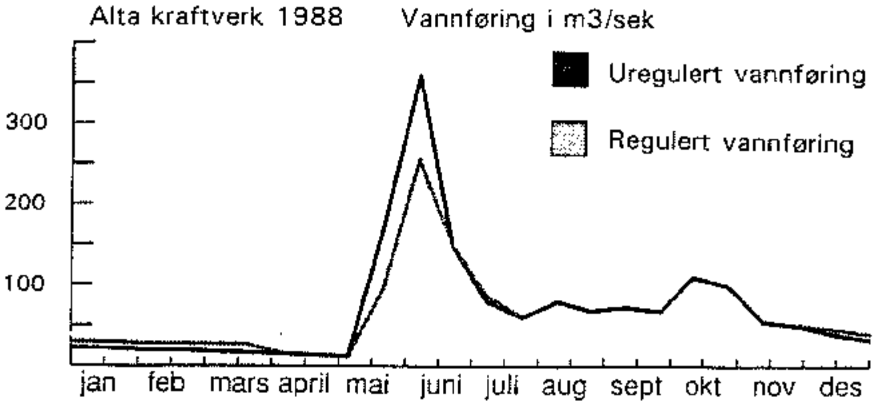

Fig.nr. 1. Regulert og uregulert vannføring.

GEOGRAFI

Målestedene er plassert på elvesletter langs Altaelva nedstrøms utløpet fra kraftverket (fig.nr. 2).
Stengelse er det øverste snittet. På Tangen har vi etablert et snitt mellom samløpet til Altaelva og Eibyelva. Furulund og Aronnes ligget nedenfor samløpet.

Alle målestedene ligger på fluviale avsetninger. Stengelse, Tangen og Aronnes har kornfraksjoner overveiende innenfor fin og middels sand med innslag av grov sand og silt/leire. Furulund har i spesielt de øvre lag et mye større innslag av silt/leire. Sonderinger har vist lagdeling med ulik tykkelse og tetthet. Ca. 5 m under bakken er det et hardt steinlag. Ved stort sett alle grunnvannsrør består terrenget av grasdekke.

MÅLEPROGRAMM

Hydrologisk avdeling startet de første grunnvannsundersøkelsene i 1972. I 1981 kom Furulund i tillegg.

Det ble satt ned 5/4" rør med 1 m filter spiss. Det ble totalt

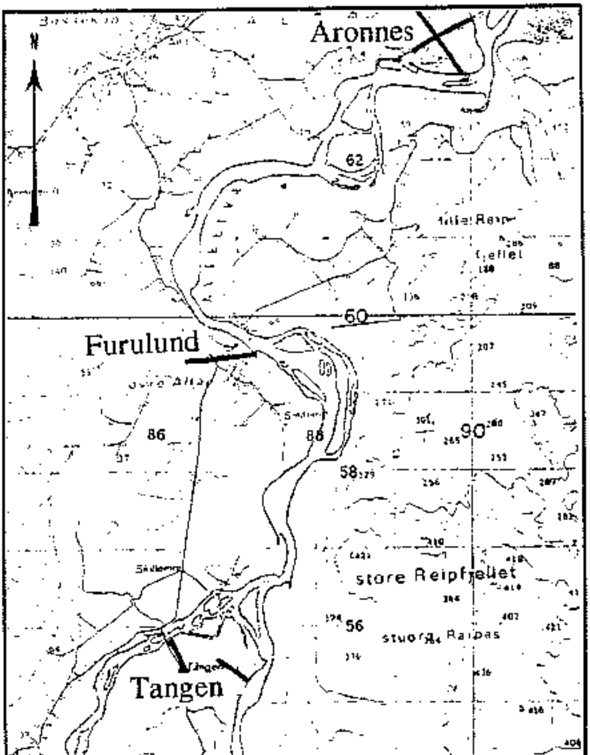

Fig.nr. 2. Kart over målestedene langs Altaelva.

satt ned 30 rør fordelt på undersøkelsesområdene. Røra er satt i rekke etterhverandre. På Aronnes er det to snitt som krysser hverandre. Vanlig avstand mellom målepunktene er ca 100 m, men dette varierer. Manuelle målinger ved hjelp av klokkemåleband er foretatt ukentlig.

Lufttemperatur og vannstand i elva målt på to steder. Det norske meteorologiske institutt har nedbør- og lufttemperaturobservasjoner ved Alta flyplass. Disse er benyttet i de senere analyser.

STENGELSE

Stengelse er det øverste profilet og ikke påvirket av andre elver enn Altaelva (fig.nr. 3).

Snittet består av 5 grunnvannsrør, måling av vannstand i elva og lufttemperatur. Rør 1 står like ved elvekanten, mens rør 5 ligger 500 m innover på elvesletta.

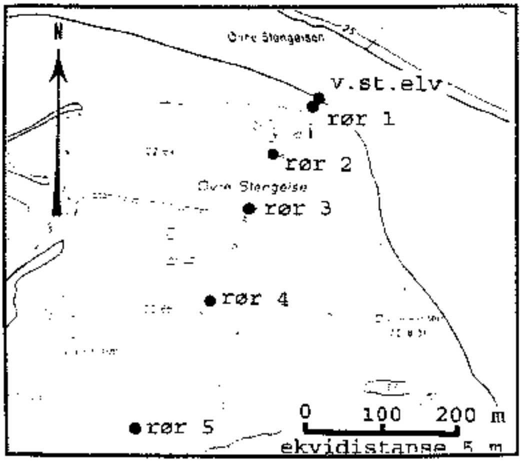

Fig.nr.3. Kart over målepunktene på Stengelse.

Vanngjennomgangen er testet på alle rør. En viss mengde vann helles i røret og tiden det tar før grunnvannstanden er gått tilbake til utgangspunktet måles. Dette brukes som et veiledende mål på rørets beskaffenhet og massenes infiltrasjonsevne. På Stengelse faller trykkhøyden svært raskt i alle rør.

Tab.nr. 1. Korrelasjonskoffisienter på Stengelse.

målepunkt	korrelasjons-koffisienter	observasjons-periode
vst. elva - rør 1	0,995	1973-1991
vst. elva - rør 2	0,975	1973-1991
vst. elva - rør 3	0,907	1973-1991
vst. elva - rør 4	0,835	1973-1991
vst. elva - rør 5	0,651	1973-1991
rør 4 - rør 5	0,948	1973-1991

Korrelasjonsanalyser er gjort mellom vannstandsobservasjonene i elva og alle rør (tab.nr. 1). Det er en klar samvariasjon mellom elva og grunnvannet. Denne er svært høy i de nærmeste

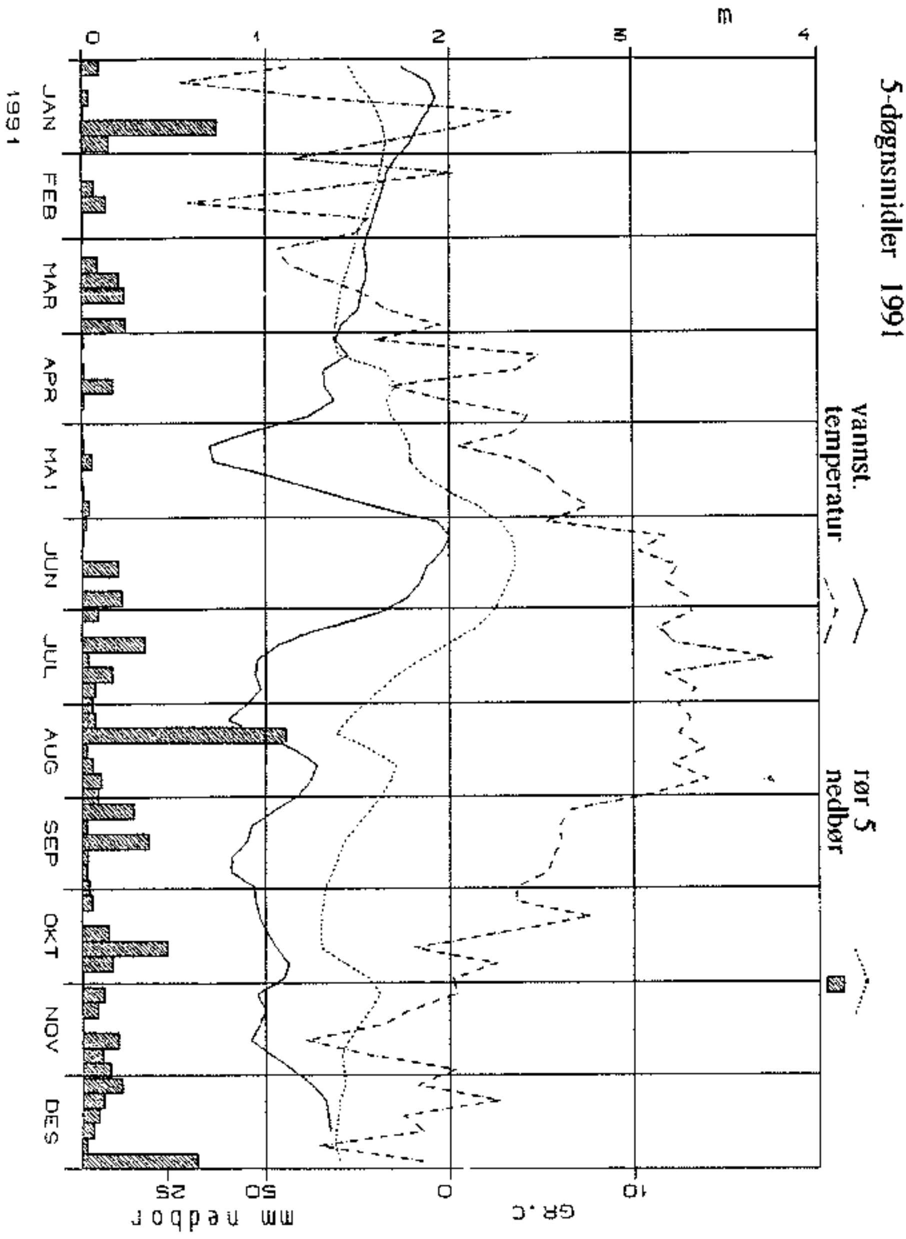

Fig.nr. 4. Grunnvannstand rør 5, vannstand i elva, nedbør og lufttemperatur. Merk 3 forskjellige målestokker.

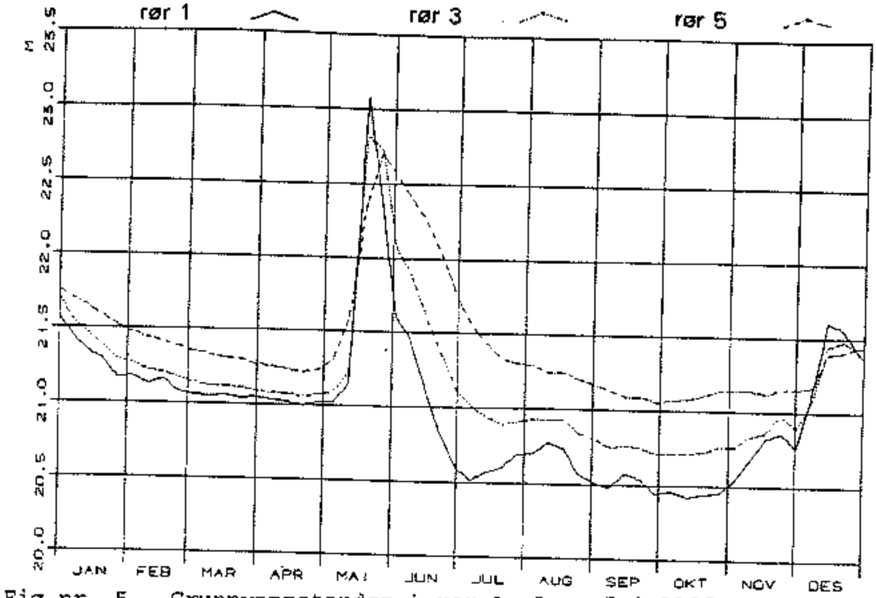

Fig.nr. 5. Grunnvannstanden i rør 1, 3 og 5 i 1986. Før regulering. Felles høydegrunnlag.

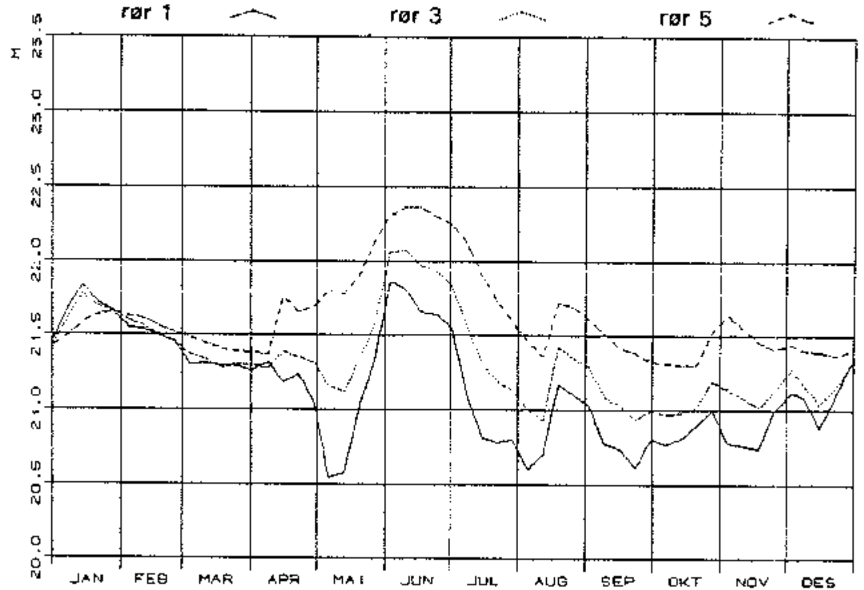

Fig.nr. 6. Grunnvannstand i rør 1, 3 og 5 i 1991. Etter regulering. Felles høydegrunnlag.

målepunktene og noe lavere lenger bort fra elva.

Grunnvannstanden i rør 5 som er lengst bort fra elva og vannstanden i elva har en tydelig samvariasjon (fig.nr. 4). I løpet av ettervinteren minker grunnvannstanden gradvis ettersom det er lite nydannelse. I mai etterhvert som temperaturkurven stiger, stiger også vannstanden i elva og grunnvannet som en følge av snøsmelting.
I august 1991 kom det mye nedbør, like etter steg grunnvannstanden merkbart. Det samme skjedde etter en mye mindre nedbørtopp i oktober.
Grunnvannstanden har en god samvariasjon med både vannstanden i elva, temperatur og nedbør.

Grunnvannstandene i rør 1 som er nærmest elva ligger lavere enn lenger inn på elvesletta. Det vil i praksis bety at grunnvannspeilet heller i retning mot elva. I mai under snøsmeltingen stiger grunnvannstanden vesentlig i alle rør.

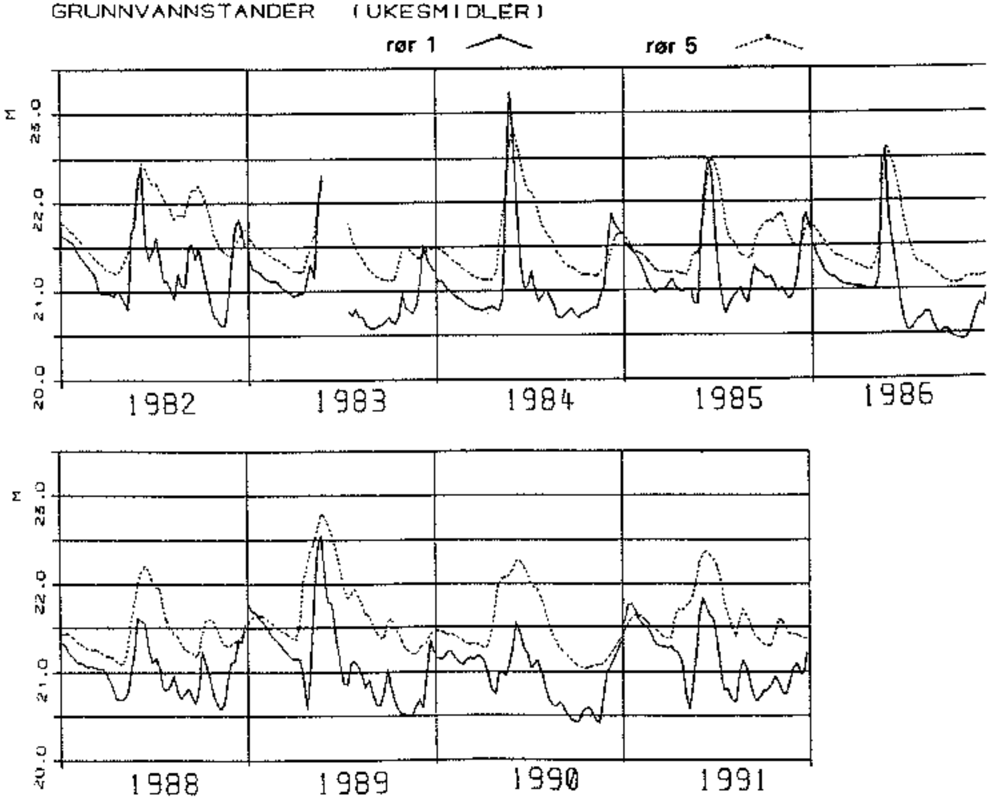

Fig.nr. 7. Grunnvannstand før og etter regulering. Rør 1 og 5.

I 1986, før reguleringen var økningen størst i rør 1 (fig.nr. 5 og 6). Dette medførte at grunnvannspeilet i denne perioden endret hellningsretning, fra å drenere mot elva til å drenere fra elva. Under vårflommen var det altså elva som matet grunnvannet.
Som tidligere nevnt er det stort sett bare i vårflommen det er en reduksjon i vannføringen etter reguleringen (fig.nr. 1). I 1991 er situasjonen anderledes, økningen er ikke lenger vesentlig mye større i rør 1 enn i røra lenger inn på elvesletta.

Vårflommen i mai er tydelig markert i alle grunnvannsrør i alle år (fig.nr. 7). Tendensen er noe større topper i grunnvannstanden før regulering enn etterpå. En kan også se at helningen på grunnvannspeilet ikke endrer fallretning etter regulering.

Konklusjon

Grunnvannstanden på Stengelse er påvirket av flere faktorer. Før regulering var vårflommen såpass stor i elva at elva matet grunnvannet. Grunnvannsdannelsen skjedde da etter infiltrasjon fra elva, nedbør og snøsmelting.
Etter reguleringen er stigningen i elva mindre om våren. Tiltross for at endringene i elva ikke har vært særlig store, har det likevel ført til at elva ikke lenger mater grunnvannsmagasinet under vårflommen. Dette har betydning kun for de elvenære områder, lenger inne på elvesletta vil det ikke ha noen effekt. Nydannelse av grunnvannet er etter regulering stort sett avhengig av infiltrasjon fra overflaten, d.v.s. fra nedbør og snøsmelting.

DEVELOPMENT OF HYDROMETRIC NETWORKS IN THE NORDIC COUNTRIES

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ABSTRACT

In the late 1980s, many Nordic countries started a national programme to develop their hydrometric monitoring networks. In 1990, a Nordic working group was appointed to improve cooperation in this field. The national discharge and water level networks comprise almost 3 000 stations in the Nordic countries, and the overall annual budget of the operation is estimated to be about 90 million Swedish crowns. The central part of network development is composed of measures, by which the networks can be restructured. Among these are inventories of data utilization, integration of networks, combined operation of monitoring and modeling, new monitoring strategies and statistical network analyses. The instrumentation of hydrometric stations has improved much recently, and this fact will also influence on the design of networks.

GENERAL BACKGROUND

During the 1980s, new and significant factors began to affect the design of hydrological monitoring networks. The needs of budgetary contractions became obvious in many countries - perhaps for the first time during the operation. The importance of environmental aspects was generally recognized, and hydrological monitoring produced basic information which could be utilized in many ways in this field. Integration of climatological, hydrological and other environmental observations was also set as a central goal in national as well as global monitoring.

Due to these general and various local factors, many countries wanted to evaluate their hydrological data collection systems. In the late 1980s, the Nordic countries started several national programmes to develop the main hydrometric monitoring networks - the national discharge and water level networks. In 1990, the Nordic Working Group on Hydrometric Networks was established to promote cooperation in this field. The group was appointed by CHIN, after which the project was also linked to the Nordic Hydrological Programme 1991-92.

NATIONAL INSTITUTIONS AND OBJECTIVES

The institutional background of hydrological surveys varies, and this fact has some influence on national objectives that are set for monitoring. In Denmark and Finland, the ministry of the environment represents the main public guidance. In Iceland and Norway, the surveys are organized under the ministries of industry and energy, respectively, and in Sweden the SMHI works under the ministry of communication. The Greenland Field Investigations, which is responsible for hydrometric monitoring in the island, is guided by the Department of public work.

In addition to some special tasks, there are many central objectives which are common to all Nordic countries. Among these are:

- to study the demand for hydrometric data
- to improve the cost-efficiency of monitoring
- to support water quality monitoring and other environmental research
- to improve data quality and reliability and
- to develop data service.

PRESENT HYDROMETRIC NETWORKS

The current volume of national hydrometric monitoring in the Nordic countries is shown in table 1.

Table 1. The number of stations in the national hydrometric networks[1] at the beginning of 1992.

Country/ region	Discharge stations	Water level[2] stations
Denmark	375	27
Finland	330	290
Greenland	20	4
Iceland	112	26
Norway	839	489
Sweden	408	40
Sum	2 084	876

[1] National network comprises the stations which produce data for national hydrological survey and its data base.

[2] Water level stations in lakes, reservoirs and rivers which are (at least partly) operated for other purposes than discharge calculation.

Almost half of the stations are situated in Norway, where the volume of data collection for hydro power sector is especially high. The Greenlandic network comprises only 1% of all Nordic stations, as very limited parts of this vast area are currently being monitored. The network density is highest in Denmark.

The figures in table 1 are not completely comparable, as the structure of national networks varies in different countries. For instance, the proportion of stations which are maintained or financed by other organizations than the national hydrological survey varies greatly. However, the table gives a relatively good picture of the total volume of hydrometric monitoring.

The current objectives and use of discharge stations has been studied in the frames of the Nordic Working Group on Hydrometric Networks. Almost 40% of the stations have the primary objective to produce continuous runoff data for the study of hydrological variability and conditions of the watershed. These basins are either regulated or large, natural watersheds. Some 30% of the stations are used primarily for data transfer to ungauged watersheds of similar character. These stations are situated in natural, regionally representative basins. About 15% of the stations serve primarily daily operational use, and the same proportion of the stations is used for project planning and design. Only 1% of the national discharge stations are situated in special research basins; however, separate networks of small hydrological basins are operated in many countries. The above classification and more detailed information on data demand can be utilized in many ways in future network design.

During the last 10 years, the number of national hydrometric stations has increased in Denmark by 100, in Sweden by 50 and in Iceland by 15. In Finland, Greenland and Norway the volume of national monitoring has slightly decreased. Many factors and decisions have influence on the size of networks, and it is very difficult to make prognoses of the future development - even if some principles have been stated.

ECONOMICAL ASPECTS

Overall costs of national hydrometric monitoring in the Nordic countries are roughly 90 million Swedish crowns in 1992. This estimate is based on the relatively well defined budgets of the national surveys and the assumption that in each country, the average cost per station is the same for other organizations which maintain hydrometric stations. The budget includes investments as well as administrative and overhead costs. As the total number of stations is some 2 800, the annual cost per station is in average 32 000 Swedish crowns. More detailed cost analysis will be completed by the end of 1992.

A much more difficult question is that of the overall benefits of hydrometric observations. Hydrological monitoring systems always include potential future benefits, the monetary values of which are impossible to calculate. One way of assessing the benefits is to study the actual and potential uses of each hydrometric station. Also this work is being done in the Nordic hydrological surveys. The study of economical aspects is expected to improve the cost-efficiency of monitoring.

MEASURES TO RESTRUCTURE NETWORKS

The central part of monitoring development is composed of measures, by which the networks can be restructured. This may be done e.g. by integrating different networks, by choosing a set of stations for discontinuance, by network extensions or by changing the measurement strategy. The whole process is based on the inventories of current and foreseeable data utilization.

Integrated network design

All of the Nordic countries are currently planning integration of hydrometric networks and other monitoring systems. This will no doubt lead to some changes in the structure of hydrometric networks; however, major development is expected to take place in the field of station instrumentation. According to the present plans, integration of national hydrometric monitoring will be of special importance in the following three areas: (1) hydrometeorological monitoring, (2) water quality and environmental monitoring and (3) local hydrometric monitoring.

Monitoring strategy and modeling

The rapid development of hydrological modeling and geographical information systems are creating new starting points for the design of monitoring networks. Obviously this fact was not recognized until a few years ago, because the traditional roles of observed time-series and models seemed to be relatively clear and stable. In the near future, field measurements and models will create an interactive system where the both "parties" support each other.

Monitoring strategy is closely linked with this thinking. In this context, the term "strategy" means the duration and frequency of measurements. In hydrometric data collection, three main strategies can be used: (1) continuous monitoring, (2) temporary observations (in most cases less than 10 years) and (3) measurement campaigns for seasonal extremes or other momentary values. So far, continuous measurements have been dominant in the Nordic countries, though the use of primary and secondary stations has a long international tradition. In the future, the whole spectrum of monitoring strategies will probably be used more effectively than today.

Statistical network design methods

Different types of statistical models have been developed to increase the information value of hydrological networks - or in many cases, to support decisions on station discontinuance so that the information loss will be as small as possible. Moss (1982) has made a well known summary of the methods that were developed in the 1970s. At present, the largest and best known international network design project is HYNET (Intercomparison of Operational Network Design Techniques), the main objective of which is to maximize regional runoff information within a limited budget and time horizon.

In the Nordic countries, statistical methods have not been applied for hydrological network design until very recently. The first steps were taken in 1991 at the NVE in Norway, where several different methods were preliminary tested during the winter 1991/92 (Roald, 1992).

MEASURING TECHNOLOGY

The instrumentation of hydrometric monitoring stations has developed considerably during the last two decades. The most important issues have been the introduction of automatic data transmission and local "intelligent" data loggers. The current standard of instrumentation is presented in table 2.

Table 2. The standard of instrumentation at the national hydrometric monitoring stations at the beginning of 1992.

Country/ region	Proportion of stations (%)			
	Data[1] transfer	Data logger	Chart recorder	Staff gauge
Denmark	10	44	40	6
Finland	39	1	35	25
Greenland	8	84	8	0
Iceland	21	14	64	1
Norway	40	25	25	10
Sweden	42	1	54	3
All Nordic countries	35	20	35	10

[1] Hydro power plants which produce discharge data are included here.

The type of instrumentation clearly reflects the structure of the networks. The volume of operational stations, for example, has its effects on the proportion of data transfer stations. In the future, the proportions of data transfer stations and data logger stations are expected to increase due to the purchase of new instrumentation.

FUTURE REALIZATION OF THE PROGRAMMES

This paper has described the main issues within hydrometric network design and the current status of development in the Nordic countries. One central part of the monitoring systems has not been discussed: data processing and data service. In this field, the general objectives are very much the same, though practical solutions may vary in different countries.

As mentioned above, national programmes form the core of the development activities. The Nordic Working Group on Hydrometric Networks will probably work for another two-year period, first of all to change information and strengthen cooperation between the Nordic countries while the development programmes are carried out. Well organized cooperation will also make it possible to test applications of network design methods in different circumstances.

ACKNOWLEDGEMENTS

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AN EVALUATION OF METHODS FOR STATION NETWORK ANALYSIS

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ABSTRACT

Three methods for evaluating station network representativity are applied to sets of Norwegian discharge stations. The purpose of the study is to examine the potential for rationalizing the extensive Norwegian station network.

INTRODUCTION

The hydrometric network has grown considerably in Norway since the systematic monitoring started in some larger rivers in the 1840-ies. The network comprises now approx. 840 discharge stations and 340 stations monitoring the levels in natural lakes and reservoirs. The operation of this network requires large resources, and it is now necessary to evaluate and rationalize the network. The need for analysis of the current network combined with systematic planning for the future has been realized in all the Nordic countries. The study presented in this paper is part of the ongoing work of the Nordic working group (Puupponen, 1992).

USE OF DATA FROM HYDROMETRIC NETWORKS

A hydrometric network comprises a number of stations monitoring the discharge at fixed locations in the rivers of a region or a country. The discharge data are used for assessing the water resources, for design of hydraulic constructions, for water resources management and for many other purposes. Many networks were originally set up for some specific purpose. The objectives for the data collection at a site may later have changed as new needs arises. Most water resources projects require knowledge of the mean values as well as the variability on annual and seasonal basis. For design of hydraulic constructions flood data are required. If a river is utilized as a recipient for effluent water or for providing water for domestic use or irrigation, low flow data are essential.

When flow characteristics are needed in connection with a water resources project, data are frequently not available at the site of interest. Data must therefore be estimated or existing series prolonged based on data from other stations with a similar flow regime. This can be done by a number of methods, such as scaling based on catchment area or normal runoff, use of regional statistical techniques or on use of rainfall-runoff models. When data are estimated at an ungauged site, the data will have an error because of lack of representativity in space and the time sample used in calibrating the model used for the prediction. A third part of the error is the model error due to the inability of the chosen model to describe the discharge at the actual site.

STATION NETWORK DESIGN

Given a network comprising a number of stations which has been operated concurrently or at different periods, similar methods can be applied to predict data at a site with observations as for ungauged basins. By estimating the prediction error, the increased uncertainty in a statistics of interest can be identified. Most series are used for a multitude of purposes. It is therefore not sufficient to examine the transferability of the mean values, but also other characteristics describing the variability of the flows, (Nemec & Askew, 1986).

The methods considered in this study are aimed at answering the basic questions of classical station network design, (Rodda, 1969):

- How many stations?
- Where?
- For how long?

The first question requires that the maximum acceptable error is identified as well as the economical constraints for operating the network. The regional variability of the runoff regime must be known to identify the transferability of data, and thereby the optimal location of the gauging stations. This can be examined by studying the representativity of each station and to map the prediction errors. The length of the observation period required depends on the data use, the life-time of the actual project and on whether the flowgenerating processes can be considered as stationary or not. The Norwegian discharge series does not show any long-term trends, except in the South-west part of Norway, but there are indications of sequences of dry and wet years (Roald & Sælthun, 1990). Current work on region flood analysis for Norway indicates that the most recent 15 years of data only introduce marginal changes in the regional flood frequency curves estimated on series of 30 year or more of data up to 1976.

Station network analysis can include cost-benefit analysis, but this aspect is not dealt with in this study.

METHODS

Two of the methods considered are based on regression analysis between data series and basin characteristics at a number of stations and basin characteristics and has been developed at the United States Geological Survey (USGS). The third method utilizes cluster analysis to identify groups of similar stations in terms of hydrological response. Both approaches are suitable to analyze existing networks with a number of concurrent years at each site.

The USGS-methods

The two regression based techniques are Network Analysis for Regional Information (NARI) (Moss et al., 1982) and Network Analysis Using Generalized Least Squares (NAUGLS) (Tasker, 1986). These two methods examine the standard error of estimate for a hydrological statistics, in this version the mean annual runoff.

The NARI-method assumes that the annual runoff has a constant coefficient of variation, has a two-parameter lognormal distribution and is serial independent at all sites within a homogeneous region. The cross-correlation between each two sites is assumed to be constant over the region. The metod is based on establishing relationships between the mean annual runoff and the basin area:

$$\log_{10}\bar{Q}=a+b\ \log_{10}AREA+e$$

The drainage area and mean discharge are randomly selected for each site. The standard deviation is estimated from the regional coefficient of variation (CV). Utilizing a random number generator and taking into account the constant cross correlation structure over the region a synthetic series are generated for each site. Then the mean runoff is regressed against the basin area after a logarithmic transform of the variables. Experiments are run for a large number of different combinations of number of sites and lengths of record. Based on the results of the analysis, the true and sample standard error can be estimated.

The NAUGLS method utilises the generalized-least-squares (GLS) estimator (Stedinger & Tasker,1985) to estimate the parameters of a regression model:

$$\log_{10}\bar{Q}=a+b\ \log_{10}AREA+c\ \log_{10}MAP+e$$

where AREA is the area of the catchment, MAP is the catchment average annual precipitation, e is a random error and a,b and c are unknown constants. The GLS-estimator is based on the GLS covariance matrix of regression errors. The method takes into account that the series may be of different lengths, and that the records may be cross correlated. The network is optimized by developing relations for the entire data set, and then eliminating stations one by one until the associated costs are within the budget constraints. The method requires that a planning horizon is defined, and that a set of representative stations has been selected initially. The initial set of stations can include sites without observations, but with the basin characteristics known.

The performance of these two techniques can be explored by the program HYNET (Moss & Tasker, 1990). The manual describes 17 experiments which has been run on datasets from many countries (Moss & Tasker, 1991). The experiments have generally confirmed the superiority of the NAUGLS-method.

Data requirements for running the HYNET experiments are:

- at least 51 stations
- at least 30 years of concurrent data
- all stations belonging to a homogeneous region

Cluster analysis

This approach was first described by Burn & Goulter (1991) and utilizes cluster analysis to identify sites with a similar regime. The method produces a list of stations which are considered for possible close down based on other criteria.

Given a station network with simultaneous observations at M sites over N years. For each year and site K annual measures characterizing the flow are determined. The correlation matrix between the sites is calculated for each of the measures:

$$r_{ijk}=\frac{N\sum_{l=1}^{N} X_{ikl}\,X_{jkl}-\sum_{l=1}^{N} X_{ikl}\sum_{l=1}^{N} X_{jkl}}{\sqrt{[N\sum_{l=1}^{N} X_{ikl}^{2}-(\sum_{l=1}^{N}(X_{ikl})^{2}][N\sum_{l=1}^{N} X_{jkl}^{2}-(\sum_{l=1}^{N}(X_{jkl})^{2}]}}$$

where r_{ijk} is the correlation between measure k for station i and station j and X_{ikl} and X_{jkl} are the values of the measure for station i and j in year l.

The overall similarity is characterized by a number of annual measures such as the mean annual flow, an annual flood and an annual low flow characteristics. For each of these K measures a correlation matrix is calculated.

$$R_{ij}=\frac{1}{K}\sum_{k=1}^{K} w_k\; r_{ijk}$$

where the similarity R_{ijk} is the correlation between stations i and j for the k-th statistics, K is the number of statistics included in the similarity and w_k is the weight reflecting the relative significance of the k-th statistics. The weights are chosen to sum up to one for all the K-components of the similarity. Alternatively can the distances in an euclidian data space by utilised for the cluster analysis procedure.

The results are presented as a dendrogram and provides the station network manager with a list of stations within each group. The decision on changes in the network will be taken considering the length of records, actual data use and the regional coverage of data.

APPLICATION OF THE METHODS ON NORWEGIAN DATA SETS

The HYNET-method

Many Norwegian rivers are regulated for hydropower. Few reservoirs has a multi-year storage, the annual mean can be utilized directly even for regulated series excluding those with upstreams diversions. For analysis of the seasonal variability or extreme flows, it is neccessary to analyze naturalized flow data rather than observed flows. A data set was compiled of data from 106 sites for the period 1949 to 1978. By reducing the length of record to 20 years a considerable larger data set could be made available for the analysis. The data set comprises data from all over Norway because of the constraints on the record length and the number of stations.

The resulting data set is highly heterogeneous even in terms of the mean annual flow. The CV ranges from 0.09 to 0.51 in the data set. The serial correlation is less than 0.1 except at sites with large lakes upstreams. The cross-correlation varies regionally and can be utilized to subdivide the data set in smaller regions. Each region will have far fewer sites than required by the HYNET approach.

The NAUGLS method utilizes the basin average precipitation as one of the independent variables in the analysis. Most of the basins included in the analysis are partly mountaineous. As the precipitation stations are located in the lowlying part of the basins, area precipitation can be better estimated from the specific runoff with a suitable correction for the evaporation based on regional maps; a problem also encountered by the USGS for the Rocky Mountains,(M.Moss, priv.comm.).

The HYNET-program is therefore not applicable on the Norwegian station net in its present setup. Most of the constraints is imposed by the NARI-method. We plan to explore the NAUGLS-method on smaller data sets for other hydrological statistics and with alternative basins characteristics.

The cluster method

The cluster method can be applied to smaller data sets than the HYNET-method and do not need as many as 30 years of concurrent data. Three regions with a reasonable dense coverage of stations were tested; one extending from inner Nordfjord across the mountains to the upper part of river Laagen (A), one covering the southern part of Norway south and east of the main mountain range (B), and one covering the southwest part of the country (C), see Figure 1.

Correlation matrices were established for the four flow measures:

- the mean annual flow
- the maximum daily flow
- the minimum daily flow
- the ratio between the maximum daily spring and annual flood

and an average correlation was calculated for each basin as a similarity criterium. The similarity matrix was used as input to a hierarchical clustering program, (Gottschalk, 1985). The resulting groups comprised stations belonging to the same part of the river system. The similarity was fairly low; even for adjacent sites. Most of the problems seems to be caused by the low flow correlation. These values are often corrected for backwater effects due to ice and are rather uncertain. The analysis was therefore repeated without the low flow included in the similarity index for the three regions.

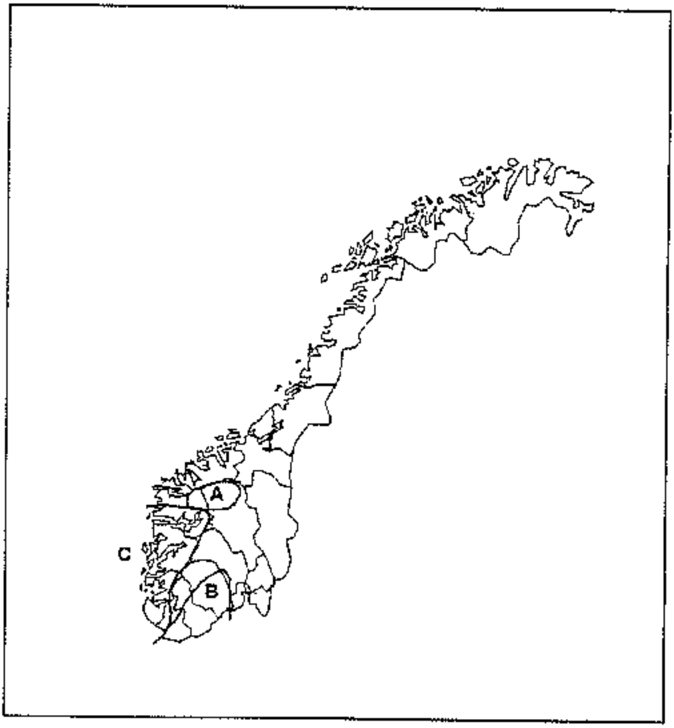

Fig. 1. Location of the three regions used in testing the cluster method.

The results are shown for Region A as a dendrogram in Figure 2 with the similarities plottet along the abscissa. A high similarity implies that data can be transfered to the another station with small prediction errors. We note that the similarities are fairly low, which indicates that the region is quite heterogeneous. By defining a similarity of 0.65 as a limit, we find that the 15 stations in this group fall into seven groups, of which four comprise only one station. Two of the stations, 1489 and 623 belong to other regions. The groups comprising more than one station are from the same branch of the rivers included in the region. Table 1 summarises the number of stations, the common period used in the analysis and the number of groups with similarity, R_{ij} greater than 0.65.

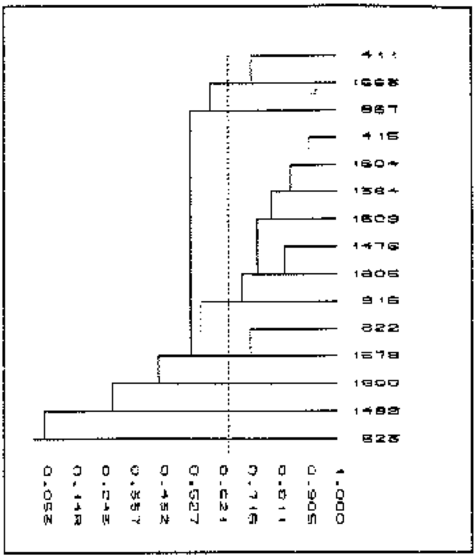

Fig.2. Dendrogram for Region A

Table 1. Number of stations, common period and number of groups based on similarity greater than 0.65 for each region.

REGION	No. of stations	Common period	No of groups
A	15	1972 - 1989	7
B	15	1973 - 1990	8
C	14	1973 - 1990	9

We note that one group comprise the six stations: 415, 916, 1364, 1476, 1604, 1605 and 1609. These stations are all on the upper Otta River. If one or more stations are to be closed down, stations should be preferably selected who belong to a group with more than one member. The decision of which station within a group that could be closed down will depend on additional information such as: the record length, data use, basin characteristics, cost of operations and the quality of the data. Groups formed by one station only may indicate that the data collected at the station is erroneous, but can also indicate that the station belong to a different regime, and therefore should be kept operating.

CONCLUSIONS

The hydrological regime in Norway is highly variable even within regions of limited extension. Although many series are available the requirement of at least 51 stations within an homogeneous region makes the HYNET-approach unfeasible unless it can be modified to operate for a heterogeneous set of series. The mean annual runoff is neither the most important statistics in many actual design cases. The NAUGLS-method utilises the mean annual precipitation which is difficult to assess in the mountaineous part of Norway and requires some alternative basin characteristics. The cluster method can be applied to smaller data sets and does not require as long series as the HYNET-method. It has the disadventage of not being able to indicate how the station network can be redistributed. The cluster method seems to be the most promising of the techniques attempted in this study and will be added to the set of operational tools for the staff responsible for managing the networks.

FURTHER WORK

Another tool applicable to station network analysis is Kriging, (Villeneuve & al,1979). This approach is also examined at the USGS and will be explored in the work of the Nordic working group. The NAUGLS technique will be explored further when more software is available from the USGS. Use of data from meteorological networks will also be considered testing methods for integrated network design.

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CONTINUOUS WATER QUALITY MEASUREMENTS

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ABSTRACT

Measurements of rain, dust fallout from air, dust amount on a surface and discharge from a $270\ m^2$ big urban surface to a single outlet were performed. Turbidity, temperature, Ph and conductivity was measured immediate in the effluent water, just beneath the grid of the gully-pot. The resolution during storm events was 10 sec and the measurements were conducted continuously over more than 6 months, in 1991.

God relations were observed between rain intensity, flow and turbidity in single storm events. A first flush was apparent in many storms.

INTRODUCTION

Measurements of quality parameters in stormwater by means of turbidity, pH, conductivity and temperature are going on at the Department of Water Resources Engineering at the University of Lund.

Continuous runoff quality measurements with god time resolution are needed to increase the understanding of the processes going on at the urban impermeable surfaces due to accumulation and migration of pollution to the urban stormwater system and receiving water.

Modelling urban stormwater pollution discharge is not a simple task, however. A number of research efforts has been done on this item, but the success was not revealed. This is probably because the accuracy and time resolution of data used in these attempts were not good enough to reveal the involved processes. Therefor the collection of data with sufficient resolution in time, space and concentration levels is a necessity.

The factors governing the processes are probably many, e.g. flow, rain intensity, rain duration, traffic, prevailing climatic conditions, duration of dry period, slope of the surface, the extent, slope and condition of the urban stormwater network etc. An practical approach may be that the number of factors is minimized and the measurements simplified. This may give possibility to discover any deterministic relations except observed stochasticity.

The choice of turbidity as an quality parameter is related to the fact that it is rather simple and cheap to measure continuously, although it is a quality parameter of second order. However, it is possible to relate turbidity to first order parameters such as BOD and COD

(Merchandise and Legendre 1987).

The time resolution of measurements must be much less than the time of concentration (t_c).

OBJECTIVE and METHODOLOGY

The aim of the measurement program was to: a/ discover the factors governing the process off pollution accumulation and migration on the urban surface, as well as wash-off to the urban drainage system, b/ give a mathematical model, and c/ create a database with respect to quality in urban storm water.

By monitoring some simple quantities with god time resolution and in a well defined area, some deterministic relations should be possible to prove if there are any. In a more complex system such as a drainage network pollution wash-off would appear stochastic behavior, mostly due to our inability to sort and classify the most important quantities and to find governing relationships.

By choosing a small parking lot and measure the quality parameters as named above, many problems were circumvented and the number of factors to take into account was reduced. Additionally, the expenses of equipment could be kept low. If it is possible to evaluate the factors governing the process of pollution release and model this from such a small and simple area, we could proceed further, and in the next stages gradually reveal the relations in a more complicated system.

Measurement of the suspended solids in the outlet of a small well defined area, the pollution accumulation on the surface, the rainfall over the surface and the discharge of the outflow is a god starting point towards the development of pollution model from urban areas. In order to enable estimation of the mass balance and the influence of the weather conditions, the measurements should be carried on continuously during at least one season.

MEASUREMENT PROGRAM

The measurement program started in the late spring 1990 but was interrupted in the autumn depending on inconsistency of results. This was probably due to bad performance of the measuring box and a raingauge with too low volume resolution of the rain measurements. Large fluctuations of the turbidity were caused by air bubbles entering the turbidity measurement compartment. The measuring compartment was to large which caused dilution of turbidity content present in incoming water. The design of the measuring compartment and the geometry of measurement was changed several times until above mentioned problems were solved. The program recommenced in late spring 1991.

Quantitative and qualitative parameters by means of runoff, rain resp. turbidity, pH, conductivity, temperature in the effluent water, wet and dry fallout and dust accumulation on the surface, was measured during a period of a half year with start from the early summer

1991.

Turbidity, pH, conductivity and temperature was recorded by probes installed in a special designed measuring box (se fig.1) which in turn was installed in a bigger box (see fig.2 and Falk and Niemczynowicz 1979) placed in a gully-pot forming the outlet of a 270 m^2 parking lot (se fig.3). The runoff was measured by means of a v-notch weir in the bigger box. The rain was measured by two tipping-bucket raingauges.

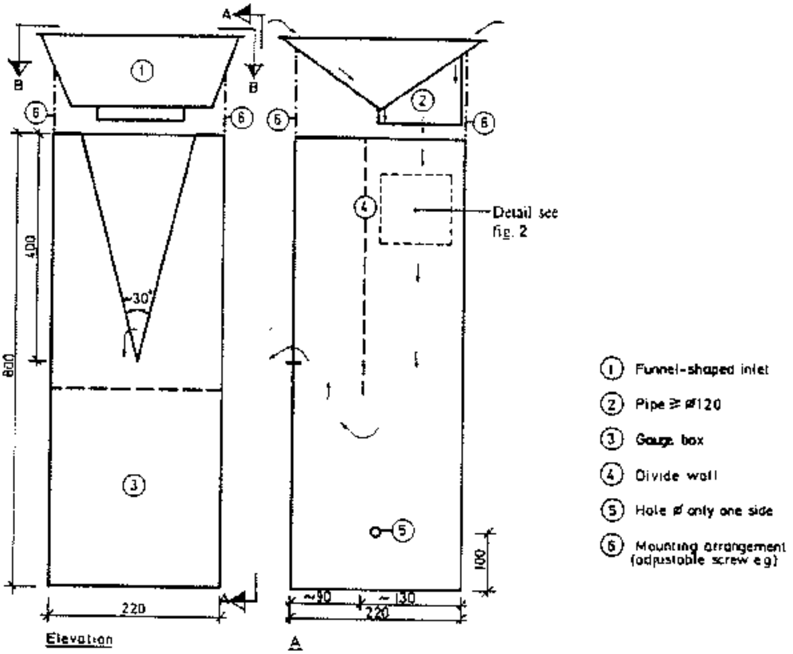


Figure 1. The gully pot gauge.

The time resolution was 10 seconds during a storm when all data from the instruments where scanned. Between the storms, the instruments were only red once an hour just to check the accuracy of the equipment. Records started after less than 0.035mm of rain and stopped half an hour after the last indication from a raingauge.

Wet and dry dust-fallout was collected in a plastic box placed 2m above the ground, the box was rinsed once a week with distilled water, which was filtered and thereafter the filter was dried (110°C, 2h) and balanced.

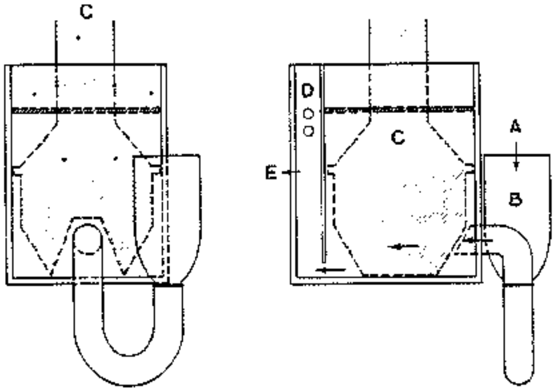


Figure 2. Front and side view of the small box containing the quality probes.
Legend: A Inlet; B Buble trap; C Turbidity probe; D Place for the pH, Conductivity and temperature probes; E Outlet.

The amount of dust on the surface was also estimated by vacuumcleaning on special marked spots on the surface. The spots consisted of three squares $1m^2$ in size and one line 20m in length (see fig.3). Vacuum cleaning was done twice a week during the period and the dust collected in normal dust filter bags, performed for vacuum cleaning. The bags were only dried in 50°C and balanced, then stored, in case of an eventual future chemical analyze. The surface dust collection was only possible during dry weather, if the surface were wet we skipped this occasion and had to wait for the next opportunity in the scheme.

INSTRUMENTATION

Quantity measurements

Flow was registered by means of a V-notch weir in the box installed in the gully pot (see fig.3). The level over the weir was measured by a displacement transducer (type GYTL/TLC-07 manufactured by Sankyo, Japan) with very high accuracy and reliability. Precipitation was measured by to tipping buckets (type PLUMATIC, 0.2mm/tipp resp own construction see Niemczynowicz 1984, 0.035mm/tipp) placed in the immediate vicinity of the drainage area.

Quality measurements

Turbidity was measured by a turbidimeter with an immersible probe (type CSP-A resp. IT-500 manufactured by CERLIC, Sweden). Measurements of conductivity, pH and temperature (type LF219, pH-219 manufactured by WTW, Germany, thermoelement type-K resp.) was accomplished to.

Wet and dry fallout was collected in a plastic bucket with an opening area of 0.0314 m^2 (type SF1, NILU, Norway).

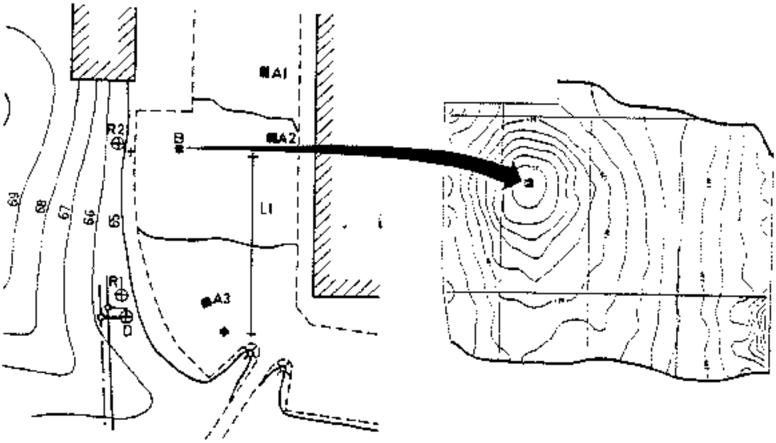


Figure 3. Map of experimental area and the area with it's contour lines and watersheds.
Legend: A1-A3,L1 Dust collecting areas; B Gully-pot; R1,R2 Rangauges; D Air dust collecter.

The measure box was constructed to ensure that the first discharge was conveyed straight to the probes by a small by-pas tube connected to the small box from the inlet.

Data acquisition

All data were stored to a central unit a datataker (type DT500 manufactured by Data Electronics, Australia). The datataker were storing and governing the acquisition of the data from all electronic instruments. With a memory workspace of about 100,000 measurements. This way of collecting data ensured absolute synchronization of time. The time was also punched together with the data, from a real time clock within the datataker.

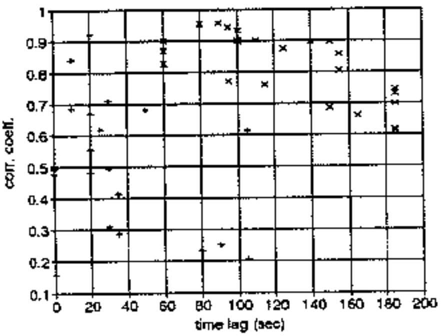
DATA PROCESSING

The data was regularly emptied from the datataker directly to a computer in an ASCII format, for storing and further processing. Much effort has been devoted to data processing since the information forms a very big database (nearly 9 mb from 1991 only). The rain storms bigger than 5 mm of precipitation have been processed on event basis, but the processing proceeds, to comprise continuously measurements i.e. processing events in a succession basis.

The data was treated by regression analysis. Correlation coefficients were determined between rain intensity, temperature, pH, conductivity, flow and turbidity. Lag cross-correlation were also calculated for rain intensity versus flow and turbidity in the same storm events (see fig.4) resp. flow versus turbidity (see fig.5).

RESULTS

A first flush is clearly prevailing in many events. This observation is done in storms mainly depicting high intensities with relative short duration. Lag cross correlation graphs for five selected storm events are showed in fig.5. They depict a well gathered maximum around the mean of 60 sec. of time lag i.e. maximum of turbidity occurs 60 sec. before maximum of the flow. This is also clearly obvious in the fig.6 depicting the whole storm in one selected event.



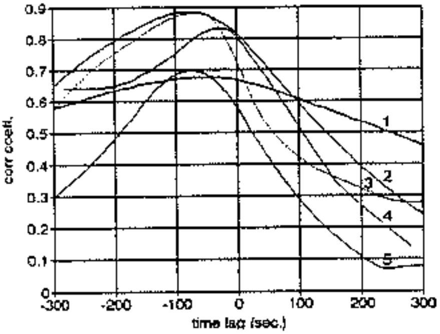


Figure 4. Maximum lag cross correlatioin coefficients from 24 events. Rainintensity versus turbidity (+) resp. discharge (x).

Figure 5. Lag cross correlation curves for 5 selected storm events.
Legend: 1-5 Storm events 910807,910719,910619,910614 and 910816 respectively.

Cross-correlation between rain intensity versus turbidity resp. discharge gives a rather well defined picture of the time lag between the quantities (se fig.4). The time sequence of the peeks occurring within a storm event is: rain intensity, turbidity discharge. The two latter occurs in average around 35 sec. respective 126 sec later than the peak of rain intensity.

An interpretation of the above succession regarding the three quantities is that the first part of the flow remove the most pollution from the surface and transport it to the outlet.
Another explanation is that the energy from raindrops erode and lift up the dust particles and make it possible for the flow to convey them further. Which wouldn't be the case if only the flow was apparent. The latter interpretation is implied by the observation that there can be

several turbidity peaks in succession when there are several peaks of rain intensity (see fig.6).

Dust fallout seems to have small influence on the total amount of dust on the surface, regarding chemical compounds and substances it hasn't necessarily to bee so. This imply that the accumulation occurs by different mechanisms on different levels.

Good correlation was found between rain intensity, flow and turbidity. Weak or very weak correlation was found among pH, conductivity and temperature also versus the former quantities.

The time synchronization was of utmost importance to detect and prove these relations and so was the time resolution. It may be for example concluded that measurements performed with time resolution of 1 minute or more, would not reveal time sequential dependence between peaks of rainfall, runoff and turbidity.

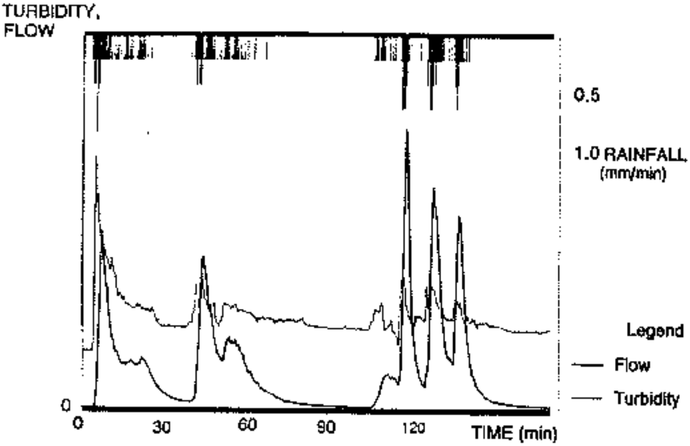


Figure 6. A single rain event (event 910816).

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A NEW DATABASE SYSTEM FOR HYDROLOGICAL DATA IN NORWAY

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ABSTRACT

A new database system for hydrological data is being developed at the Hydrology Department of the Norwegian Water Resources and Energy Administration. The system has the ability to handle long time series with variable resolution in space and time. Although the main purpose is to store data from the Norwegian national monitoring networks of hydrology, the flexible structure will enable handling of other environmental data as well. The database comprises mostly observed data stored in a format suitable for data with high time resolution. Some derived data, mostly daily values after corrections and infilling of missing values, will be stored as well as algorithms for calculation of derived data from observed values. The data model links all data to geographical locations. All data may be referenced by UTM-coordinates or the indices of the Norwegian Water Information System. A vital part of the data processing is quality control by interactive and automatic methods. All data will be flagged to show the control level they have been subject to.

INTRODUCTION

The Hydrology Department of the Norwegian Water Resources and Energy Administration (NVE) is responsible for operating the national monitoring networks of hydrometry, snow, glaciology, sediment transport, ice and water temperature. Groundwater levels are observed in a network owned jointly by the Norwegian Geological Survey (NGU) and NVE. A small network of soil moisture monitoring stations is now under development.

All historical observations of daily stages were transferred to magnetic tape at the end of the 1960s. The archive was later moved to a database system developed at NVE. The database was also extended to contain data collected in the other networks. In addition, the database at NVE contains meteorological data and data from different projects in Norway and other countries, e.g. the FRIEND-database for Northern Europe (Gustard et al., 1989). Due to plans about coordinating the activity of several institutions involved in the collection of environmental data in Norway, NVE will probably be storing several other hydrological parameters in the future, e.g. water quality data (Tvede et al., 1992).

NVE is now redesigning the database and will be using a commercially available system. The purpose of the new system is to store and perform quality control of environmental data with variable resolution in space and time. Data from the monitoring networks of NVE as well as data from other sources will be stored in the same database. The requirements of a database management system (dbms) for time series data and the tests performed in order to select a new system are described by Roald and Beldring (1991)

DATA MODEL

During the process of designing the database, modelling of data has been performed by the NIAM-method. This is a binary-relationship method which is more detailed than the entity-relationship methods (Verheijen & van Bekkum, 1982). The result of this process is a conceptual schema consisting of a group of records which are in the fifth normal form. The conceptual schema is an abstract representation of the entire information content in the database (Date, 1986). The fifth normal form implies that every field in a record is either part of the primary key or provides a single-valued fact about the whole key and nothing else, a record does not contain two or more independent multi-valued facts and the information content of a record may not be reconstructed from several smaller records. The purpose is to avoid redundant information and maintain database consistency. Normalization however tend to penalize retrieval, there is therefore no obligation to fully normalize all records when actual performance requirements are taken into account (Kent, 1983).

The conceptual schema may be implemented using different database technologies. For reasons of efficiency and limitations in the particular dbms chosen it may be necessary to adjust the structure of the database (Skagestein and Thorvaldsen, 1986). The dbms chosen for implementing the new database at NVE has the ability to reference matrices with dynamically varying length from fixed-length records. This property is normally not found in relational database systems and is considered an advantage with regard to performance and storage requirements. However, the conceptual schema could very well be implemented using a relational database system.

The central concept in the database is the station. A station is always linked to a geographical location. Data are monitored in points such as gauging stations, meteorological stations etc. Some data sampling programs monitor data in many points on well defined geographical objects, such as glaciers, lakes or aquifers and can with advantage be stored together. The system defines two types of stations, point stations which refer to one single geographical location, and area stations which refer to all the data observed for a spatially extended geographical object. Each station may own one or more time series. The series must be representative for the actual point or the upstreams catchment in case of flow data. The data can be observed or derived from other series. A station may be referenced by its primary key, by UTM-coordinates or by the indices of the Norwegian Water Information System.

Data from observations are stored in observed series. Several observed series can be linked to one station, but in general only one series for each hydrological parameter. All the data in one observed series must represent the same hydrological parameter. If two or more observed series belong to a station for the same parameter, each series will be identified by a version number. Each observed series will be divided in periods with equal attributes, e.g. the class of quality control performed.

Most of the application programs utilise time series from fixed geographical locations. These data series are in many cases identical to a series of observed data. A data series may comprise two or more series which are adjusted to define one series representative for the point of interest. Such derived series will normally not be stored in the database. The algorithm for deriving the series will be stored instead, and applied whenever the series is read from the database based on the actual observed data. Data series which are used very frequently, will however be stored on separate archives, one example of this is a database for daily data. A data series will be divided in periods, within each period the same algorithm and the same observed series is used for calculating the data series. Within each period the year may be divided in seasons to allow different observed series to be used for different parts of the year. Figure 1 shows the relationship between stations, observed series and data series.

The numbering scheme gives the keys to the stations and series in the database. The numbers follow a hierarchical pattern:

station: main drainage basin number + number within drainage basin +
point number (used for area stations)

observed series: station number + hydrological parameter + version (in case of more than one observed series with one parameter at one station)

data series: station number + hydrological parameter + version (in case of more than one data series with one parameter at one station)

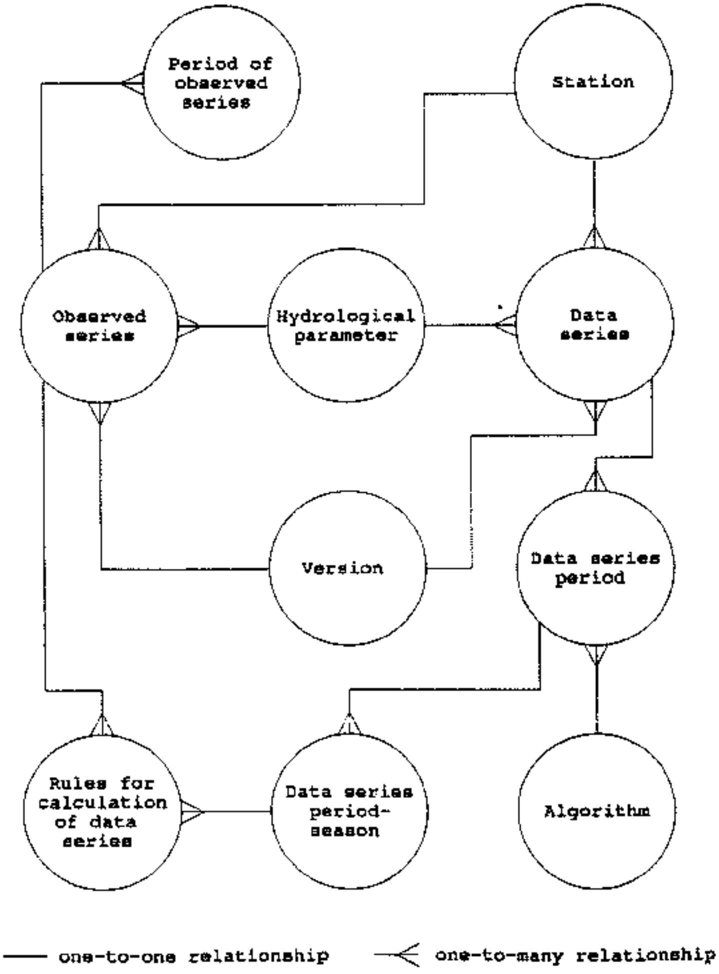

Fig. 1. Conceptual schema describing stations, observed series and data series.

DATABASES AND DATAFLOW

Information describing the stations, observed series, data series and drainage basins is stored in a database named HYSAR. It will contain all information necessary to use the observed series and data series, e.g. rating curves. HYTRAN is a transaction database where all data are stored when entering the system after collection and preprocessing of data. After primary data control has been performed the data are transferred to the database HYKVAL where the observed series are stored permanently with variable time resolution. Most of the application programs used at NVE today operate on daily data. Daily data series will be stored in a database named HYDAG, see Figure 2, which also shows the dataflow to the databases.

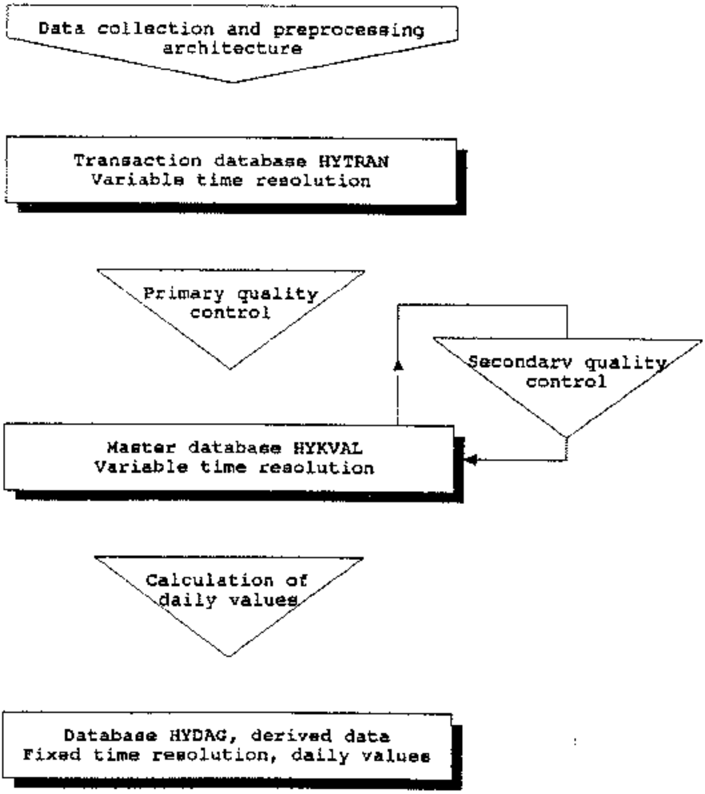

Fig. 2. Organization and dataflow of the Norwegian national hydrological database.

DATA COLLECTION AND PREPROCESSING ARCHITECTURE

NVE receives data from a wide selection of sources and data collecting systems. All systems produce data in different formats, which lead to considerable software development when new systems are put in operation. Because of the large number of data recording sites and the considerable volume of data to process, NVE has developed a new concept for collecting and preprocessing data based on a standard format for data exchange. The main purpose is to organize a system that will be operative for many years, easy to maintain and with possibilites of expansion to cover the next generation of data collecting systems based on new and more advanced technology.

The data collecting equipment in use today include both hardware and software. The software is usually only capable of retrieving data from the system itself and produce output reports of the last recording period. In order to minimize the amount of software development when adjusting to new systems and to maintain the flexibility of handling different systems, it is important to keep most of the data quality control separated from this software. The preprocessing of data before they enter the database system is organized as shown in Figure 3.

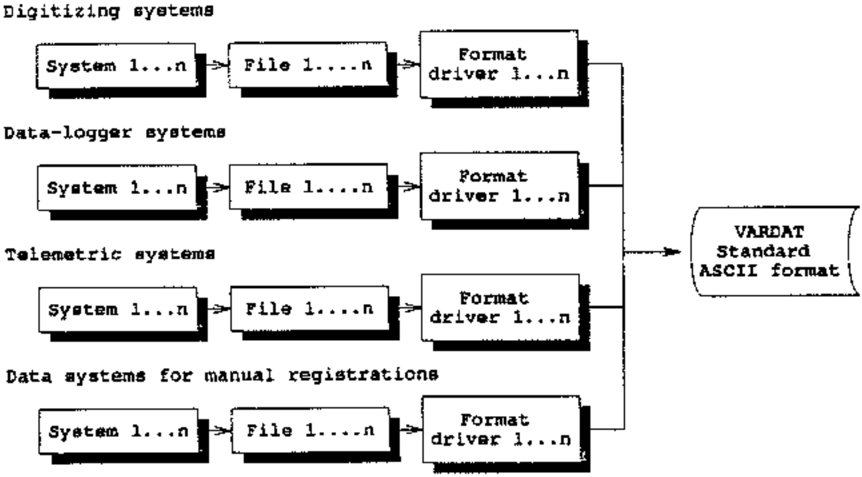

Fig. 3 Data collection and preprocessing architecture.

Data is received from manual registration systems, from digitizing systems as digitized charts, from different types of electronic data recording equipment and from telemetric systems which operate simultaneously to receive data for flood forecasting. Within these four groups of data input one has to handle several systems which all produce data in a different format. To prevent interference with the original system software, it is possible to make small software modules, equipment drivers, to process the output from different systems and convert it to a standardized data format (VARDAT). These software modules behave much in the same way as and are analogous to communication protocol drivers developed for communication between computer peripherals. They convert information from one system to another without interfering with their operation. The preprocessing which include data conversion is a tasks for front-end computer systems like workstations and personal computers.

The standard ascii file format VARDAT (VARiable DATa format) plays an important role in exchanging data between the data collection systems and the databases. It is used for storing data with fixed or variable time resolution and is developed for handling environmental data. It describes both the data structure of the collected data and the information necessary to identify the time series in space and time for quality control systems and permanent archiving. The VARDAT-files are exported immediately to the database HYTRAN for further processing.

DATA QUALITY CONTROL

Possible errors in the data should be detected at the earliest possible moment. Many important checks are made in the field or during the registration of the incoming data before it is loaded to the systems. The guidelines for these controls will be revised before the new system is put into operation. The controls comprise three classes:

- Controls during the primary data processing.
- Secondary quality control.
- Supervision of long term trends.

The primary data control and correction comprise:

- Instrument specific checks on data.
- Verification of the proper identification of stations and measured series against HYSAR and already existing series.
- Control of start and end point on charts compared to the observers notes with automatic correction if the deviations in time and level falls within narrow predefined limits.

- Automatic correction in case of errors made by the observer because of change from winter time to summer time or vice versa.
- Comparison between observed data and predefined limits for the range and the change per day.
- Visual control. Data outside the predefined range is indicated to the operator of the control program. Errors can be corrected interactively by the operator.

The initial checks are made by the drivers transfering data from the recorders into the common data format prior to the loading on HYTRAN. The remaining primary control is made by an interactive program operated by the engineer responsible for each district as data are transferred from HYTRAN to HYKVAL.

The secondary data control comprises control of the water balance within a river system with several stations by comparing daily flow data and possibly precipitation data. This control is preceeded by transfer of data from HYKVAL to HYDAG with subsequently correction for backwater effects due to ice or vegetation. This correction is done by an interactive program which utilises adjacent stations and meteorological data as background information. The subsequent control program calculates naturalised flows corrected for operation of hydropower systems prior to the control.

The long term supervision comprises homogeneity controls both on annual values and the seasonal cycle. The performance of each instrument in terms of deviations between the observers notes and the actual readings will also be recorded in order to trap systematic errors as soon as possible.

Each observed series on HYKVAL will have an attribute describing the data quality for the period covered in the current object. Each data point will in addition have a mark describing whether the data has been corrected and by which method this is done. The application programs will be able to read this information. Unreliable data can therefore be excluded from certain applications.

CONCLUSION

Data hold the key to the orderly an efficient development and control of water resources. Procedures for procession and transmission of data are a vital component in the data acquisition sequence. The efficiency of a data network is in large determined by the manner in which these procedures are developed (WMO, 1981). The new database at NVE is designed for controlling and storing environmental data with variable resolution in space and time. All data from the monitoring networks of NVE as well as data from other sources will be processed by the same system. This is necessary in order to handle large volumes of data efficiently. Since all data are stored in the same databases it will be easy to combine data from different networks in analysis and presentations.

The separation between observed series and data series is necessary to conserve the original data. Transformed data will be stored as data series. If it appears at a later time that the transformations not were correct the original data will still be available. The possibility to store algorithms for calculating data series will allow easy access to data from different transformations without having to store all these series in the databases.

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ICE-REDUCTION OF WINTER DISCHARGES

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ABSTRACT

In Finland there are about one hundred discharge observation sites, where ice disturbs the water stage - discharge relationship and normal summer rating curves give biased winter discharges. Nowadays, the correction is made graphically. The extra winter measurements thus needed are laborious and expensive. So all methods which reduce the need of measurements are valuable. One possible method is to apply both watershed models and winter rating curves to estimate winter discharges. The accuracy of these methods in simulating the discharge values were studied in 20 observation sites. The results showed that neither method is accurate enough estimating winter discharges. More work is needed especially to develop watershed models for simulating low flows.

INTRODUCTION

The discharge measurements in winter conditions are often very troublesome and unpleasant. Two or three persons, as well as money, time and brave mind in -30 °C cold, taking care that the ice is not breaking-up under feet etc., are needed in the measurements.

The costs of one measurement are about 1 500 marks and the discharge measurements in winter is two or three, so the costs are 3 000 - 4 500 marks in winter per one observation site. Thus it can be estimated that the total costs, for example in the winter 1990/1991 have been about 290 000 - 430 000 marks. These measurements must be done every year and the costs are continual and rising. To save

Fig.1. Observation sites.

both money and labour it is necessary to find out new methods to determine winter flows.

One possible method could be the use of winter rating curves and another method may be the use of watershed models. For testing the ability of these methods, 20 observation sites (Fig.1) were chosen - mostly from northern Finland. The years of 1989 and 1990 were used as test periods.

THE ICE-REDUCTION TODAY

The old and good method to do ice-reduction (Hyvärinen, 1986) is to draw an uncorrected annual hydrograph or many hydrographs of nearby stations on the same semilogaritmic paper, as well as the relevant temperature, precipitation, ice break-up/freeze-up observations and the measured discharge values (Fig.2). Then a person with a good experience of the ice-reduction draw through measured values the line that represents, preferably, the right form of the hydrograph. The corrected discharge values are read from this line and stored to the database.

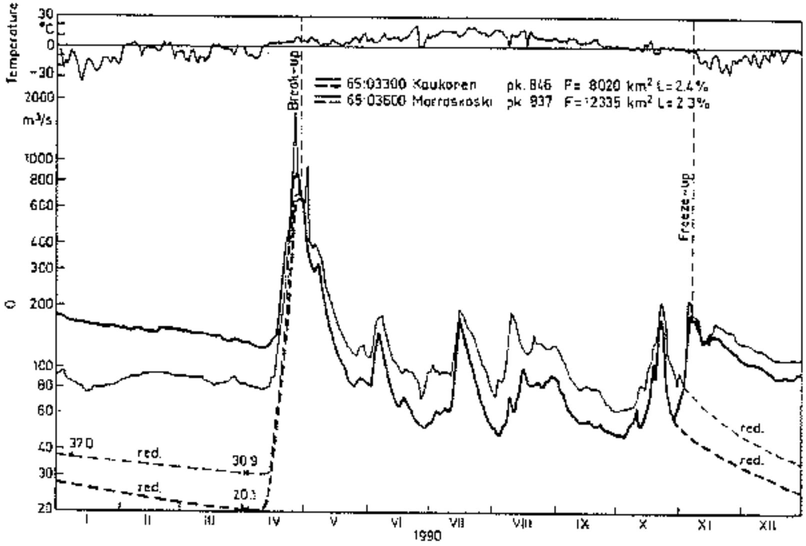

Fig.2 Graphical ice correction of winter discharge.

WINTER RATING CURVES AND THE WATERSHED MODEL

When constructing discharge rating curves the winter points gather on a quite small area and form a rather vertical line for observation sites where the ice damming is quite regular.

This line can be considered as a winter rating curve. Its typical feature is that the discharge values depend usually very little on the water level (Fig.3).

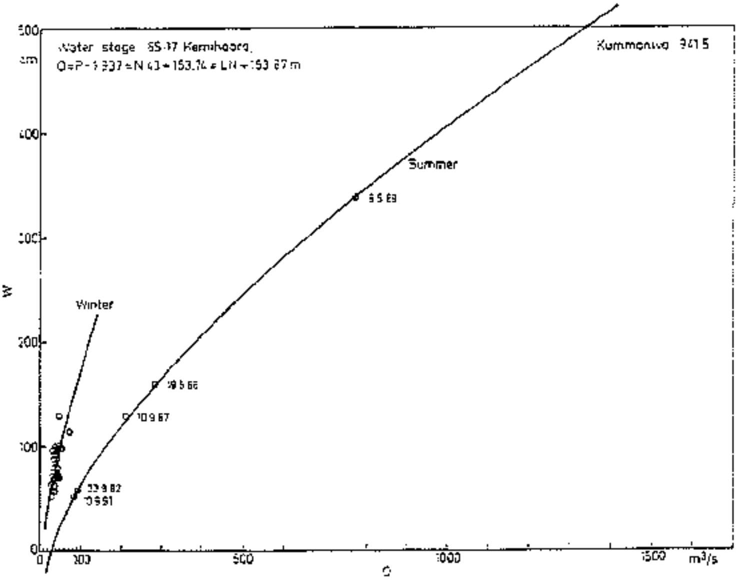

Fig.3 Winter and summer rating curves for the observation site 6501700 Kummaniva in the Kemijoki river.

In Finland an approximate winter rating curve can be drawn for about 64 observation sites. Most of these sites are situated in Lapland or in eastern Finland, but also in southwestern Finland there exist some observation sites with a possibility of a winter rating curve.

Watershed models are in operative use in real-time forecasting of discharges, especially for high flows (Vehviläinen, 1992). Low flows have been of less interest in this context. When estimating winter flows the low flows, however, are of most interest. A question arouse: are the existing watershed models suitable for this purpose?

RESULTS

The discharges calculated with the aid of the rating curve for ice-free period and the winter rating curve, values simulated by the watershed model, and the reduced values were drawn on same paper (Fig.4). It seems that the values given by winter rating curves corresponded quite well with the reduced discharges in winter and spring. Difficulties are encountered in autumn when freezing-up and ice damming starts. Then the winter rating curve does not give "right" discharge values, the estimated discharges are too high or too low, and the differences change yearly.

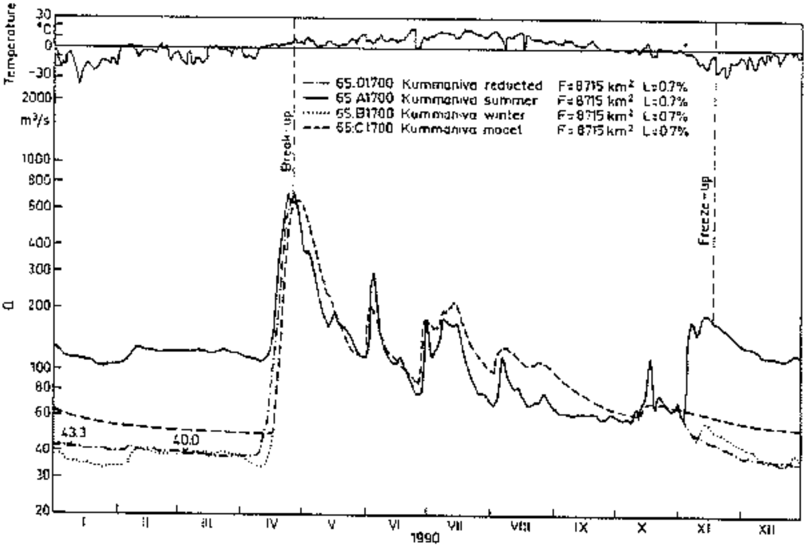

Fig.4 Discharges calculated with the aid of summer and winter rating curves, simulated by watershed model and graphically reduced discharges and measured discharges in 6501700 Kummaniva.

Results given by watershed models differ quite a lot depending on a tested site. In some cases the simulated values were quite near the supposed real values. On the other hand it seems that for the same observation site the agreement with simulated values and reduced values are different in different years. Especially the end of each year seems to be difficult to simulate by the watershed model; alike with the winter rating curve.

CONCLUSION

1. At the beginning of a year it is easy to estimate the effect of ice damming on discharge with the help of winter rating curve or by the watershed model.

2. The hydrograph given by the winter rating curve must be smoothed because a small amount of variations caused by fluctuations of water level.

3. The real problem is the end of a year, because it is difficult to know when the ice damming start to affect the discharge and because the winter rating curve or the watershed model are of little help.

4. If better discharge estimates in late autumn are wanted, it is necessary to measure a discharge immediately when the ice freezed-up and it is safe to operate on the ice. Then the right discharge is known and the estimation of discharge for the rest of the winter is easier. In early winter, however, the direct discharge measurements are usually very difficult to do.

5. The improvement of the watershed model for ice-reduction work could be get through updating the watershed model with the help of measured discharges during winter. Updating of the model before freeze-up will improve the simulation also during winter. To be effective in use an automatic updating procedure is needed. This can be developed from the existing updating model used in flood forecasting.

6. The reliable observations of freezing and ice break-up are of very great value.

7. One measurement during winter is necessary whatever method is used for the winter discharge data determination.

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VANNFØRINGSMÅLING MED DEN RELATIVE SALTFORTYNNINGSMETODE - VALG AV MÅLEINSTRUMENTER

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ABSTRACT

The paper is based on discharge measurements using the salt dilution method with sudden injection. A desription of the principle behind the method is presented together with the work involved in evaluating a suitable datalogger / computer concept for sampling and computing the measurements in the field. The final concept consists of a conductivity meter, datalogger and a pc. The computer connection provides instant screen presentation in graphical and tabular form. Further, a dataprogram is provided to convert the field measurements into discharge etc.

INNLEDNING

Den relative saltfortynningsmetode benyttet til måling av vannføring i turbulente elver er en velkjent metode.
Vi vil i det følgende bygge på kjent teori og fokusere på teknisk og elektronisk måleutstyr.
Det har de senere år kommet på markedet nye instrumenter for måling av konduktivitet, dataloggere til billige priser samt rimelige bærbare datamaskiner.
Vi vil i fortsettelsen redegjøre for våre vurderinger ved valg av måleutstyr for vannføringsmåling med den relative saltfortynningsmetode.

TEORI

Vi vil ikke gå i detalj vedrørende den grunnleggende teori, men repeterer for ordens skyld måleprinsippet.

Vannføringsmåling med den forenklede, relative saltfortynningsmetode går i korthet ut på at en kjent saltmengde (NaCl) tilføres elvevannet mer eller mindre momentant. Det betinges gode blandingsforhold med turbulent strømning slik at det oppnåes homogen blanding, i det tverrsnitt hvor konduktivitetssensor plasseres.
Konduktiviteten registreres kontinuerlig når saltbølgen passerer, slik at arealet under kurven med naturlig konduktiviet som nedre begrensning, kan beregnes.
Konduktivitet (elektrisk ledningsevne) er proporsjonal med tilsatt saltmengde innenfor de grenser for konduktivitet som vi normalt har ved vannføringsmålinger i Norge.
Vi kan dermed fremstille proporsjonen:

$M/q = A/k$ eller omgjort: Vannføringen $q = M*k/A$.

M er tilsatt saltmengde i elva i mg.
q er vannføring i l/s.
A er arealet under kurven når saltbølgen passerer der konduktiviteten fremstilles som funksjon av tiden.
k er kalibreringsfaktor som uttrykker konduktivitetsøkningen ved tilsetting av for eksempel 1 mg salt til 1 liter vann.

TILBAKEBLIKK

Ved NVE, hydrologisk avdeling har den relative saltfortynningsmetoden vært benyttet til måling av vannføring helt siden Søgnen lanserte den. Megger og elektrode ble benyttet til måling av elektrisk motstand når saltbølga passerte målestedet. Elektrisk motstand er den inverse verdien av konduktivitet og danner en ikke lineær funksjon.

I de senere år har ledningsevnemålere (konduktimeter) overtatt som feltinstrument ved NVE, hydrologisk avdeling. Måling av konduktivitet gir en tilnærmet lineær kalibreringskurve.
WTW konduktimeter, som vi har flere eksemplarer av, har oppløsningen 0-200 µS/cm for det aktuelle måleområdet, med steg på 0.1 µS/cm. Instrumentet har også innebygget temperaturkorreksjon.
Vi viser til VHO-notat 5/88, ved L.E. Pettersson : Foreløpig veiledning i bruk av den relative saltfortynningsmetoden.
Dette er en veiledning som baserer seg på manuell registrering av saltbølgen med 5 sekunds intervall og manuell beregning av måleresultat.
Ved bruk av metoden må en normalt være to personer.

AKTUELLE UTSTYRSKONSEPT

Ved bruk av logger får en hyppigere registrering av verdiene (hvert sek.), noe som øker nøyaktigheten. Man får eliminert feilkilder som feil avlesning og problemer med å få med siste desimal når saltbølgen passerer sensoren. Målingen får en bedre dokumentasjon. Målinger kan utføres av en person når dette er sikkerhetsmessig forsvarlig.

Da vi eier flere WTW konduktimetre med temperaturkorreksjon og er fornøyd med disse, ønsket vi primært å knytte en logger opp mot WTW-instrumentet. Krav til logger er at den har signalinngang 4-20 mV, loggerintervall på minimum 1 sek, har tilstrekkelig lagerkapasitet, har software for datakommunikasjon til pc og er vannbestandig.

Etter en sondering i markedet og kontakt med diverse ressurspersoner fant vi 3 forskjellige konsepter som det ville være naturlig å undersøke nærmere.

Konsept 1.

Det ville være en bra løsning å knytte et medium opp mot WTW instrumentet for å kunne lagre verdier oftere enn vi klarer å skrive. Det ville også være en fordel å få målingen beregnet, og få en grafisk beskrivelse av saltbølgen for å kunne vurdere kvaliteten på målingen.

Dette kan løses ved at en knytter WTW instrumentet til en A/D konverter og videre til en regnemaskin med muligheter for grafikk. Dette er en løsning som Bernhard Luder fra Sveits har beskrevet i et nr. av "Wasser, energi, luft", og som teknisk ikke skulle være noe problem. Dette medfører at vi må skrive et program for beregning av målingene.

Prismessig vil dette alternativet falle gunstig ut. Prisen vil ligge mellom kr 10500 og kr 26000 i totale kostnader, alt etter om en velger en programmerbar kalkulator eller en bærbar pc til logger-jobben. Vi ser her bort fra kostnader til konduktimeter og skriving av uteregningsprogram.

Konsept 2.

Dette konseptet bygger på at vi har med oss WTW instrumentet og en "ren" logger til målestedet. Denne vil kunne lagre de verdier som WTW produserer etter som saltbølgen passerer, men vil ikke gi mulighet for beregning av målingen på målestedet.

Dersom vi stiller som krav at en skal kunne ta mange målinger i rekkefølge på forskjellige lokaliteter uten å måtte tømme loggeren mellom målingene, så har vi funnet to loggere som tilfredsstiller dette:
- Squirrel loggeren er forholdsvis dyr, kr 20000. Program for databearbeidelse koster kr 3500.
- Kane-May loggeren er billigere, pris kr 8500. Dette inkluderer programvare for utlesing av data samt grafikk.

Med denne loggeren er det mulig å importere data til et regneark (lotus 123) for beregning av måleresultatet.
Bruk av logger sammen med WTW vil gjøre det lettere å operere i ekstremt vær sammenlignet med konsept 1.
Ulempen er at vi må vente med måleresultatet til vi er tilbake på kontoret til en pc.

Konsept 3.

Dette baserer seg på konsept 2 men i tillegg kommer en kraftig programmerbar kalkulator eller en bærbar pc til beregning av måleresultat i felt. Her vil en kunne logge målingene, og senere trekke seg tilbake til et egnet sted for utregning av målingene. Denne muligheten vil kunne bety mye for bruk av metoden i ekstremt dårlig vær, evt. i temperaturer mellom 0 og 10 grader C, da kalkulatorer og billige bærbare datamaskiner ikke trives så godt.
Kostnadsøkningen fra konsept 2 vil ligge på mellom 4000 og 20000 kr, avhengig av hvilken regnemaskin man velger.

VALG AV UTSTYRSKONSEPT

Før vi bestemte oss for målekonsept studerte vi spesifikasjoner og priser på loggerutstyr fra flere leverandører, blant annet Intab AAC-2, Intab målepakke, Kane-May 1410, Squirrel 1200 med flere. En grundigere gjennomgang av aktuelt loggerutstyr finnes i et internt notat som ikke vedlegges her.

Etter en totalvurdering fant vi konsept 3 som det mest hensiktsmessige til feltbruk.
Som logger har vi valgt Kane-May 1410 som har følgende sterke sider: Lav pris, lang levetid forbatteri, minne på 40k, indikator som viser ledig minnekapasitet, vekt 690 gram, kan ta flere etterfølgende måleserier uten tømming av minne.

Svake sider ved logger er: Sprutsikker men ikke vanntett, loggeren er standard hendelsesstyrt med datakompressjon noe som kan gi problemer med bruk av regneark. Ombygging til en ren tidsstyrt logger koster kr 2500.

Loggeren produserer ascii-filer med følgende format:
År, måned, dag, time, minutt, sekund, måleverdi.
Signal fra WTW-instrument til logger er standard 4-20mV.
Måleområde for logger er -1000 til 2000mV med oppløsning 1 mV.
WTW har måleområde 0 til 200 µS/cm med oppløsning 0.1 µS/cm.
Dette gir samme dataoppløsning som for WTW-instrumentet.
Det raskeste loggerintervall er 1 sekund.

Av WTW-konduktimeter benytter vi type LF 191 og LF 95 og konduktivitetssensorer type LA 1/T og Tetracon 96A.

Kjell Dalviken, hydrologisk avdeling, har laget et pc program som beregner arealet for saltbølgen (se figur). Programmet inneholder også en meny for innlesing av kalibreringsfaktor og benyttet saltmengde, slik at vannføringen beregnes.

Vannføringsmåling i Sula på Fillefjell.

Måleforhold: Bratt fossestryk like nedstrøms målestasjonen gjør den relative saltfortynningsmetode godt egnet, med aktuell målestrekkning på kun 150 m og ingen bakevjer.

To uavhengige målinger utføres der sensor plasseres ved vekselvis venstre og høyre elvebredd, ifølge instruks. Sensor er forsynt av vann fra hovedstrøm. Tilført saltmengde bør være minimum 0.5 kg/m^3/s. Vi velger her å bruke ca. 1 kg/m^3/s.
Det er stor vannhastighet og god turbulens i punktet der saltet tilføres.

Når alt utstyr er utplassert, startes WTW-instrument og logger. Tid, naturlig ledningsevne, målested, saltmengde, med mer noteres. Oppmålt saltmengde tømmes i elva og saltbølga registreres i logger.
Sensor flyttes og samme prosedyre gjenntas.

Kalibrering

Når målingene er utført, gjøres kalibrering for å bestemme kalibreringsfaktor, k.
Primærløsningen har konsentrasjonen 4000 mg salt / 1000 ml vann og volum i kalibreringskaret er 7.00 liter.

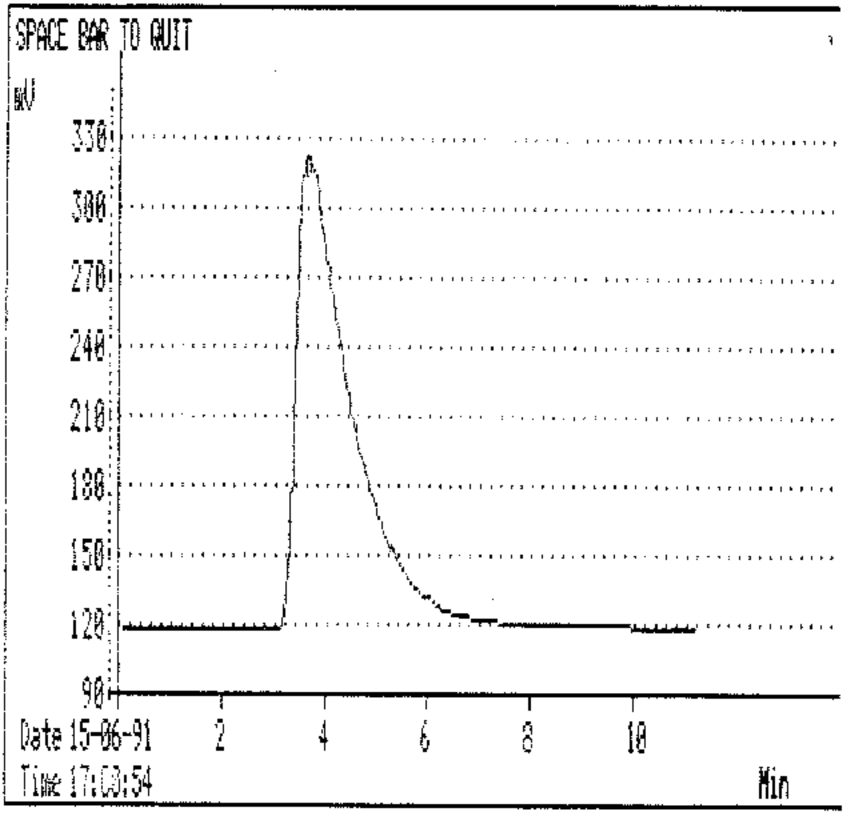
Ved tilsetting av saltløsning får vi følgende instrumentutslag:

Tilsatt sekundærløsning ml	Instrument-avlesning WTW µS/cm	Instrument-avlesning KM mV	Vann temperatur °C
0	12.4	124	3.4
10	24.5	245	3.5
20	36.7	367	3.5
30	48.8	487	3.6

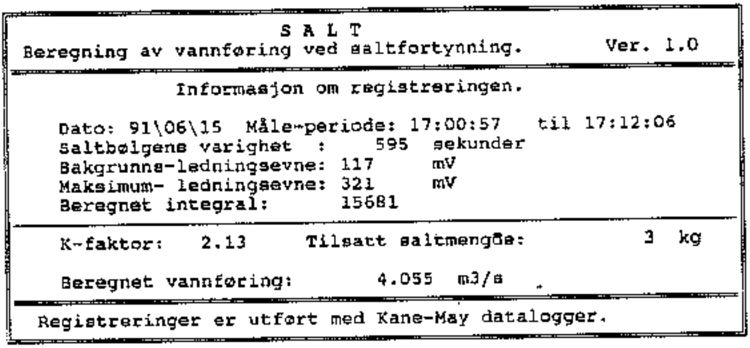
Ved tilsetting av 20 ml sekundærløsning får vi kalibreringsfaktor:

$$k= \frac{36.7\ -\ 12.4}{\frac{4000}{1.00}\ .\ \frac{0.02}{7.00}} = \underline{2.13}$$

Figuren under viser saltbølga registrert av logger.



Figuren under viser utskrift fra beregningsprogrammet.



```
                              S A L T
Beregning av vannføring ved saltfortynning.          Ver. 1.0

                  Informasjon om registreringen.

   Dato: 91\06\15  Måle-periode: 17:00:57    til 17:12:06
   Saltbølgens varighet  :     595  sekunder
   Bakgrunns-ledningsevne: 117      mV
   Maksimum- ledningsevne: 321      mV
   Beregnet integral:       15681

   K-faktor:   2.13     Tilsatt saltmengde:             3  kg

   Beregnet vannføring:         4.055  m3/s

 Registreringer er utført med Kane-May datalogger.
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Utskriften gir beregnet vannføring 4.055 m^3/s.

Vi har planlagt revisjon av beregningsprogrammet slik at vi kan opperere med flere k-verdier med forskjellige gyldighetsområder. Dette vil medføre større nøyaktighet når kalibreringskurven ikke er helt lineær for det aktuell måleområde.

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HYDROLOGICAL USE OF RADIOCESIUM FALLEN DOWN

Servo Kasi Kerava (Kervo) Finland

ABSTRACT

Radiocesium fallen down since 1945 is positioned in topsoil centimeters. In the Nordic Countries this cesium deposition magnified many times 1986 after Chernobyl disaster. Cesium-137 has been successfully used as a tracer in erosion research. Cesium-134 is also still useful. Repeatable measurement of cesium profile is presented. The gamma radiation of cesium through snow should be used for snow mass determinations. When combined with the traditional potassium-40 measurement we have the sensitive determination of topsoil moisture.

Hydrologisk använding av nedfallet radiocesium: Radiocesium fallet från 1945 har placerat sig i jordytans första centimeter. I nordiska länder blev denna cesiumdeposition mångfaldig efter olyckan i Černobyl. Cesium-137 har använts som ett bra spårämne i forskning av erosion. Också är cesium-134 ännu brukbart. Upprepbar mätning av cesiumprofil framställs. Cesiums gammastrålning genom snö skulle brukas för snösmassbestämningar. Om även strålning av potassium-40 mättes hade vi den sensitiva bestämningen av övre jordskiktets fukt.

Radiocesiumlaskeumasta on hydrologista hyötyä: Vuodesta 1945 tullut cesiumlaskeuma on deposoitunut maanpinnan ylimpiin senttimetreihin. Pohjoismaissa se moninkertaistui 1986 Tšernobylin onnettomuuden jälkeen. Cesiumia-137 on menestyksellä käytetty eroosiotutkimusten merkkiaineena. Myös cesium-134 on vielä käytettävissä. Toistettava cesiumprofiilin mittaus esitellään. Cesiumin gammasäteilyn lumenläpäisyä tulisi käyttää lumenmassan määrityksiin. Yhdistämällä tähän mittaukseen perinteinen mittaus kalium 40:llä saadaan herkkä pintamaan kosteuden määritys.

INTRODUCTION

The radioactive products of manmade nuclear reactions, fission etc., can also be utilized in industry and science (e.g. *Kasi* 1988b, 1986). It is best, they have then sealed encapsulations. Since the second world war such products have caused radioactive contamination of the earth surface. Nevertheless, the fallout materials can still then be utilized, especially in science. E.g. the radiocesium, ^{137}Cs, or ^{134}Cs – which are positioned close to the earth surface – can be used as a tracer for erosion research. Radiocesium can also be applied as a plane source of gamma-photons on the interface between the air and soil half spaces.

The atombomb explosions 1950-1965 (top 1963) caused ^{137}Cs fallout all over the nothern hemisphere. Its deposition was uniform in Finland (*Salo* 1966) and the other Nordic Countries. A good 20 years later in 1985 the soil ^{137}Cs content in Finland was 1.8 kBq/m^2. The half life of ^{137}Cs is 30.03 a.

During 1986 the total ^{137}Cs amount increased considerably in large areas of Europe and some of Asia. *Arvela* ET AL. (1987) measured that in Finland the averaged ^{137}Cs increase was 10.7 kBq/m^2, but this deposition was 1.22 in Rovaniemi, 0.32 in Sodankylä, and 0.185 kBq/m^2 still more into the north in Ivalo. The Chernobyl fallout also had ^{134}Cs component. The ratio of ^{134}Cs and ^{137}Cs activities at 1^{st} Mai 1986 was 0.57 (*Aaltonen* ET AL. 1990))). The half life of ^{134}Cs is 2.062 a.

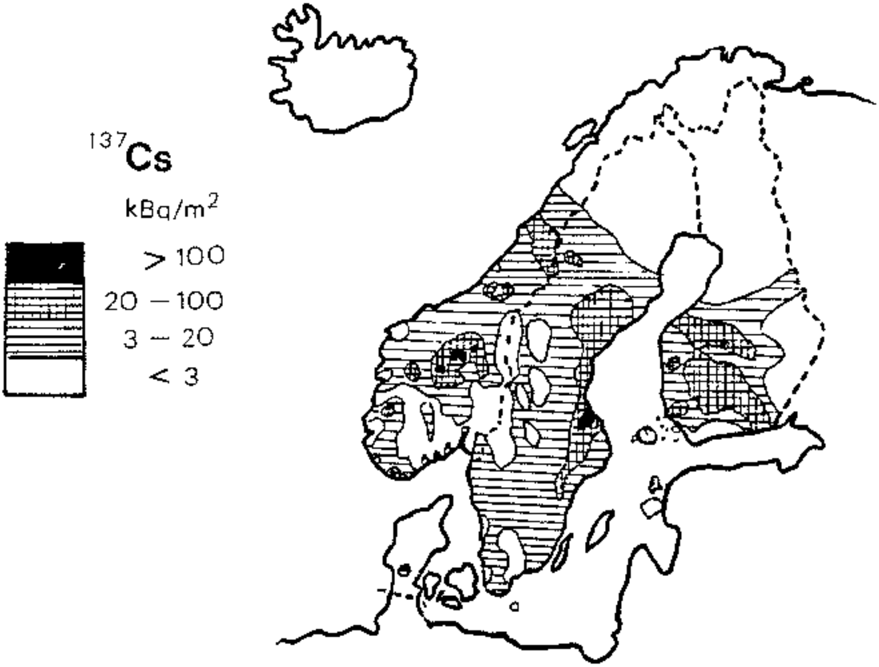

Fig. 1. **^{137}Cs DEPOSITION IN THE NORDIC COUNTRIES.**

As said, the cesium isotopes (*Riise* ET AL. 1990, *Konoplev* and *Golubenkov* 1991)) are firmly adsorbed on mineral, especially clay, and other soil particles in the first few centimeters of topsoils. They are useful for erosion, suspension and sedimentation research. The profile of radiocesium can be determined and followed nondestructively. The plane source is useful for the snow mass and the topsoil moisture determinations.

Table 1. ^{137}Cs **DEPOSITIONS IN THE WORLD**

Site	*kBq/m*^{2}
Jyväskylä, Finland	20.5
Saskatoon, Canada	2.5
Exeter, England	0.8
Newcastle, Australia	0.1

EROSION AND SUSPENSION EXAMINATIONS

In USA in the WEPP (Water Erosion Prediction Project) has been found that development of mathematical models demands a lot of new research (*Nearing* ET AL. 1990). A need is to find and minimize the risks of erosion (*Ahlström* and *Bergman Åkerman* 1990). They and *Martz* and *De Jong* (1991) are in similar ways approaching topographic patterns for fields. *Peart* and *Walling* (1986) have compared physical and chemical properties of suspended solids for revealing their sources. The properties ^{137}Cs content and magnetic susceptibility varied most for bank material, arable and pasture topsoils of the basin. But in use the information should be corrected by weighting the fines and organics, in which the suspended solids are enriched.

Detailed knowledge of radiocesium transports and distributions in the drainage basins of the deposition area may give valuable information about erosion in fields and forests, suspension transport, and sediment accumulation (*Bonnett* 1990, *Ritchie* and *McHenry* 1990). Measures for the effects of ditching, clear-cutting and road-building can be obtained. Data have been collected, applicable to determine the patterns of correlation between suspended solid and phosphorus loads (*Hasholt* 1990, *Rekolainen* 1989, and probably, the others).

The ^{137}Cs and ^{90}Sr transfer in the catchment areas of the rivers Pripyat, Uzh and Braginka flowing through the Chernobyl 30 km zone were swiftly investigated in 1986, but accurately enough, to give useful relevant information for prognoses of the flux and concentration of the nuclides in these rivers (*Borzilov* ET AL. 1989, *Vakulovski* ET AL. 1991).

Kansanen ET AL. (1991) have started the research of accumulation of radiocesiums on the bottoms of the large lake Päijänne and three other lakes in the Finnish deposition area. Calculated ^{137}Cs concentrations of Päijänne water fit experimental when 25 % of ^{137}Cs is assumed soluble (*Korhonen* 1990). *Saxén* (1990) has continued determination of ^{137}Cs fluxes, e.g., in the mouths of the five largest river basins of Finland. Cesium transport with water in the head parts of Finnish catchments has so far had few sporadic observations. Some I presented in NHK-88 in Rovaniemi. Geologists since 1989 and 1990 all over Finland in about 1200 small headwater basins have taken systematically samples of bottom mud, outflow and soil. I have proposed analysis of ^{137}Cs and ^{134}Cs in these samples. For instance, the ratios of concentrations of these nuclides in the samples of bottom mud – from main brook or from tributaries – may vary, because the ages of the muds are different. Preliminary analyses in the Kuopio University, by *Raunemaa* (1992), have given results to this direction.

By "ion-change" solvents and other processes possible in the nature *Riise* ET AL. (1990) extracted from seven topsoils of the Central Norway only 18 %, but by 7n HNO_3 51 %, and 31 % on the average dissolved not at all. ^{137}Cs in soil in practice has the conditions of the stable ^{133}Cs. Also in bottom-sediments radiocesium is fastened tightly (*Konoplev* ET AL. 1992). What is the influence of baseflow run-off in the bead erosion.

In WEPP, for detachment, entrainment, deposition and sediment delivery of water catchments with sheets and rills, *Nearing* ET AL. (1990) have steady state models. For those the dynamic models of hydrological events are adapted by rough means. Certain dynamic models of erosion there are. *Begin* (1985) has used a diffusion equation for channel processes. The PULS-model and stochastic MCFP-model, applied by *Kämäri* ET AL. (1990) for acidification research, seem interesting.

It is still possible to determine the portions of ^{137}Cs from atom bombs and that from Chernobyl by means of ^{134}Cs from Chernobyl. Even small quantities of radiocesium tells from origin of the deposited sediments, that may be under new ones (*Bishop* ET AL. 1991).

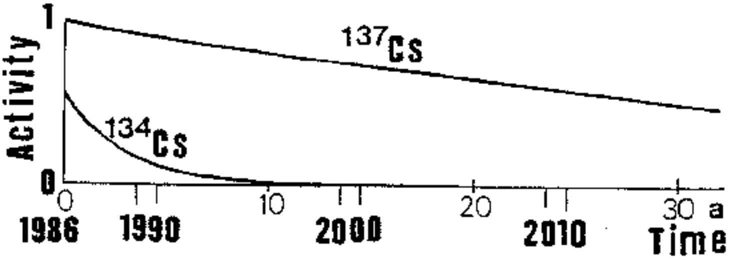

Fig. 2. RELATIVE ACTIVITIES OF CHERNOBYL RADIOCESIUM NUCLIDES.

INVERSION DETERMINATION OF VERTICAL RADIOCESIUM PROFILE

The conventional method to determine the vertical distribution of nuclide in soil or rock is to take vertically sequential samples of certain extent and thickness, and analyze them as to the nuclide. The content (Bq/kg) of radionuclide is usually obtained very accurately. However, the sample thickness may have a very large relative error, then causing the nuclide content (Bq/m²) of the soil layer has at the least the same relative error. When separating samples one destroys the profile.

The first determinations of vertical radiocesium distributions in some soils by inversion method I have described (*Kasi* 1988a, 1988c) and presented calculation details (1992).

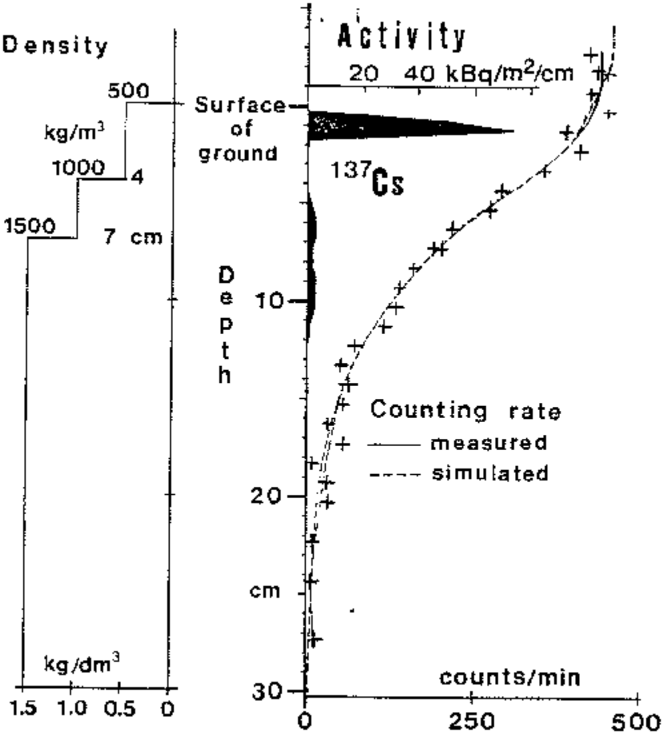

Fig. 3. **INVERSION DETERMINATION OF ^{137}Cs-PROFILE IN LAMMI, FINLAND** SUMMER 1987. LEFT THE ROUGH DENSITY PROFILE APPROXIMATION USED IN CALCULATION.

SNOW COVER MASS MEASUREMENTS

The angular distribution of the uncollided "photopeak" γ-photons at the earth surface is profile-dependent. Their number radiance (in the direction r^0, see Fig. 4) can be written

$$I(\mathbf{r}^0) = \frac{dN}{dA\ d\Omega} = \frac{1}{4\pi}\int_0^{\infty} q(z)\ dz\ \exp\Big(-\int_0^z \mu\varrho_e(z')\ dz'/\cos\theta\Big). \qquad (1)$$

dN is the number of photons that go through the element dA of soil surface in the solid angle $d\Omega$, when $q(z)$ is the emission rate of photons at the depth z. μ is the mass attenuation coefficient. The assumption that radiocesium forms a surface source $q = q_{Cs}\delta(z)$ leads to the direction-independent radiance

$$I_{Cs} = \frac{q_{Cs}}{4\pi}. \qquad (2)$$

In mineral soil or rock touching the earth surface we can have the homogeneous potassium photon source (q_K) and soil density distribution. Then the radiance from (1) obeys

$$\begin{aligned} I_K = \tfrac{\cos\theta}{4\pi}\textstyle\int_0^\infty q_K \exp(-\mu\varrho r)dr &= I_0\cos\theta, \\ I_0 &= \tfrac{q_K}{4\pi\mu\varrho_e}. \end{aligned} \qquad (3)$$

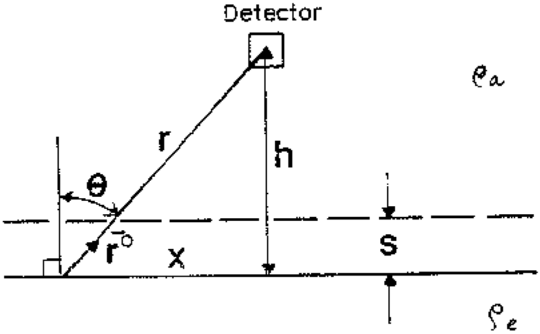

Fig. 4. PRINCIPAL OF CESIUM SNOW COVER MEASURING

The counting rate of the detector depends of detector type, cross section $A(\mathbf{r})$ and efficiency $\eta(\mathbf{r})$, where $\mathbf{r}$ is the distance from the emission point at the ground surface. The product

$$D(\mathbf{r}) = \eta(\mathbf{r})\ A(\mathbf{r}) \qquad (4)$$

can be called the detector function. If the detector has cylinderical symmetry, the absolute value r and an angle θ from the symmetry axis (Fig. 4) are the sufficient coordinates of the detector function, as above for $I(\mathbf{r}^0)$ in Eq. (3) (and 2). Snow cover has the water equivalent s. Then at the height h above the ground the uncollided photons cause the counting rate

$$R = \int_h^{\infty} \frac{D(\mathbf{r}^0) I(\mathbf{r}^0)}{r^2} \exp(-\mu\varrho r)\ 2\pi r dr, \qquad (5)$$

$$r^2 = x^2 + h^2, x dx = r dr,$$

$$\mu\varrho r = \mu_a\varrho_a(h - s)\sec\theta + \mu_w\varrho_w s\sec\theta. \tag{6}$$

If we have a plane photon source at the depth d then we can include the influence of the soil layer above it by including the term $\mu\varrho_e d\sec\theta$ in the right side of Eq. (6). $\mu_a\varrho_a$, $\mu_w\varrho_w$ and $\mu\varrho_e$ are the products of mass attenuation coefficient and density for air, water and earth, respectively. *Kasi* (1988d, 1992) has investigated the ground influence by this kind of calculation. They show that the measurement is very sensitive to changes of radiocesium distribution in soil.

Measurements can be made by flying, using terrain tops, or when the detector is at certain place, or is driven, at the height of about one meter. *Kasi* (1988a,1988c) presented two measurements in the last case. The IAEA (*International Atomic Energy Agency* 1991) has recommendations for the height of airborne measurements. In the *Kasi* (1988a, 1988c) results, for the scatter of Lammi points — those of Padasjoki do not scatter, measured on the former gravel road — the most probable error of points is weak (manual control) stability of pulse heights.

TOPSOIL MOISTURE BY Cs- AND K-RADIATION

The intensity of the airborne natural radiation, i.e. the flux of γ-photons emitted mainly by ^{40}K, ^{214}Bi and ^{208}Tl everywhere in soil and rock, varies when the topsoil moisture changes.

Let us assume varying but homogeneous moisture of soil. The I_0 of Eq. (3) is proportional to $(\mu\varrho_e)^{-1}$. If the moisture of soil (dry density ϱ_s = 1500 kg/m^3) increases from 0 to 200 kg/m^3 (13.3% by weight) then

$$\mu\varrho_e = \mu_s\varrho_s + \mu_w\varrho_w \tag{7}$$

increases (μ_s and μ_w for dry soil and water are given in Table 2 at two energies) and counting rate (Eq. 5, where $s = 0$) decreases μ_w/μ_s times more, that is 14.9%.

Table 2. **MASS ATTENUATION COEFFICIENT IN 10^{-3} m^2/kg FOR TWO PHOTONS**

Matter	661 keV (^{137}Cs)	1461 keV (^{40}K)
dry soil	7.67	5.23
water	8.57	5.84
air	7.71	5.26

Because the radiocesium deposition is near by soil surface, but the ^{40}K profile is constant or, in humic soils, the potassium content increases with the depth, and because the attenuation of coefficient of ^{137}Cs photon 661 keV is clearly larger than that of ^{40}K photon 1461 keV, then by measuring counts in windows of both these nuclides we can determine the moisture in the soil layer just below the soil surface in the addition of water equivalent of snow cover.

We take an example. We assume varying but homogeneous moisture of soil. The ground is covered by snow with equivalent water height s. The ^{40}K and ^{137}Cs photon radiances from the ground are as (2) and (3). In airplanes there has been used the package of several rectangular scintillators. For the detector, with the area A downwards, we (omitting the complicated effect of airplane lower parts) have

$$D = \eta A cos\theta = D_0 \cos\theta \tag{8}$$

for photons arriving direct from the ground in the angle θ to the vertical.

Table 3. VALUES OF AN AIRCRAFT DETECTOR. $A = 0.30\ \mathrm{m}^2$

Energy/keV	*Efficiency*	D_0/m^2
661	0.72	0.22
1461	0.45	0.14

When the airplane is at the height h, we can write (5) into the form

$$R = \int_0^\infty \frac{D(\theta)I(\theta)}{r^2} \exp(-\mu_i \varrho_a r)\ 2\pi x dx, \tag{9}$$

$$\mu_i = \mu_a + (\mu_w \frac{\varrho_w}{\varrho_a} - \mu_a)\frac{s}{h}, \tag{10}$$

i= c (Cs) or K, and the subscript a denotes the air. The solution of (9) is

$$R_{Cs} = 2\pi D_{0c} I_c E_2(\mu_c \varrho_a h), \tag{11}$$

for the cesium photons, and

$$R_K = 2\pi D_{0K} I_0 E_3(\mu_K \varrho_a h), \tag{12}$$

for the potassium photons.

From the results R_{Cs} and R_K the water equivalent and surface soil moisture (using equations (11) and (12); the functions $E_n(x)$[1] of these equations are easily calculated numerically) or other relevant quantities are solved with good accuracies.

Let us assume $h = 50$ m, use the values of tables 2 and 3, and assume that the dry soil has the potassium content 2.1%. Then the soil of density 1500 kg/m^3 has the 1461 keV photon emissivity 103 k/m^3. The ^{137}Cs activity we assume 30 kBq/m^2. On the ground surface we have the cesium photon (661.6 keV) radiance $I_{Cs} = 2030$ m^{-2}s^{-1}sr^{-1}. I have calculated the counting rates of these photons when $s = 0$ and 100 mm (= H$_2$O kg/m^2) and $\varrho_w = 0$ and 200 kg/m^3.

Because radiocesium is some inside in soil the counting rates of cesium photons should be smaller than in Table 4. Therefore also the soil moisture influenses in the ^{137}Cs counting rates. However, the principal difference between the cesium and potassium photon counting rates prevails decades ahead.

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[1] $E_n(x) = x^{n-1} \int_x^\infty \frac{e^{-t}}{t^n} dt = \frac{1}{n-1}[e^{-x} - x E_{n-1}(x)]$

Table 4. Calculated counting rates. s is the snow cover thickness, ϱ_w soil moisture

s (mm, kg/m^2)	0		100	
ϱ_w (kg/m^3)	0	200	0	200
R_K (s^{-1})	295	256	112	97
R_{Cs} (s^{-1})	919		251	

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USE AND AVAILABILITY OF DIGITAL GEOGRAPHICAL DATABASES FOR HYDROLOGICAL MODELLING

A SURVEY FOR THE NORDIC COUNTRIES

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ABSTRACT

A summary of the answers to a questionnaire covering the use of digital databases for hydrological and hydrochemical modelling in the Nordic countries is given. Present and planned activities are described, in the context of promises and difficulties with introducing of GIS and remote sensing into hydrological modelling. A review is made of the availability and use of relevant geographical databases, including information about meteorological, geological, land use, point sources, water in soil and ground, and surface water parameters. The used equipment and models are also given.

INTRODUCTION

A geographical information system (GIS) can be used as a tool to integrate and analyse spatial information relevant to hydrological and hydrochemical processes. The spatial information can consist of digitised maps or by remote sensing data. The information can include spatial parameters such as topography, soils and vegetation, and variables such as precipitation, snow accumulation and atmospheric deposition of various substances. Integration of GIS and hydrological models gives a possibility to relate spatial and temporal variability of hydrological processes to the heterogeneity of the landscape mosaic.

Internationally, the use of GIS as a tool in hydrological modelling is an expanding area, although, most publications still seems to be more method-oriented than result-oriented. The first large international conference, fully dedicate to this field will be held in spring 1993 (Hydro-GIS in Vienna). The potential of integrating GIS and hydrological models is much discussed in the Nordic countries. Most research groups are, however, still in the planning phase, and there is a need for co-ordination and exchange of ideas. The use of GIS-systems is widely spread among data-producers. Many have started by developing their own in-house systems, and gradually in-quite well spread among data-producers. Many have started by developing their own in-house systems, and gradually increased the use of public domain systems. It seems, in general, that the GIS-competence in areas related to hydrology is concentrated towards using the technique for mapping purposes and not so much for modelling.

A Nordic working group was established within the NHP-programme (1991-1992), with the aim to investigate the present availability of GIS-systems among those producing data-bases relevant for hydrology, and among users of hydrological models; the availability of digital geographical data bases relevant for hydrological modelling; and the present use of GIS in connection with hydrological modelling. This paper gives a brief summary of the Nordic state-of-the-art within this field, based on questionnaires. The questionnaires were sent to relevant governmental authorities, universities, county and municipality administrations and a few private companies. Full national reports will be presented in a NHP-report in connection with a workshop about GIS and hydrological modelling that will be held in Linköping, Sweden in November 1992. The final report will also contain relevant literature references, which not yet are put together.

GIS IN USE

Denmark

The main users are governmental institutes, dealing with mapping and data collection in the fields of soil resources, geology and hydrometry at Dept. of Land data (ADK), Danish Geological Survey (DGU), and Hydrometrical Survey (HU). Within these institutes, there is an extensive use and much experience within the field of GIS. All uses systems developed by themselves, which at DGU and HU are complemented by systems from the public domain (mainly Arc/Info and Intergraph). The used GIS are all vector-based. There are both plans for further development of inhouse systems and for an increased use of commercial systems. The use of GIS within water resource responsible authorities varies from many years of experience to none. There is an increasing use of commercial systems as Arc/Info and MapInfo. DHI (Danish Hydraulic Institute) and VKI (Water Quality Institute) uses Arc/Info. At DHI there are also plans on starting to use Intergraph.

Finland

The main GIS users in hydrology-related fields are the National Board of Survey and the National Board of Waters and the Environment. The main software used consists of FINGIS, Arc/Info and UNIRAS. The hardware consists of VAX, DEC and HP APOLLO mainframes and workstations. The FINGIS software is developed in Finland.

Iceland

Within the municipal technical divisions of Reykjavik (engineering, planning, water and geothermal heat distribution, local PTT), and the engineering firm Hnit Ltd., specialised in map production, Arc/Info is used. For the moment (April-October 1992) Arc/Info is being tested at the National Energy Authority (Orkustofnun) for hydrological and geological purposes. Intergraph is in use at the State Town Planning Department, at the Agricultural Research Institute, and Hnit Ltd. The Nordic Volcanological Institute has been using Genasys.

Norway

The most used software is Arc/Info, mainly run on PC's. The Norwegian Institute of Land Inventory (NIJOS), the Norwegian Geological Survey (NGU), and the Norwegian Water and Energy Authority (NVE) uses workstation-based Arc/Info. A few are also using Intergraph, IDRISI, and image processing systems, such as ERDAS and IIS. NGU and NIJOS have large experience within the field. The competence seems to be good also at Statkraft and the Department of Geography at the University of Trondheim. NVE started an extensive development within the field during 1991, and do now have a group of 5-10 persons that uses GIS.

Sweden

Dominating trades are Arc/Info and MapInfo. Including some specialised systems from own developments, the number of systems, mentioned in the answers on the survey was about 15. Among the users are governmental institutes such as the National Land Survey (LMV) using Arc/Info, GRASS, MapInfo, SPANS and AutoKa, the Environmental Protection Board (SNV), using Arc/Info, the Swedish Meteorological and Hydrological Institute (SMHI) using FINGIS, the Swedish Geological Survey (SGU) and the Swedish Statistics (SCB), using MapInfo and SPANS. GIS is also available, although not very much used for hydrological applications, at some universities. There are also a number of companies that uses GIS. The competence within the GIS-field seems to be quite good, although concentrated towards mapping applications. The Swedish part of the questionnaire did not cover county and municipality administrations which have a quite extensive use of GIS but with a limited number of applications of hydrological interest.

AVAILABILITY OF DIGITAL GEOGRAPHICAL DATABASES FOR HYDROLOGICAL MODELLING

Denmark

Most databases are available from governmental institutes, and are in general publicly accessible. Data are mainly stored digitally, after standard concepts which facilitate the data exchange. Meteorological databases are available as time series related to a national net of stations at DMI (Danish Meteorological Survey) and AJMET (Dept. of Agrometeorology). Areal estimates have to be made by the user. Soil databases and geological databases containing soil, reservoir- and stratigraphical information is available as points (drillings) and as areal maps at ADK/DGU (1:25000 and/or 1:50000). In connection to the national soil classification, field capacity for the soils have been determined. Land use databases are stored as areal maps at ADK (1:25000) and as databases containing statistical information (population concentration, agricultural activities *et c*) for administrative units at DS (Danish Statistics). The use of remotely sensed data for evaluation of land use changes is increasing. At the moment the first national-wide database of this type is established at ADK as a part of the EEC-CORINE project. Databases for soil- and groundwater are available as points, areas and time-series. Databases containing discharge and surface water quality exist as points, lines and time-series. Point sources (*e.g.* industries, water treatment plants) exist both as points and as areal averages. Databases for lakes, water courses, catchment areas and coastlines exist at several institutes. Monitoring networks in connection to the Square Grid and the Aquatic Environment Plan give detailed information of soil- ground- and surface water. Digital information of wetlands (1:20000) exists at ADK while information of ditching and drained areas are available as maps at DDH (Danish Land Improvement Service).

Finland

The establishment of the Environmental Data Centre (EDC) in 1988, as a unit of the National Board of Waters and the Environment, was the turning point of enlargement of digital geographical databases. The Environment Data System (EDS) consists of more than 50 data bases of which some are digital map data bases. There are several usable geographical databases, of which some yet only covers part of Finland. The most important of those with at national coverage are land use and forest stand, which have been made in co-operation of many authorities. The basic information was interpreted from LANDSAT images, with a pixel size of 25x25 m. Fifty land use and forest stand classes are included. Updatings will be made with 5-10 years' intervals. A drainage basin register, with over 9000 basins, was completed in 1991. This will be used as the basic land unit for statistical data. Surface temperatures and a vegetation index (NDVI) are interpreted from NOAA-AVHRR satellite images, with a pixel size of 1.1 x 1.1 km. An elevation model, based on 1: 20000 maps, with a grid size of 50 x 50 m is covering the whole of Finland. A digital database of soil types, also based on 1:20000 maps, is under construction, starting with southern Finland.

Iceland

No digital elevation grid-model is available for the whole of Iceland. It does exist, however, at the Defence Mapping Agency (USA), who did the military mapping of Iceland in co-operation with the Iceland Geodetic Survey. Attempts are now made to make this information available. Meteorological and hydrological databases (discharge, surface water levels, groundwater levels) are related to measurement stations, and some point information is also available from drillings in connection with water power plants and geothermal prospecting. Geological databases are available as point data from drillings, and vector-based information about quaternary geology and sediments from parts of the country. In connection with hydrological modelling (the NAM-model, linked to the finite-difference based AQUA-model), estimates of hydraulic conductivity and anisotropy were made available in digital form for parts of the country. A large work does still remain before all relevant geographical information will be made available in digital form for future hydrological modelling.

Norway

A number of institutions do today have the responsibility to collect, store, and handle environmental information, including databases relevant for hydrological modelling. A programme (MISAM), run by the Norwegian Mapping Authority has been initiated with the aim to co-ordinate environmental data in Norway. Time-series of meteorological variables from a national-wide net of stations are available at The Norwegian Meteorological Institute(DNMI). A number of power-companies have the HYDMET-database, which contains time-series with meteorological and hydrological data that are relevant to the management of water-power plants. Statkraft and NVE have snow-data bases. Norwegian Polar Research Institute has snow-data from Svalbard and two glaciers in Norway. NVE´s database HYDRA contains daily values of hydrological parameters. NVE´s digital database REGINE (register over watersheds) contains divides for ca 1 500 watersheds or parts of watersheds. The data-base is nation-wide, with a resolution of 1:50000. NIJOS has digital and analogue data-bases of soil characteristics, land use and vegetation, produced with varying methods and coverage. Geological databases are available at the NGU. The databases relevant for hydrological purposes consists of information about wells, hydrogeology, waste-deposits, and geochemistry in digital form. Information about soil types and bedrock is available from conventional maps. Digital data of groundwater levels is obtainable for a number of measurement sites in a national-wide net. The Norwegian Mapping Authority has the responsibility for the Norwegian digital elevation-data base. There are a number of land-use bases and registers that could be used for hydrological modelling purposes. The State Pollution Control Authority and the Directorate for Nature Management have manuals for most of these data-bases.

Sweden

Contour maps are available (1980-) from the Department of Meteorology, Stockholm University, of the main components of wet-deposition, and dry-deposition of S- and N- compounds. There is, however, not yet a good geographical coverage of the dry deposition. Some of the information is available as digital maps (17x17 km resolution). Meteorological and hydrological databases, with dynamic variables, mostly contain series from point observations. The Swedish Meteorological and Hydrological Institute (SMHI) is the authority responsible for handling and storage of these series. There are, though, some digital geographical databases within this category. Most of them cover limited regions and they have generally been created for specific projects. An example is radar images of precipitation and uses of satellite images and air-borne radar for snow mapping. A few exceptions, with a national coverage exist, however. One example is digitised runoff maps (SMHI), and descriptions of surface water quality emanating from remote sensing analysis (the Swedish Space Corporation, SSC). Digital geographical databases, with variables related to hydrology, such as hydrographic descriptions (lakes, water courses, wetlands, coastlines, *et c*). are in relatively wide usage. Original producer of these databases is in most cases the National Land Survey of Sweden (LMV). There are exceptions, such as mappings of wetlands with remote sensing. The reported existence and use of digital geological databases was sparse. Mappings of soil type, soil depth, various soil properties and bedrock are available from the Geological Survey of Sweden (SGU). The digitising of the geological maps is a current project and so a total coverage of the country in digital form is not available. Some other authorities present mappings of these variables for small regions or at a local scale. More frequent, was the presence and use of digital elevation model data-bases. LMV produces such data-bases with a resolution down to 50x50 m. Elevation and terrain type classifications from SPOT images are also available, from SSC, down to a resolution of 10x10 m. Among land use characteristics of relevance to hydrological modelling, several authorities reported the availability of digital information on the distribution of forests and field. Type and age of the vegetation cover was available in some cases. A few reported information on the extent of ditching. Information on locations of industries, waste water- treatment plants and land-fills are available from LMV, SGU, and form the National Environment Protection Board (SNV). Digital registers of the distribution of population and agricultural activities are available on a parish level from SCB.

HYDROLOGICAL MODELLING APPLICATIONS

Denmark

In Denmark, there is a combination of an intense land-use and a geology that consists of large, complex sedimentary layers. This makes it natural to divide the use of models into the following categories: **Point-related models** used in applications based on climatic time-series and detailed information about soils- and vegetation. Examples are modelling of water and nutrient contents in the root-zone, with models like EVACROP, SOILN, OMS and DAISY. Especially DAISY and SOILN are based on detailed land use and soil information. **Grid-based models** that, literally, is the only type of models that belong to integrated hydrological models. This type of models is used for 3-D modelling of ground- and surface water. The main model used is the SHE-model, which is based on point- area and time series information. DHI is one of the developers of SHE. Several institutes used SHE in co-operation with DHI. **GIS-modelling** is used for regionalisation of point-data and/or creation of new geographical databases, based on overlays of existing maps. ADK has at several occasions used GIS in combination with point-related models with the aim of distributing model results to a nation-wide scale (*e.g.* USLE, OMS). **Terrain-models** are not specifically used. Instead a hydrological reference-system is used for runoff-calculations for a chosen area. Today, none of the mentioned hydrological models are directly based on remote sensing data. Remote sensing interpretations concerning crop monitoring, and mapping of soil moisture contents (*e.g.* wetlands) are, however, made with consideration of their potential use for hydrological modelling purposes.

Finland

The use of GIS linked to hydrological modelling is not yet very wide in Finland. Most hydrological modelling is made with the HBV-model, where the cover of forest and open land is used as geographical parameters. In water quality modelling, the land use interpretation (LANDSAT) has been used for some years for parameter estimation. Estimations of snow- and water equivalents have been made using NOAA-satellite images and gamma ray spectrometry, combined with field measurements.

Iceland

The use of GIS in hydrological modelling is still in the initiating phase. The first attempts at extracting useful geographical information from digital maps with a real GIS, for the benefit of hydrological modelling, will be done during the test period in 1992, using the Arc/Info system at Orkustofnun. The hydrological model in question is the Swedish version of the HBV model. The model, run in Iceland, with the best integration with geographically distributed parameters is the NAM/AQUA model. The NAM part of the model is quite similar to the Norwegian version of the HBV model, with the exception of the groundwater part, which has been replaced by the numerical, finite element based AQUA model. This approach has been shown to be necessary for adequately describing the Icelandic groundwater conditions, which are of overriding importance for the hydrological dynamics in large parts of the country. Models of the NAM/HBV type have problems in handling runoff dominated by input of groundwater, as the variance is much lower than for the usual surface or intermittent runoff. The water balance for such watersheds is also problematic, as the surface and groundwater divides do not necessary coincide, and variable underground losses or gains of water from other watersheds are frequently occurring. These local features and associated time dependant or anisotropic problems can be handled by the AQUA model, which also can be used for estimates of temperature and pollutant distribution, both in groundwater, lakes and near the shore.

Norway

Four different hydrological models were mentioned in the answers achieved from the questionnaire. The direct use of digital geographical data in connection with the parameterisation and running of the models is not known. The HBV model is used for runoff-simulations by a number of power-companies. At NIJOS, USLE is used for simulation of the risk of erosion. USLE needs data on soil texture, drainage, soil structure, organic content, slope-gradient, slope-length, and precipitation data. NGU has been working with modelling of flow in porous media, using FEPOLL, with the aim of studying dispersion of pollutants in sand and gravel. The Department of Geography, University of Trondheim, use a model for simulation of soil moisture deficits in Europe.

Sweden

Among the answers to the questionnaire, only a few contained applications where GIS was used to support hydrological modelling. None of the applications meant an integration of the GIS and the hydrological model. The descriptions of model use below are limited to those that in some way have used GIS in the model work. SCB and the Department of Water and Environmental Studies, Linköping University, have developed a statistical model for source apportionment of nitrogen to the sea. It estimates riverine import and export to sub-catchments from information on land use, lake areas, atmospheric deposition, and point sources. GIS was used to transform the geographical information from the available form (parish-level) to the used division into sub-basins. At SMHI, watershed divides, are extracted from a database, and a 500x500 m database of elevation contours and the distribution between forest and open land are used for calculation of input parameters to the HBV/PULSE models. At the department of Land and Water Resources, at the Institute of Technology (KTH), simple water quality models using GIS have been used for educational purposes. The models require information on topography, bedrock type, soil depth, vegetation, land use and precipitation. Determination of watershed divides from digital terrain models were reported from LMV and from the Dept.. of Water and Environmental Studies, Linköping University. The latter are also using GIS for the calculation of a hydrological index (used in TOPMODEL), based on accumulated areas and slopes, calculated from elevation-databases. They have also used GIS for calculation of wetness-distribution in a 100-years perspective, and for modelling of the geographical distribution of erosion risk, using a modified version of USLE. For the moment, they use GIS for determination of linkages between land-use and land management changes and trends in nitrogen concentrations for some forested catchments. A the Division of Hydrology, Uppsala University, a programme for calculation of morphometric data for lakes and coastal areas from digital nautical charts has been developed. They are also setting up the SHE model for a small catchment (Buskbäcken) with the aim to study the effects of forest drainage and clear-cuttings on the water balance. A few applications in foreign countries, *e.g.* simulations of erosion and runoff in Nicaragua at the Dept. of Hydraulic Engineering, KTH, were also reported.

CONCLUDING REMARKS

The most resource and discipline demanding part of GIS-work is the establishment and updating of geographical databases. The existence and availability of these databases will determine if the linkage between GIS and models will be possible, other than for small site-specific applications. The access can be hindered by economical reasons or by the lack of general standards of data formats. It is therefore necessary that the responsibility of these databases is taken by institutions that have the motivation, and not the least enough personal and economical resources for the purpose. Since the building-up of digital geographical databases still is in an initial phase, it is important that hydrological modelers defines which geographical data bases that they need, and in which form, in order to be able to influence the future availability of data-bases.

One problem is the lack of areas estimates of driving variables, such as precipitation. In addition to interpolation of point-values to areal estimates, where GIS can be used as a tool, an increased use of remote sensing data on *e.g.* precipitation and snow distributions is needed. These techniques are, however, at present often not developed in the way that they can give reliable quantifications of the amount of *e.g.* rainfall, *i.e.* they are better in answering "where" than "how much".

The questionnaire showed that some data-bases exists with good spatial or temporal resolution for only one of the Nordic countries, *e.g.* the data-base of land use and forest stands, based on LANDSAT images for the whole of Finland, or only for a specific region, *e.g.* the digital database of hydraulic conductivity and anisotropy for parts of Iceland. It is hoped that the final state-of-the-art report, will act as a promoter for the finding of regions, anywhere in the Nordic countries, where the needed geographical parameters for a certain model application are available in a digital form. The success (or lack of success) of such initiatives, could then be used for future decisions of which new digital-data bases that are worth to invest in.

The reason behind the very sparse use of digital geographic information in the model applications in the Nordic countries is probably linked to the extensive use of traditional hydrological models, mainly the HBV-model or other similar models, which are not constructed to take advantage of geographically distributed data, but only uses the percentage of a few parameters, such as areas in various elevation zones, forest and open land.

A model that uses GIS has the advantage that it can calculate the geographical distribution of a relevant parameter from others (*e.g.* slope, aspects, or accumulated areas from elevations). It can also be used to define the distribution of hydrologically similar elements from overlays of different physiographic factors. Such information can *e.g.* be used to calculate the distribution between recharge- and discharge areas, and it can be included in a hydrological regionalisation. The effect of land-use or land-management changes in various parts of a catchment can also be assessed (*e.g.* why the effects of fertilisation, ditching- or clear-cutting on nutrient transports varies between catchments or within a catchment). A spatially distributed model can also be a tool for determination of the distribution of internal variables, such as the geographical distribution of ground-water levels and soil moisture conditions. Such information, is of vital importance when modelling chemical and biological processes, when it is important to know where the runoff emanates from.

To be able to take advantage of the possibilities with GIS, the present models have to be adapted for this, or new models have to be developed. Exchangeable configurations between the models and the GIS must be found. The fact that a model is based on the spatial distribution of geographical data, does, however, not necessary make it suitable for integration with GIS. It is only if the necessary parameters are available from digital maps that an integration is possible. This limits the practicability of physically-based models, *e.g.* the SHE model. A maybe more fruitful path for model development, linked to GIS, could be based on the assessment of hydrologically similar elements from overlays of generally available geographical information.

GEOGRAFISKA INFORMATIONSSYSTEM (GIS) INOM HYDROLOGI I NORDEN

Gunlög Wennerberg SMHI Sverige

ABSTRACT

A working group in the Nordic countries - Denmark, Finland, Island, Norway and Sweden - has been studing the use of GIS at the hydrological services of the countries. An extensiv study of the equipment, systems, programs, data bases, applications and future plans has been performed. An exchange of experience is done during the work. In connection with the meetings of the group visits to study some of the systems of the hydrological services have been possible. Lots of demands and applications are the same in the Nordic countries, but as different systems are used (Finland and Sweden however have the same GIS), different approaches are available.

Cooperation is suggested in glacial mapping, water divider handling, runoff maps and especially in the case of purchasing of systems. Further exchange of experience and knowledge will be performed and hydrologists and programmers will meet at conferences. A proposal to the Nordic Association for Hydrology to have GIS-workshops at their conferences will be handed over.

UPPDRAGET

Vid möte mellan Cheferna för Hydrologi i Norden - CHIN - i Oslo 1991-03-01 beslutades att en samarbetsgrupp inom GIS-området skulle tillsättas. Bakgrunden till detta var att alla de nordiska länderna arbetar med GIS i en eller annan form, men koncentrerat sig på olika områden. De olika länderna har därför kommit olika långt inom områdena och borde kunna ge nyttig information till varandra.

Målsättningen för gruppen skulle vara att kartlägga och främja gemensamma intressen i förhållande till system- och applikationsleverantörer samt sörja för ett optimalt nordiskt användande av resurser vid eget utvecklingsarbete inom GIS-området. Inom denna målsättning skulle

-varje representant informera om GIS-utveckling i sin egen organisation; GIS-applikationer som har utvecklats, är under utveckling eller planeras
-gruppen efter denna genomgång identifiera gemensamma applikationer och utarbeta en plan för vidare samarbete för varje applikation
-gruppen titta på möjligheterna till gemensamma systemanpassningar för de organisationer som har samma GIS
-gruppen också samordna de olika organisationernas krav på GIS för att om möjligt föreslå en gemensam specifikation.
Gruppen skulle rapportera till CHIN-möte den 5 mars 1992.

Gruppens sammansättning har varit:
Gunlög Wennerberg, SMHI, Sverige; sammankallande
Anna Hamström, SMHI, Sverige
Skúli Víkingsson, Orkustofnun, Island
Matti Ekholm, Vatten- och miljöstyrelsen, Finland
Jari Lohvansuu, "   "
Jørgen Erup, ersatt av Mogens Buchwaldt, Hedeselskabet, Danmark
Astrid Voksø, NVE, Norge
Vidar Raubakken, NVE, Norge

Gruppen har hållit två möten, det första på SMHI i Norrköping 17-18 september 1991 och det andra på NVE i Oslo 14-15 januari 1992.

GENOMGÅNG AV LÄGET I DE NORDISKA LÄNDERNA

Med geografiska informationssystem avser gruppen ett ADB-baserat system för insamling, lagring och presentation av geografiska data. Geografiska data definieras som upplysningar om egenskaper och tillstånd hos objekt, samt händelser som är lägesbestämda.

En GIS-kedja kan byggas upp av kombinationen av kompetens, strukturerade data, organisation och utrustning/program.

Vid genomgången har gruppens deltagare svarat på två enkäter samt redogjort muntligt vid möten för läget på sin arbetsplats. Gruppen har härvid endast tagit med förhållandena vid de sk hydrologiska tjänsterna i Norden, som gruppdeltagarna representerar. Övriga institut, högskolor och organisationer som arbetar med hydrologi och GIS har inte medtagits i denna genomgång.

Gruppen har vid de två mötena fått se demonstration av FINGIS på SMHI och ARC/INFO på NVE. Detta har varit mycket intressant för deltagarna. Presentation av projekt med anknytning till GIS har genomförts vid mötena. Vid SMHI redovisades ABQ (Automatisk beräkning av vattenföring) och vid NVE föredrogs projekten Vassdragssimulator, användningen av satellitbilder i snökartläggning och planerna för vattenbalanskarta.

Utrustning

I Finland och Sverige arbetar man med det finska systemet FINGIS sedan 1985 respektive 1986. I Finland skedde valet av GIS med hänsyn till att detta var ett finskt system, som användes av Lantmäteristyrelsen. Arbetet sker på en VAX 8500 Dec station 325. I Sverige föll valet av GIS på FINGIS eftersom de svenska vattendelarna digitaliserades på Finska Lantmäteristyrelsen och det var enkelt och prisvärt att fortsätta att arbeta med FINGIS. En VAXstation 3100 är fn värddator. I Finland arbetar man också med UNIRAS sedan 1991.

I Danmark har man sedan 1989 arbetat med Intergraph, som valts för att det är ett internationellt erkänt proffessionellt system, som också används av den Danske Kort- og matrikelstyrelse, Skov- og naturstyrelsen och andra danska myndigheter. På Island har man f n inget GIS, utan arbetar med hemgjorda program för digitalisering, plottning och diverse beräkningar. I Norge har man tidigare arbetat med Interaktivt Grafisk System (IGS), men under hösten 1990 påbörjades en behovsutredning och kravspecifikation på NVE. Efter ett anbudsförfarande har ett omfattande utvärderingsarbete gjorts och NVE valde ARC/INFO som under hösten 1991 installerades på NVEs Sun Sparc 2-dator. PC med X-emulator används som terminaler mot Sun-datorn. Systemet består av ARC/INFO arbetsstation för fleranvändare, TIN-modul (terrengmodell) och GRID-modul (raster). Gruppens medlemmar har fått ta del av kravspecifikationen och av enkätsvar framgår motiv för val av utrustning. Vi har haft möjlighet att komma med frågor om funktionalitet och att även se utrustningen i funktion under gruppens andra möte.

Databaser

Vid första genomgången av situationen och den första enkäten fann vi ett behov av att närmare följa upp vilka databaser, lämpliga att arbeta med i GIS, som redan lagts in, respektive där arbete pågår eller planeras. En speciell enkät gjordes som även tog med frågor om databaser som skulle vara önskvärda att ha tillgång till.

Inlagda databaser och pågående arbeten

Uppgifter om sjöar och vattendrag har digitaliserats i alla länderna, dock med varierande omfattning. Uppgifterna varierar från linjer och polygoner till textuppgifter. Även kustlinjen har lagts in.

Sverige, Norge och Finland har digitaliserat klart huvudvattendelare och ytterligare underindelning av vattendelare. Danmark avslutar sitt arbete med detta under 1992. Island har digitaliserat vattendelare inom utbyggnadsområden och planerar att digitalisera övriga huvudvattendelare. Hierarkin för avrinningsområdena är en viktig del för att man skall kunna arbeta vidare med data. De olika nordiska länderna har härvid arbetat på olika sätt. Administrativa gränser som kommuner finns tillgängliga i Danmark, Finland, Norge och Sverige.

Höjddata finns tillgängliga i GIS i Finland i 50m x 50m rutor, medan Sverige har data från 500m x 500m grid. I Norge har man data från försöksområden med 100m x 100m grid. Beträffande markanvändning har Finland en klassning i 50 klasser för hela landet i raster om 25m x 25m och ett register över markanvändning inom avrinningsområdena. I Sverige innehåller höjddatabasen information om skog, sjö och öppen mark. I Norge tas översiktlig information fram om motsvarande markanvändning.

Hydrologiska mätstationers placering har digitaliserats i Danmark och Sverige. Arbete pågår på Island och i Norge. Uppgifter om glaciärer på Island finns tillgängligt. Norska isohydater dvs linjer som förbinder punkter med samma avrinning per ytenhet finns inlagt i systemet för perioden 1930 - 1960.
I Finland pågår arbete med att lägga in uppgifter om jordart (9 klasser) och jordmån
I Finland arbetar man också med ett grundvattenregister innehållande uppgifter om grundvattennivåer och kvalitet.
I Sverige lagras beräkningsområden. Dessa består av avrinningsområden uppströms punkter som används för prognosering eller beräkning av vattenföring. Detta arbete avslutas under vintern. Arbete pågår också med att beräkna egenskaper för varje avrinningsområde. Uppgifterna lagras i mimerdatabas. Även detta arbete blir klart under vintern och innefattar areor, medelhöjd, in- och utloppspunkt. Markanvändning inom avrinningsområdet i form av skog, sjö och öppen mark per hypsograf i 10-meters intervall lagras.

Behov och önskemål av data

Av ovanstående redovisning framgår att omfattande arbeten utförts och pågår. I alla länderna arbetar man vidare med förbättringar och anskaffande av bättre och "nya" databaser. Norges önskemål på data gäller i första hand bearbetning av underlagsdata. Dessa data är kartverkets ansvar. NVE bearbetar nu på försök de data man köpt från kartverket till GIS-teknologi. Erfarenheterna från detta, samt en analys av hur nöjaktiga underlagsdata man behöver, kommer att ligga till grund för förhandlingar om köp av kompletta underlagsdata för hela landet. För närvarande bygger uppgifterna på en digitalisering av kartor i skalan 1:1 000 000, medan arbete från 1:250 000 pågår och 1:50 000 är planerat.

I såväl Sverige som Norge är man litet osäkra på vilken ytupplösning som är rimlig att arbeta med beträffande höjddata och markanvändning. Inom vissa områden och dicipliner ställs mycket höga krav på data, medan man i andra fall inte har klart för sig hur tex en detaljerad markanvändningsdatabas kan utnyttjas i modeller. I Finland har man hunnit längre med dessa databaser och avser att utnyttja dem i avrinningsmodeller. På Island önskar man sig hypsografisk information inom utbyggnadsområden, för användning i avrinningsmodeller. I Sverige diskuteras också behov av uppgifter om jordarter mm i första hand för miljöstudier (växtnäringsläckage), men man är ännu inte mogen för att veta vad man skall satsa på.

I Sverige avser man att ta fram isolinjer för nederbörd, avrinning och avdunstning per ytenhet över hela landet. I Norge har man rutiner för avrinning - isohydater - och avser att producera nya kartan för 1960-90.

Applikationer

GIS används för att hantera den stora mängd geografisk information som idag utgör en grund för hydrologernas arbete. Från GIS hämtas underlag för beräkningar och modeller. Inmatning, lagring och uttag ur databaserna görs via GIS. Kombination av databaser är en viktig tillämpning. Som exempel kan nämnas statistik om markanvändning för varje 10-meters höjdintervall i visst avrinningsområde. Dels kan koefficienter som fältparametrar tas fram ur markanvändnings- och jordartsuppgifter, dels kan uppgifter om arealer m m tas fram.
Uppgifter om vattendrag, vattendelare, sjöar och mätstationer används för plottning och beräkning av arealer mm. Hydrologisk kod och ordning används också för uträkning av arealer. Administrativa gränser används för sig eller i kombination med andra databaser för plottning och beräkning av arealer.

GEMENSAMMA KRAV/APPLIKATIONER PÅ GIS

Vi arbetar med helt olika GIS, men ofta med samma applikationer och problem i de olika länderna. Bland de saker som diskuterats fann vi att följande gemensamma krav/applikationer var av gemensamt intresse:

Digitalisering

Digitalisering är en grundläggande funktion som alla länderna aviserat behov av.

FINGIS bedöms vara ett bra program för digitalisering både i Sverige och Finland. Intergraph är också mycket bra för digitalisering. I Danmark hade man tidigare problem med linjer som korsar varandra eller inte hänger ihop, men detta är löst i en utvidgad version där nätverksanalys och korrektion ingår.

På Island arbetar man med hemmagjorda program där standardkartblads koordinater söks fram utifrån kartnummer. I övrigt är inte programmen särskilt användarvänliga.

I Norge har man valt att utnyttja det norska PC-programmet (FYSAK) för att efter rättning och konvertering föra in data i ARC/INFO. Detta fungerar bra. PC-programmet är bättre än den delen av ARC/INFO och arbetsstationen avlastas.

Grafisk editering

Det är viktigt att editering kan ske smidigt i systemet. I Norge räknar man med att för varje timme som läggs ned på digitalisering tar arbetet med editering också en timme. Generellt verkar det som editering är invecklat vid inlärningsskeden, medan det för den vane användaren, som känner till möjligheterna och regelverket för logiken, går lätt.

Intergraph är bra när man lärt sig att använda det. Man kan själv ordna otroligt många former för manipulation, något som dessvärre också innebär att en icke rutinerad användare kan råka ödelägga data.

I Finland anser man att FINGIS och UNIRAS är bra för grafisk editering om det inte är fråga om rasterdata. I Sverige anses FINGIS bra, men krångligt för en användare som inte är rutinerad. På Island har man inte möjlighet till grafisk editering, utan plottar och editerar sedan koordinatfiler. I Norge editeras data i FYSAK, där även digitalisering sker. ARC/INFO anses tyngre att jobba med.

Overlayteknik

Att arbeta med overlayteknik - sammanslagning av många informationsskikt - har blivit viktigt. Med detta avses t ex att kombinera vattendelare med kommungränser, församlingar, snöutbredning eller höjddata.

Danmark och Island har inte arbetat med tekniken. Från Norge rapporteras att ARC/INFO kan koppla samman tema som innehåller punkter, linjer och polygoner. Begränsningen utgörs av antal polygoner och är på 100 000. Detta utgör inte något problem. Overlay går snabbt att göra, 3 - 7 minuter beroende på datamängden.

I Sverige har konstaterats att FINGIS inte klarar att göra overlay i någon större omfattning. Test på avrinningsområden i Skåne mot församlingsgränser visar att FINGIS ej är gjort för så stora datamängder som vi hanterar på SMHI.

Framtagning av isolinjer

Många gånger har man behov av att ur rasterdata konstruera isolinjer. Det kan röra djupkartor för sjöar från handlodning, höjdkurvor från gridnät eller bestämning av vattendelare ur höjddata.

I Norge avser man att kombinera data från mätstationer med avrinningsområden och höjdinformation för att utarbeta isolinjer för avrinning för perioden 1960 - 1990. Detta skall göras under 1992 - 1993. Norge har för perioden 1930 - 1960 en motsvarande manuellt framtagen detaljerad karta som digitaliserats. Denna används f n för att beräkna avrinning från ett avrinningsområde. I Sverige tycker man inte att FINGIS fungerar tillfredsställande.

Hydrologisk ordning

Gruppen har konstaterat att det finns inget GIS som innehåller standardfunktioner för det som hydrologiskt sett är mycket viktigt, nämligen att veta var i vattensystemet man befinner sig. Problemet tycks bara återfinnas inom hydrologin. För en viss punkt vill man t ex veta inte bara vilket avrinningsområde den tillhör, utan också vilka områden som ligger uppströms.

Hantering av hydrologisk ordning i ett GIS kräver en grundlig planering av datastruktur. Det är många saker som påverkar hur man klarar detta:
- Begränsningar i program
- Användarens önskemål om tillgång till data
- Programmerarens möjlighet att ordna program
- Databasadministratörens möjlighet för att designa en effektiv databas
- Hydrologens strukturering av den hydrologiska ordningen.

I Danmark håller man nu på och implementerar den "hydrologiska referensen" i den grafiska och alphanumeriska databasen. Man har digitaliserat vattendragen med en kod som byggts upp med hjälp av vattendragsnummer, avståndsindex från mynningspunkter och tilläggsuppgifter med nya avståndindex för varje utlopp för biflöden. Slutligen ingår en avståndsuppgift från senaste angivna punkten. I Finland har man satt symboler i form av pilar på vattendragen. I Norge har man givit en identifikation till varje avrinningsområde och delområden inom detta. Programmering i ARC/INFO pågår för att man skall kunna utifrån identifikationen se om ett område ligger i ett visst huvudavrinningsområde och sedan även söka ut de områden som ligger uppströms. Arbetet är inte färdigt så man vet inte hur omfattande det blir.

Hydrologiskt läge anges i Sverige med ett hjälpsystem som beskriver vattendrag och sjöar. Vattendrag identifieras med koordinater för vattendragets utlopp och läge inom vattendraget anges med avstånd från utloppspunkten till önskad objektpunkt. Avståndet räknas längs en tänkt mittlinje i vattendraget. Kopplingen mellan vattendragen och mellan vattendrag och sjöar sköts med pekare (vägvisare). I en inflödespunkt i en beskrivning av ett överordnat vattendrag finns en pekare som pekar mot en beskrivning av ett biflöde (eller en sjö). I biflödet (sjön) finns en pekare som pekar mot inflödespunkten i det överordnade vattendragets inflödespunkt.

Utritning av kartor

Möjligheterna att presentera data på karta i ARC/INFO i Norge är stora och man kan välja linje, färg, skala, utsnitt och text. Det är lätt att få fram enkla kartor. För att få vackra kartor måste man arbeta med layout och detta tar mer tid. Man kan standardisera om man vill ha flera likadana kartor. Hittills har version 6 av ARC/INFO haft problem med att fylla polygoner. Det går inte att fylla polygoner om de inte är slutna inom plottningsarean. I nya versioner torde detta rättas till.

Att kunna rita kartor är inte något tekniskt problem, men är på Intergraph i Danmark f n mycket tidskrävande, när man vill ha annat än standardkartor. Användarna vill ha andra färger, tjocklek på linjer, textinformation m m. Vid Hedeselskabet avser man att utveckla en applikation som åstadkommer en snabbare design av kartor.

Detaljeringsgrad i databaser

Inom gruppen har också diskuterats vilken detaljnivå på databaser man behöver inom olika projekt.

Bland det som diskuterats kan nämnas höjddatabas, där det i de olika länderna finns tillgång till olika grid och höjdintervall. En annan intressant del är data om markanvändning, där man hittills bara utnyttjat detaljerad information i vissa testområden. Frågan vad en tillgång på markanvändningsdatabas medför för hydrologiska modeller är intressant. Kan en sådan databas leda till att det lönar sig att omarbeta modeller så att den detaljerade informationen utnyttjas? För närvarande används bara några få uppgifter operationellt och då i en ganska översiktlig skala (vatten, skog/öppen mark, snö).

GEMENSAMMA DATA

Att byta data i gränsområdena är de aktuella länderna helt inställda på. Inga administrativa problem har funnits mellan de hydrologiska institutionerna beträffande vattendelare och vattendrag. Litet mer komplicerat blir det då data köpts in från andra myndigheter.

Som exempel på att det inte är problemfritt med datautbyte kan nämnas att Sverige arbetar med en höjddatabas i grid 500 x 500 m och har lagt ut detta på avrinningsområden per 10 meters höjdintervall. När man vill ha uppgifter från Norge om gränsområden så finns basmaterial på Kartverket och det som NVE skulle kunna lämna till SMHI idag är digitaliserade höjdkurvor med 300 meters höjdintervall.

Tekniska problem uppstår p g a att vi arbetar med olika ellipsoider. Koordinatomvandling till eget system måste göras och data måste stuvas om till eget format.

ERFARENHETSBYTE

Under projektet har en mängd information utbytts mellan gruppens deltagare. Vi har fått veta vilka utrustningar, vilka databaser och applikationer man arbetar med. Vi har vid de två mötena tittat närmare på FINGIS på SMHI och ARC/INFO på NVE och vissa projekt med stor anknytning till GIS.

Bland det mest intressanta är att Norge just gjort en grundlig inventering av GIS på marknaden och valt ARC/INFO. Närmaste halvåret sätter man det i drift. Just nu arbetar 4 - 5 personer på NVE med detta, förutom en konsult på halvtid. Man framhåller att allt kan göras, men att ingenting är enkelt. Island diskuterar inköp av ARC/INFO och har då stor nytta av Norges erfarenhet. Vi har alla tagit del av NVEs kravspecifikation och motiv till valet.

FÖRSLAG TILL SAMARBETSPROJEKT

Gruppen har haft ett stort erfarenhetsutbyte. Eftersom vi har olika GIS (utom Sverige och Finland) och olika databashanterare har vi inte funnit några rena GIS-projekt som vi kan föreslå som samarbetsprojekt. Gruppen har huvusakligen bestått av personer som arbetar med att programmera GIS och att samarbeta kring ett visst GIS-program eller rutin är inte möjlig f n. Däremot har vi en del hydrologiprojekt med GIS-anknytning, där samarbete borde komma till stånd mellan två eller flera länder. Gruppen har dock inte klarat (kompetensmässigt och i tid) att formulera fullständiga projektbeskrivningar. Idéerna redovisas här. Gruppen har också funderat kring fortsatt erfarenhetsutbyte inom GIS-sidan och lämnar vissa förslag nedan.

Glaciärkartering

Norge och Island har ett gemensamt intresseområde i glaciärkartering. Härvid bör planering ske på hydrologbasis med ett upplägg som leder till att man utnyttjar GIS på ett lämpligt sätt.

Vattendelare med hjälp av höjddata

I Sverige och Finland finns visst intresse för möjligheten att med hjälp av höjddata rita vattendelare automatiskt. I Sverige har Lantmäteriverket, Tekniska Högskolan i Stockholm och Tema Vatten jobbat litet med detta. SMHI undersöker läget och informerar Hydrologiska Byrån om möjligheterna.

Isolinjer för avrinning

Sverige och Norge är intresserade av att rita avrinningskartor för perioden 1960 - 1990 i GIS. I Norge avser man att göra en mycket detaljerad karta liknande den som finns för föregående period. Detta är projekt där samarbetet måste börja på hydrologbasis rörande metoder och hur man täcker upp gränsområden. Planerna på användandet av GIS måste in på ett tidigt stadium, men är inte det primära. Vi föreslår en nordisk samarbetsgrupp.

Hydrologisk ordning

Beträffande hydrologisk ordning vore det önskvärt att samla beskrivningarna av de kod- och referenssystem som byggts upp i de enskilda länderna i en skrift. Beskrivningarna finns säkert på olika håll men är idag inte samlade. Givetvis hade det varit lättare om man enats om ett gemensamt system i grunden, men f n ser det svårt ut att få till en samordning. Detta leder till att hanteringen i GIS gått olika vägar.
Gruppen föreslår att en redaktör och kontaktpersoner i respektive land utses för att samla in uppgifterna om hydrologisk ordning och kod.

Anskaffning av GIS

Övriga länder kan vid en eventuell anskaffning den närmaste tiden utnyttja det stora arbete Norge lagt ned på sin specifikation och upphandling. Island ser idag över sitt behov och diskuterar anskaffning av GIS. Under mars - maj provar man ARC/INFO på Orkustofnun och fem personer deltar i kurser. I Sverige har man problem med att FINGIS-systemet inte klarar att skapa isolinjer, göra overlay och hantera attributdata (textinformation) på ett tillfredsställande sätt. Dessutom vill man ha fler möjligheter till analyser av grafiska data. Situationen ses över f n.

Om vi hade samma system i Norden skulle fler rena GIS-programmeringsvinster kunna göras.

Fortsatt utbyte av erfarenhet

Det bedöms av gruppen värdefullt att utbyta erfarenhet mellan de som jobbar inom GIS-området. Vi har diskuterat uppföljning av detta arbete och fortsatt utbyte. Givetvis kan alla i gruppen tänka sig att utbyta rapporter i fortsättningen. GIS-möten har sällan hydrologisk karaktär, men i april 1993 hålls en Hydro - GIS - konferens i Österrike i IAHS regi. NHK innehåller ibland enstaka GIS-inriktade föredrag, men inte nog för att ha ett nordiskt utbyte. Gruppen föreslår följande:
- Hydro GIS bevakas av de nordiska länderna
- GIS-personerna håller kontakten genom utbyte av rapporter, telefonsamtal, mail m m. Eventuellt lägger CHIN in en rutin att avrapportera läget för detta vid CHIN-mötena
- GIS-workshop vid NHK 1994 arrangeras.

ON THE CHOICE OF THRESHOLD LEVEL IN PARTIAL DURATION SERIES

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ABSTRACT

An objection against the use of Partial Duration Series in flood frequency modelling is the subjectivity involved in the determination of the threshold level. Alternatively some rigorous rules for the threshold determination are formulated and compared. This includes use of a test of significance for selection of extreme events, use of standard frequency factors, use of a fixed number of flood peaks, and selection of the threshold level on basis of the coefficient of variation of the exceedances and the ratio of variance to mean of the annual number of exceedances. The rules are applied to data sets of 30 years' length from 20 Norwegian catchments.

1. INTRODUCTION

In comparison to the Annual Flood Series (AFS) the Partial Duration Series (PDS) method - also denoted the Peaks Over Threshold (POT) method - has proved to be more efficient in many applications as basis for flood frequency studies. In the case of a Poisson-distributed annual number of threshold exceedances and exponentially distributed peak exceedances, which results in the Gumbel distribution for the annual maximum exceedance, the efficiency of the T-year event estimator has been examined. (Cunnane, 1973) concluded that the PDS method produces smaller sampling variance of the T-year event estimator than the AFS method if the PDS contains at least 1.65t extreme events, where t is the number of years of record. Based on Cunnane's results (Rosbjerg, 1985) derived small sample expressions for the variance of quantile estimates of the AFS and PDS model, respectively, and concluded that the PDS and AFS models are of similar efficiency for high quantile estimation.

Recently (Wang, 1991) examined the PDS model with generalized Pareto-distributed peak exceedances. He concluded that even when a high threshold is used for the PDS model - implying only relatively few exceedances to be included in the analysis - the PDS and AFS models are of similar efficiency. Thus, he suggested that there is no theoretical reason for using the AFS model in preference to the PDS model.

In spite of the fact that the PDS model has some preferable predictive properties, an objection against the method is, however, the subjectivity involved in the determination of the threshold level. Not much effort has been made to examine this problem, and only some more or less arbitrary rules for choosing the threshold level have been used in applications of the PDS model.

Obviously the PDS model has to be analysed with respect to both its descriptive and predictive abilities. It is evident that the threshold level should be chosen high enough to satisfy the model asumptions, i.e. the asumptions of, respectively, a Poisson process describing the flood peak arrivals and independent and exponentially distributed flood peak exceedances, but not too high to significantly reduce the sample size. On this basis rules for the threshold determination can be formulated in terms of the statistical properties of the analysed samples, using for example the coefficient of variation of the exceedances or the ratio of variance to mean of the annual number of exceedances. Some other methods for selection of the base level may be formulated as more "general" rules, using for example a standard frequency factor or a fixed number of threshold exceedances.

The above methods, however, do not explicitly ensure that the peak exceedances above the chosen threshold in fact constitute the extreme value region of the sample. As an alternative a test of significance for selection of the extreme value region, introduced in meteorological time series by (Gerstengerbe and Werner, 1989), is applied in the PDS context and compared to the above mentioned rules. In the comparison of the rules data sets of 30 years' length from 20 Norwegian catchments will be employed.

2. THE BASIC PDS MODEL AND SOME ALTERNATIVES

By introducing a threshold level, q_0, in a continuous flood hydrograph and considering only flood peaks above this level a PDS is obtained. If a flood peak exceeding the threshold level is detoted by Q_i, then the basic variable to be used in the flood frequency analysis is

$$X_i = Q_i - q_0 \tag{1}$$

If multiple peaks occur in the PDS, only the largest peak is extracted. To obtain a mathematical model of the process defined by (1) a statistical description of both the occurrence of the peaks in the time dimension and the magnitudes of the peaks is needed.

The basic model assumes that the occurrence of flood peaks above the threshold level is described by a non-homogeneous Poisson process. If the intensity of the process is periodic with a period of one year, then the number of flood peaks above the threshold in time t is Poisson-distributed

$$P\{N(t)=n\} = \frac{(\lambda t)^n}{n!}\exp(-\lambda t) \quad ; \quad n = 0,1,2,.... \tag{2}$$

where λ equals the expected number of exceedances per year.

An important feature of the Poisson process is described by (Ashkar and Rouselle, 1983a). Suppose that the Poisson assumption applies for a threshold level q_0, then the PDS associated with a higher threshold q_0+h, $h>0$, also defines a Poisson process. If the number of peaks exceeding q_0+h is $N_h(t)$, then the parameter of the Poisson process is $\lambda_h t$ where $\lambda_h = \lambda(1 - F(h))$. The term $F(\cdot)$ denotes the cumulative distribution function of the model describing the magnitudes of the peaks.

The basic model assumes the peak exceedances X_i to be independent and identically distributed according to the exponential distribution (ED). The probability density function (PDF) and the cumulative distribution function (CDF) of the ED are

$$f(x) = \frac{1}{\alpha}\exp(-\frac{x}{\alpha}) \quad ; \quad F(x) = 1 - \exp(-\frac{x}{\alpha}) \tag{3}$$

The mean and the variance are $\mu = E\{X\} = \alpha$ and $\sigma^2 = Var\{X\} = \alpha^2$, and obviously the coefficient of variation is equal to 1.

The wide use of the ED in applications of the PDS model is primarily due to the simplicity of the model, but also some important statistical features of the ED make it preferable. First, the exponential tail has proved to be quite general for the description of the behaviour of extreme events, and, secondly, a truncated ED remains an ED with the original parameter α intact. Hence, if the ED applies for a threshold level q_0, then the ED will also apply for a higher threshold q_0+h, $h>0$. For a peak exceedance x_i with PDF and CDF given by (3) corresponding to threshold level q_0 the PDF of x_i conditioned on $x_i>h$ is

$$f(x \mid x > h) = \frac{f(x)}{1 - F(h)} = \frac{1}{\alpha}\exp(-\frac{x'}{\alpha}) \quad ; \quad x' = x - h \tag{4}$$

which is an ED with the same parameter α as in the unconditional distribution.

In some cases a good fit of the Poisson and exponential distributions can be difficult to obtain. This calls for alternative assumptions regarding the description of both the occurrence rate and the magnitudes of flood exceedances.

The Poisson assumption has been analysed by (Cunnane, 1979) in a study of 26 gauging stations in Great Britain. He found that the Poisson assumption had to be rejected if all the data were considered jointly, although it was acceptable in some cases. The negative binomial distribution was applied as an alternative to the Poisson distribution but it did not seem to offer any satisfactory improvement. In fact, the Poisson assumption is rather robust, especially when the process is more regular than the Poissonian (Rosbjerg, 1977).

To verify the exponential exceedance distribution it is in some cases necessary to choose a very high threshold. In such cases the high threshold may imply only very few exceedances to be extracted from the historical record, which results in a very unreliable prediction of the extreme events. Hence, alternative exceedance distributions in combination with a lower threshold may be applied. Several alternative distributions have been proposed. Distributions which have the ED as a speciel case are the gamma distribution proposed by (Zelenhasic, 1970), the Weibull distribution proposed by (Miquel, 1984) and the generalized Pareto distribution proposed by (Van Montfort and Witter, 1986) and (Fitzgerald, 1989). In a particular case study of significant wave heights (Rosbjerg, 1987) introduced the log-normal distribution which differs from the ED for all parameter combinations.

The final choice of exceedance model shall, however, not only be made with respect to its descriptive abilities. Also its predictive abilities in terms of efficient estimation properties have to be examined. In three recent studies the mean square error of the T-year event estimator has been used as a performance index in a comparision of different approaches to estimating the T-year event. (Rasmussen and Rosbjerg, 1991b) compared seasonal and non-seasonal PDS models, while (Rosbjerg et. al., 1991) compared use of the log-normal distribution and the ED, respectively, in case of a log-normal parent distribution. In (Rosbjerg et. al., 1992) the use of the generalized Pareto distribution, and the ED was compared in the case of a parent generalized Pareto distribution. In terms of efficient estimation properties the above analyses have shown that the ED should be applied in many cases in spite of large deviations from the exponentiality of the exceedances. In other words, the ED assumption has proved to be quite robust.

3. PRELIMINARY ANALYSIS OF CATCHMENT DATA

The PDS model is applied to 20 Norwegian catchments in order to examine some possible rules for selection of the threshold level. The data basis consists of daily discharge measurements of 30 years' length.

The first step in the analysis is the extraction of flood peaks from the historical records. In order to minimize the stochastic dependence between successive peaks some appropriate restrictions have to be imposed on the interarrival time between successive events. (Cunnane, 1979) defined rules to decide which of the peaks to include and which to exclude when a number of peaks occurs closely together. Two neighbouring peaks are both included only if (1) the flow between them drops to less than two thirds of the earlier of the two, and (2) the time between the peaks exceeds $3T_p$ where T_p is the average time to peak of the first five "clean" hydrographs on the record. Another guideline is proposed by the (USWRC, 1976). In order to define series of independent peaks the floods must be separated by at least five days plus the natural logarithm of the drainage area (in square miles). In addition, the discharge must drop below 75 % of the lower of the two separate maximum daily flows.

(Ashkar and Rouselle, 1983b) showed that such restrictions may violate the hypothesis of the Poisson process, especially when the intensity of the process reaches high values. They suggested that other measures for reducing dependence (such as raising the threshold level) should be examined before using any restrictions.

In this paper the (USWRC, 1976) guidelines will be used. The threshold level, q_0, will be presented in terms of the frequency factor, k, where k is defined through the equation

$$q_0 = E\{Q\} + kS\{Q\} \quad ; \quad k \geq 1 \tag{5}$$

E{Q} and S{Q} are the mean value and standard deviation of the daily discharge, respectively. To ensure that the restrictions are not too severe, only thresholds above a level corresponding to k = 1 will be examined in the following.

As the discharge is effected of both the physical characteristics of the catchment and the meteorological processes producing runoff, a determination of the extreme value region of the sample has to be based not only on mathematical and statistical theory but also on the physical reality. In catchments dominated by glacier runoff the number of flood peaks is quite low, whereas in catchments dominated by rainstorms floods will appear much more frequently. In addition, the runoff will be affected by the steepness of the catchment and by the presence of lakes.

Table 1 Catchment characteristics for the 20 sites.

Stat. no.	A_L $^0/_0$	A_{LE} $^0/_0$	A_G $^0/_0$	G $^0/_{00}$	λ year^{-1}
685	4.40	1.20	0	21.0	7.10
694	14.8	12.6	0	20.0	3.63
705	5.96	1.55	0.80	22.0	5.60
706	12.8	7.65	0	37.0	7.70
714	16.6	7.37	0.40	37.0	7.97
717	-	-	-	-	5.70
726	4.40	1.83	0	33.0	7.70
727	12.9	1.09	1.30	25.0	5.17
728	23.8	6.01	0	22.0	5.07
730	14.1	8.26	1.0	42.0	6.17
751	13.8	2.80	0	82.0	9.07
880	-	-	-	-	1.83
950	28.6	17.9	0	30.0	4.47
990	2.30	0.03	0.90	25.0	4.43
1077	12.0	7.70	0	46.0	4.23
1098	7.20	1.48	0	13.0	4.07
1167	-	-	-	-	4.67
1173	11.5	7.70	0	42.0	6.93
1176	16.7	9.07	0	45.0	8.00
1198	1.65	0.00	19.5	29.0	6.10

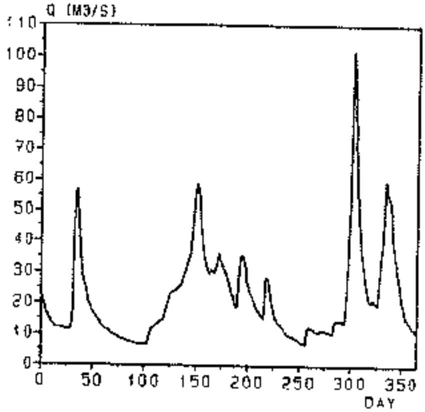

Figure 1 Station no. 694 (Large value of lake index). Flood hydrograph.

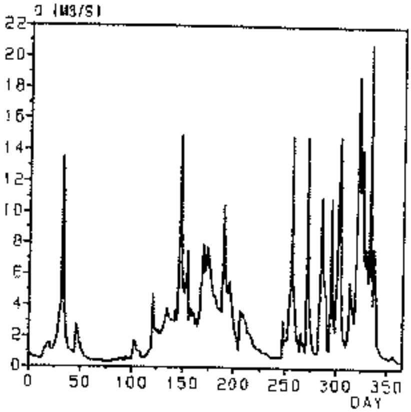

Figure 2 Station no. 751 (Large value of catchment gradient). Flood hydrograph.

Catchment characteristics are given in Table 1 comprising lake index A_L, effective lake index, A_{LE}, glacier index, A_G and catchment gradient, G. In addition, the mean annual number of exceedances λ corresponding to a fixed threshold level of $E\{Q\} + S\{Q\}$ $(k=1)$ is given.

The mean annual number of exceedances is significantly correlated with the lake index (negative correlation) and the catchment gradient (positive correlation). The effects on the hydrograph of large values of the lake index and the catchment gradient, respectively, are shown in Figs. 1-2. A high value of A_L smooths out the hydrograph, whereas the runoff from a catchment with a high value of G is characterized by a flood hydrograph with many peaks.

The effect of glacier activities is shown in Fig. 3. This hydrograph shows that the glacier melting produces runoff in late spring and summer, whereas the runoff in autumn is dominated by rainstorms. This highly irregular pattern may indicate that the exceedances have to be described by a seasonal model.

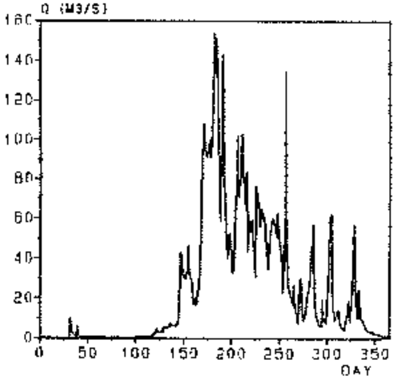

Figure 3 Station no. 1198 (Large value of glacier index). Flood hydrograph.

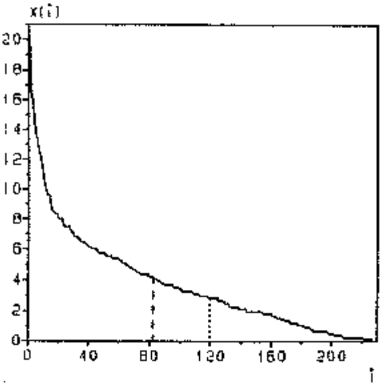

Figure 4 Station no. 726. Ordered sample of the largest peak exceedances. Limit of extreme value region for $k=1$ (dotted line) and for $k=2$ (dashed line).

4. DETERMINATION OF THE EXTREME VALUE REGION

Before the PDS model can be applied, the threshold level has to be selected. If possible, a threshold level with a physical interpretation should be chosen. A direct physical interpretation is, however, not always possible, and other criteria for choice of the threshold level have to be inferred. In addition to the objective of a good fit to the model assumptions two conflicting interests must be considered when determining the threshold level. On the one hand it is desirable to include only peaks which in fact are true extreme events and on the other hand it is desirable to include as many exceedances as possible in order to make reliable predictions.

In this section some more or less arbitrary rules for choice of the threshold level will be analysed and compared to a test of significance for selection of extreme events. From a statistical point of view rules for the threshold determination can be formulated in terms of statistical properties of the analysed samples. This includes for example: (1)

Selection of the threshold level on basis of the coefficient of variation of the exceedances and (2) Selection of the threshold level on basis of the ratio of variance to mean of the annual number of exceedances. When applying the PDS model to a region of several catchments one may formulate more "general" rules. This includes for example: (3) Use of a standard frequency factor and (4) Use of a fixed number of exceedances.

Table 2 Mean annual number of exceedances for different choices of threshold level (MK-test = Mann-Kendall test).

Station No.	Mean annual number of exceedances			
	C_v = 1	R = 1	k = 3	MK-test
685	4.90	2.50	3.30	2.73
694	0.60	2.03	1.13	1.20
705	-	2.80	1.83	2.33
706	2.03	3.40	2.97	4.07
714	4.17	3.87	3.87	4.20
717	2.77	1.27	2.83	1.30
726	3.60	2.20	3.37	4.00
727	3.90	3.37	1.97	2.00
728	4.70	-	1.90	1.10
730	-	3.50	2.37	3.57
751	1.13	1.73	4.50	4.73
880	-	-	0.97	1.53
950	-	1.87	1.37	2.57
990	1.40	-	2.13	1.73
1077	0.57	-	1.47	1.60
1098	1.60	-	1.67	2.20
1167	2.00	1.90	2.00	1.07
1173	-	3.33	2.87	3.70
1176	4.47	1.73	2.53	4.27
1198	2.73	-	1.97	0.73

(1) Coefficient of variation. As the coefficient of variation, C_v, for the ED equals one, the threshold level may be chosen where C_v stabilizes around unity. The mean annual number of exceedances above the chosen threshold when this method is applied to the 20 sites is given in Table 2. In some cases the method is not applicable because C_v is greater than or less than 1 in the whole range of analysed thresholds, which may indicate that other models yield a better fit. In other cases C_v fluctuates around 1, which implies that the threshold level can not be defined properly. Besides these problems the method in some cases leads to a very high threshold. This yields a significantly reduced sample size resulting in very unreliable predictions of the T-year event.

(2) Ratio of variance to mean. (NRCC, 1989) recommended to choose the threshold level where the ratio, R, of observed variance to observed mean of the annual number of exceedances stabilizes around unity (for the Poisson process the ratio is equal to 1). The mean annual number of exceedances above the threshold determined by this method is given in Table 2. The method creates the same problems as the C_v-method.

Besides the above mentioned problems with method (1) and (2) the two methods must be advised against because they do not account for the variation of the physical properties in the region.

(3) Standard frequency factor. (Rasmussen and Rosbjerg, 1991a) used a standardized choice of threshold in the application of the PDS model to regional flood frequency estimation. They found that the ED fitted reasonably well when the threshold was fixed at a level corresponding to a frequency factor of k=3. The mean annual number of exceedances extracted from the record with a frequency factor of k=3 varies from 1.0 to 4.5, see Table 2. This variability obviously reflects the variation of the physical properties in the region as described in section 3. Hence, the method, to some extent, ensures that the extracted peaks in fact are true extreme events.

(4) Fixed number of exceedances. The above described methods may in some cases produce insufficient data material for the statistical inference when a relatively high threshold is chosen. To remedy this problem a censoring method where the number of peaks is fixed can be used. (Buishand, 1989) analysed this method in a PDS model with a Poisson-distributed number of peaks and exponentially distributed peak exceedances and derived asymptotic expressions for variance and bias of the T-year event estimator. He concluded that the censoring methods leading to, respectively, a variable and a fixed number of flood peaks are of similar efficiency. Hence, there is no preference of one method to the other in terms of statistical efficiency. The disadvantage of the method with a fixed number of flood peaks is, however, that it does not reflect the variability of the physical properties within the region. Thus the method must be advised against unless the analysed region is very homogeneous.

The disadvantage of all the above described methods is that the threshold determination is more or less arbitrary. A method presented by (Gerstengarbe and Werner, 1989) and applied to meteorological time series remedies this disadvantage, allowing a region of extreme values to be defined by a statistical test.

The test is based on the ordered sample of the peak exceedances, $x_{(i)}$, ($x_{(1)} \geq x_{(2)} \geq$ ..... $\geq x_{(N)}$) and the series of differences between adjacent peaks, $y_i = x_{(i)} - x_{(i+1)}$, i = 1,..,N-1. The limit of an extreme value region is defined as the point above which the changes of the differences are significantly different from those of the remaining region. This is the point where a significant tendency in the differential series starts. The point can be found by the sequential version of the Mann-Kendall test described by (Sneyers, 1975).

The Mann-Kendall test is applied gradually in two directions; from the beginning of the series and vice versa. The test statistic, t_i, defined for every step i in forward direction is

$$t_i = \sum_{k=1}^{i} n_k \quad ; \; i = 2,..,N-1 \tag{6}$$

where n_k is the number of elements in the differential series from 1 to k-1 which is less than y_k. Under the null-hypothesis (no tendency in the series) t_i is approximately a normal deviate with mean and variance

$$E\{t_i\} = \frac{i(i-1)}{4} \quad ; \quad Var\{t_i\} = \frac{i(i-1)(2i+5)}{72} \quad ; \; i = 2,..,N-1 \tag{7}$$

Hence, the reduced variable u_i and the corresponding variable in backward direction u'_i

$$u_i = \frac{t_i - E\{t_i\}}{(Var\{t_i\})^{1/2}} \quad ; \quad u_i' = -u_{t_{i'}} = -\frac{t_{i'} - E\{t_{i'}\}}{(Var\{t_{i'}\})^{1/2}} \quad ; \; i' = N-i \tag{8}$$

are standardized normal deviates. The point of intersection between u_i and u_i' defines the beginning of a tendency if one of the curves exceeds the level of significance for a chosen error size.

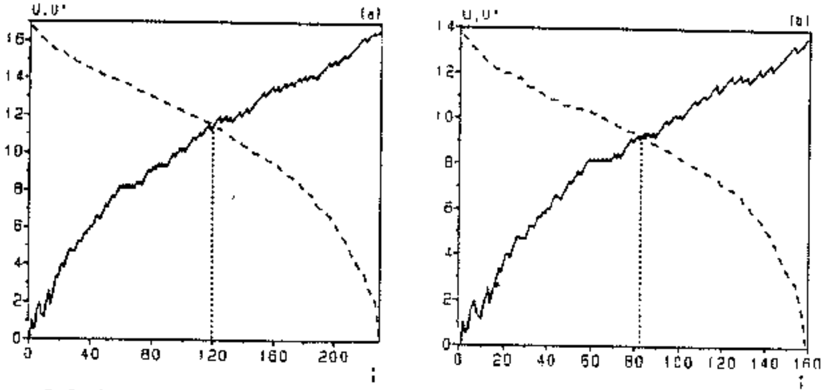

Figure 5 Station no. 726. Result of the Mann-Kendall test: u (solid line), u'(dashed line). Peaks above a threshold of (a) k=1 and (b) k=2 included in the analysis.

The method is illustrated for one of the gauging stations in Figs. 4-5. Fig. 5 shows the result of the sequential version of the Mann-Kendall test applied to the series of differences obtained from the ordered sample in Fig. 4. The test is carried out including peaks above a threshold of k=1 and k=2, respectively. Since the curves in both cases exceed a level of significance corresponding to the 99.95% quantile in the standardized normal distribution, the point of intersection between the two curves defines the limit of the extreme value region. It is seen that this limit to some extent depends on the number of exceedances included in the analysis. When more exceedances are included, the limit of the extreme value region increases and vice versa. Therefore, it is necessary in an appropriate manner to choose the site of the region within which the extreme values are sought out before the Mann-Kendall test is applied. As mentioned in section 3 the determination of the extreme value region should be related to the physical catchment properties. For that reason a standard frequency factor, k=1, is used to define the region from which the extreme peaks are selected for the PDS-analysis.

The Mann-Kendall test is applied to the 20 sites. Figs. 6-7 show the results obtained from two obviously different gauging stations. The series of the ordered sample in Fig. 6a is in the beginning very steep in comparison to the remaining of the series, which implies an extreme value region of very few exceedances (Fig. 6b), whereas the series in Fig. 7a is virtually linear implying an extreme value region including almost all exceedances (Fig. 7b).

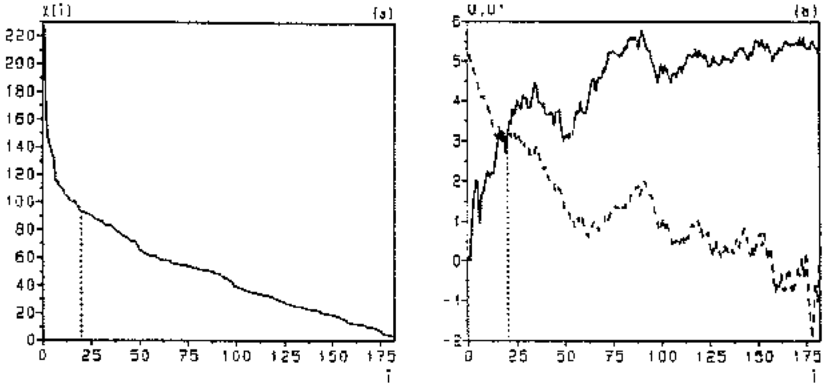

Figure 6 Station no. 1198. (a) Ordered sample of the largest peak exceedances. (b) Result of the Mann-Kendall test: u (solid line), u'(dashed line).

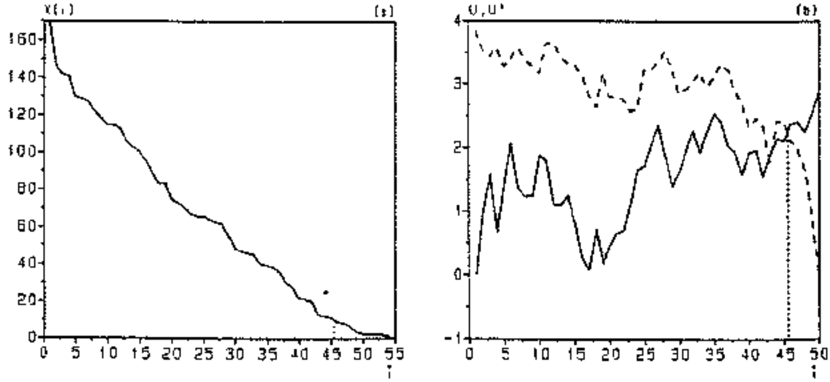

Figure 7 Station no. 880. (a) Ordered sample of the largest peak exceedances. (b) Result of the Mann-Kendall test: u (solid line), u'(dashed line).

The results of the Mann-Kendall test for all the 20 sites are given in Table 2. The mean annual number of exceedances varies from 0.7 to 4.7. When comparing the extremities it is seen that the statistical separation of the extreme value region is strongly correlated with the physical properties within the region. The flood hydrograph for station no. 751 (Fig. 2) shows that floods appear frequently throughout the year, and hence one may expect many exceedances to be included in the extreme value region. This is in fact the result of the Mann-Kendall test, which yields an extreme value region with a mean number of exceedances of 4.7 per year. Contrary to this station the floods at station no. 1198 (Fig. 3) are dominated by glacier melting, which yields very few extreme events per year. The Mann-Kendall test for this station results in an extreme value region with a mean number of exceedances of 0.7 per year.

Three other stations (no. 717, 728 and 1167) show the same seasonal pattern of flood appearence as station no. 1198. In these cases, too, the Mann-Kendall test results in an extreme value region with very few exceedances. Compared to the standard frequency factor method the four stations (no. 717, 728, 1167 and 1198) are assigned significantly smaller extreme value regions by applying the Mann-Kendall test. This may indicate that these four stations have to be modelled as two-component populations.

5. CONCLUSION

In order to remedy the subjectivity involved in the determination of the threshold level when applying the PDS model to flood frequency studies some rigorous rules for selection of the threshold level have been formulated. The rules have been applied to data sets of 30 years' length from 20 Norwegian catchments. The determination of the threshold level was not only made on statistical grounds but also the physical properties of the analysed catchments were taken into account.

Four arbitrary methods for the threshold determination have been analysed. It has been concluded that the selection of the threshold level on basis of the coefficient of variation of the exceedances and the ratio of variance to mean of the annual number of exceedances must be advised against. Firstly, because they only take into account the statistical properties of the analysed samples and, secondly, because they are difficult to apply in practice. The use of a fixed number of peaks is also advised against since it completely disregards the physical properties within the region in the threshold determination. The standard frequency factor method may be applicable because it, to some extent, reflects the physical reality and hereby ensures that the extracted peaks are true extreme events.

To obtain a more objective formulation of the threshold determination a test of significance for selection of the extreme value region has been introduced. The statistical separation of the extreme value region from the remainder of the region has been conducted by use of the sequentiel version of the Mann-Kendall test. It is shown that the test reflects the variability within the region stemming from the different physical properties of the analysed catchments. Compared to the frequency factor method the Mann-Kendall test seems to yield a threshold determination which, to a higher degree, ensures that the extracted peaks are true extreme events. Therefore, it is recommended in PDS-modelling to apply the Mann-Kendall test in the determination of the threshold level, especially when no a priori knowledge about the physical catchment properties is available.

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MULTISCALING PROPERTIES OF RAINFALL

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ABSTRACT

By investigating 2-year-series of 1-minute rainfall intensity measurements, a multiscaling behavior was indicated. This supports the theory that processes in the atmosphere may be described by multiplicative cascades, with variability at all scales related through a codimension function.

INTRODUCTION

During recent years a lot of investigations have been conducted aiming at finding out whether the rainfall process exhibit properties that are independent of scale, i.e. scaling or scale invariant (e.g. Lovejoy, (1982); Waymire, (1985); Lovejoy and Mandelbrot, (1985); Kedem and Chiu, (1987); Zawadski, (1987); Lovejoy et al., (1987); Rodriguez-Iturbe et al., (1989); Hubert and Carbonnel, (1989); Burlando et al., (1989); Olsson et al., (1992)). This was often done by estimating the "dimension" of the process, a number believed to be a fundamental constant that constituted a direct link between statistical properties at all scales, thus completely characterizing the variability of the process. Various methods, originally developed to study strange sets, were in most cases directly applied to measurements of clouds and rainfall fields in time and space. The results, however, were far from univocal. If scale invariance was indicated, it often seemed to be restricted to specific time and/or space intervals and the estimated dimensions rarely agreed. Based on these results it was assumed that atmospheric processes exhibit a much more complex structure than previously presupposed, with statistical properties at different scales related through a "codimension function" depending on the intensity level rather than a single dimension depending primarily on the scale ratio. In light of these findings a new approach called multiscaling has been introduced (Schertzer and Lovejoy, 1987; Lovejoy and Schertzer, 1990; Gupta and Waymire, 1990).

MULTIPLICATIVE CASCADE PROCESSES

The notion of multiscaling is intimately linked to a generalized type of processes normally denoted multiplicative cascades. The basic idea is that some large scale flux E is succesively broken up into smaller parts ("eddies"), each receiving an amount of the total flow specified by a multiplicative increment pE $(0 < p < 1)$. A theory is that this process is occurring in the atmosphere, where water thus should be concentrated in succesively smaller regions of space, at least down to viscosity-scale.

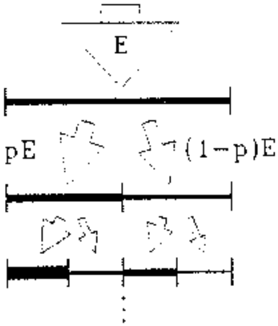

Figure 1 Multiplicative cascade in one dimension.

Figure 1 shows the principal scheme of a multiplicative cascade in one dimension. Here the flow of the "mother eddy" is unequally distributed between her "offspring eddies" in a way specified by the parameter p. By using different strategies for the flux division and for example assuming some flux dissipation at each stage of the process, this conceptually simple model can effectively imitate very complex structures such as e.g. rainfall distribution. Many of the typical features of the rainfall process, which have created severe problems for rainfall modelers, are naturally accounted for in this approach. Considering larger scales, a multiplicative cascade will automatically result in the "cellular" structure of rainfall fields that has been observed in empirical studies. Then, as moving towards smaller scales, variability keeps increasing. The extreme variability in time and space observed in high-resolution measurements, with peaks of an intensity many times the average, is a direct consequence of a multiplicative cascade process where the total flow is concentrated on succesively smaller parts of the available space.

PDMS, Probability Distribution/Multiple Scaling

A way of investigating whether a process can be characterized by multiscaling is to use the PDMS-method. Figure 2 shows the principal idea when applied to a normalized time series. The series is averaged over l intervals of succesively doubled size and then the resulting averages, f_l, are compared to a threshold value T obtained as l raised to an exponent e. Pr denotes the probability that the average value exceeds the threshold, i.e. $Pr(f_l > l^e)$. Note the relationship between the exponent e (sometimes called "order of singularity") and the intensity level. Using a high e means that only the most intense parts of the process are studied.

The uppermost time series in Figure 2 could for example be the observed rainfall for 16 consecutive days. Thus, for step 1, l is 16, T1 is 16^e and Pr is 2/16 since the measured rainfall for 2 days exceeds T1. The next step is to average the rainfall over 2 days, step 2. Now l is 8, T2 is 8^e and Pr is 2/8 since the 2-day averages in 2 cases exceed T2. In the final step the rainfall is averaged over 4 days which results in Pr = 1/4.

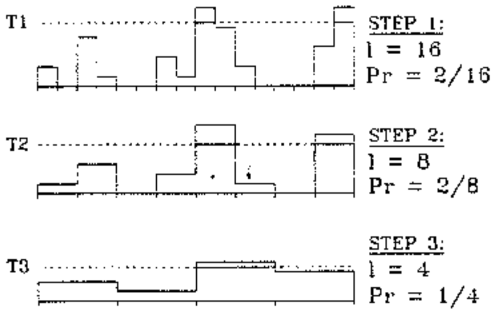

Figure 2 PDMS applied to time series.

If the time series exhibits multiscaling, the relationship between probability Pr and the number of intervals l may be written as

$$Pr \approx l^{-c(e)}$$

where c(e) is called the "codimension function". This function is scale invariant, i.e. it characterizes the variability of the process over all scales, being dependent only on the intensity level through the exponent e. A simple way of checking the relationship is to plot Pr as a function of l in a double-logarithmic diagram. If the equation is valid the points will fall on a straight line whose slope is an estimation of -c(e).

To obtain the complete codimension function c(e), the above described procedure must be carried out for different values of the threshold exponent e.

RAINFALL TIME SERIES

During the years 1979-1981 a thorough investigation of the areal and dynamical properties of the rainfall process at urban scale was performed in the city of Lund, Sweden, where 12 stations were set up covering an area of approximately 30 km^2 (Niemczynowicz, 1984). The rainfall intensity was simultaneously measured every minute by gages of tipping-bucket type having a resolution of 0.035 mm/min. Due to some interruptions the effective length of the series are 2 years. For further details about the data set and observation area see Niemczynowicz (1984, 1986a, b).

RESULTS

Figure 3 shows the result of the PDMS-method applied to the 1-minute rainfall intensity data, using values of the exponent e ranging from 0.25 to 0.55. The series was hence succesively averaged from 1 minute to 2 years, and the probability of exceeding the threshold l^e, Pr, was plotted as a function of the number of intervals, l, in a double-logarithmic diagram. Since the results from different stations were slightly different, the 6 most complete stations were analyzed, and the graphs in Figure 3 are obtained as the average result from these. The straight-lined behavior seems to be respected for the major part of the graphs, at least within the l-interval 2000 to 1000000 (corresponding to averages between 1 minute and 8 hours). The reasons for the deviations from the straight lines when averaging over the largest time intervals (i.e. $l<2000$) are yet to be fully understood.

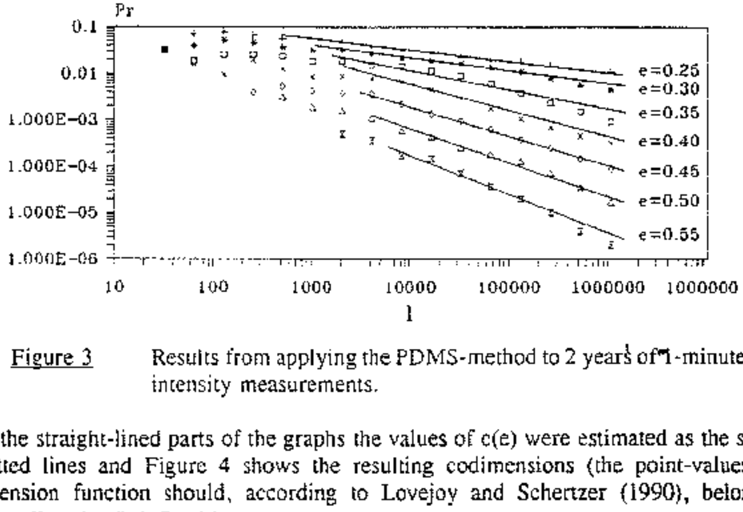

Figure 3 Results from applying the PDMS-method to 2 years of 1-minute rainfall intensity measurements.

From the straight-lined parts of the graphs the values of c(e) were estimated as the slopes of the fitted lines and Figure 4 shows the resulting codimensions (the point-values). This codimension function should, according to Lovejoy and Schertzer (1990), belong to a "universality class" defined by

$$c(e)=C_1(e/C_1\alpha'+1/\alpha)\alpha'$$

with, in this case, $0<=C_1<=1$, $0<=\alpha<=2$ and $1/\alpha+1/\alpha'=1$.

To fit this function to our calculated codimensions we use a graphical method as outlined in Lovejoy and Schertzer (1990). This resulted in $C_1 = 0.15$, $\alpha = 1.8$ and $\alpha' = 2.25$, the corresponding fit being shown as the solid line in Figure 4.

The α-value 1.8 agrees well with the value 1.7 obtained from analyzing satellite cloud pictures in Lovejoy and Schertzer (1990). However, one should not pay too much attention to the particular values since the fitting-procedure is very approximate. Let us leave it with stating that the criteria for multiple scaling seem to be reasonably fulfilled for our series.

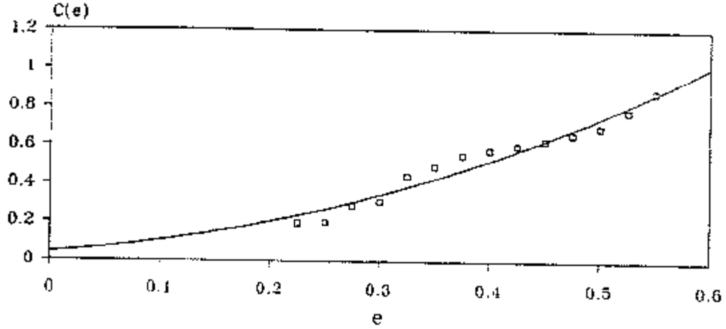

Figure 4 Point-values: codimensions obtained from the rainfall time series (the slopes in Figure 3). Solid line: fitted codimension function.

CONCLUSIONS

By applying a recently developed method for detecting possible scale invariant properties to a high-quality rainfall data set, indications of a multiscaling behavior was received. This supports the theory that processes in the atmosphere may be described by multiplicative cascades. A consequence of this is that variability at all scales are related through a codimension function. If the applicability of a multiscaling approach to atmospheric processes could be proved, this would in practice constitute a break-through for the description and modeling of rainfall fields.

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KOFOT - A PRACTICAL TOOL FOR COMPARATIVE ANALYSIS AND EXTENSION OF RUNOFF SERIES

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ABSTRACT

An important problem in hydro-power production is to establish long historical inflow series to be used for optimization and simulation purposes. This paper discusses some methods for extension of observed inflow series, when the observation period is too short for these purposes. It is particularly focused on application of the EOF-method (Empirical Orthogonal Functions). In operational use, subjective valuations and amount of work involved are minimized, at least for catchment areas exceeding some hundred km^2. The method is in no respect inferior to other methods. Methods for runoff series extension, statistical analysis, comparison of series, handling of series versus hydrological archives and comprehensive graphical presentation of results, are integrated in a program system called KOFOT. The facilities of this program will be outlined.

INTRODUCTION

In the Norwegian power production system, which is practically 100 % hydropower based, inflow series to the reservoirs play an especially important role with respect to production planning and production capacity assessment. In order to achieve reliable statistical information, these inflow series have to be sufficiently long. Normally at least 30 years of data is required, but preferably the series should be 50 years. Standard reference periods for inflow series in Norway are 1931 - 1960 or 1931 - 1980.

The existence of such long runoff series is very often limited, perhaps only 1 or 2 in a river. Furthermore the measurement location rarely corresponds to the location of the reservoir barrage, the catchment areas thus being different, both in size and vertical extension. This entails that one inflow series frequently is used for quite a few reservoirs at different altitudes, and it is well known that the representativity of the series in many cases is rather dubious.

Because the production companies normally measure inflow to each reservoir, inflow series are available for most of the reservoirs. Unfortunately they seldom cover the reference period, thus being inadequate for simulation purposes, presupposing use of standard reference period.

There were therefore obvious reasons for trying to improve the reservoir inflow statistics, taking advantage of the measurements that existed for the reservoirs.

This approach to the problem entailed two quite different sub problems:

1. How should one ascertain whether the model inflow series was of an acceptable quality compared to the measurements of reservoir inflow?
2. In case the model inflow series was found to be of inferior quality, how could an improved series be generated or how could the reservoir measurements be extended to comprise the whole reference period?

The development of the program system called KOFOT (Kontroll Og FOrlengelse av Tilsigsserier), aimed at providing methods for solutions of both these problems. The need for quality control and the need for extension algorithms were also focused on, because the lack of adequate user-oriented tools for these purposes was prominent.

The scope of this paper is to put emphasis on the EOF-method for inflow series extension, but some of the possibilities for comparative analysis and quality control will also be briefly mentioned.

METHODS FOR EXTENSION OF RUNOFF SERIES

At present there are two main methods for extension of runoff series in KOFOT: linear weighting and the EOF-method. In the near future, regression analysis will be incorporated in KOFOT as a third possibility.

In the following $Q(u_i,t)$ refers to measured runoff values at the i'th station among N ($i=1,\ldots\ldots,N$) in a certain domain Ω. t represents the time and u corresponds to geographical coordinates and t is the time. $Q'(u_i,t)$ refers to simulated runoff at the i'th station.

Weighting

Weighting is a very simple method. It means extending a short series from one station by multiplying a longer series from another station (reference series) by factors, a_k ($k=1,\ldots\ldots,n$),calculated on the basis of the differences between weekly mean values (based on standardized observations in the common observation period) at the two locations. To reduce effects of unreasonable fluctuations in the inflow differences, the factors are smoothed by using moving averages. Mathematically the weighting procedure can be described as:

$$Q'(u_i,t)=a_k \cdot Q(u_j,t) \tag{1}$$

Where:

$Q(u_j,t)$ is an existing runoff series at location u_j (the reference station)

Good correlation between the runoff at two locations is important to get reliable results.

The EOF-method

The method of Empirical Orthogonal Functions (EOF-method) has been used in statistical analysis since the 1930-ies. It is suitable for studies of variation patterns in time and space and for concentration of information in large data sets. The meteorologists started to use the EOF method for extrapolation purposes, and for studies of variation patterns in temperature, precipitation and pressure fields in the 1950-ies and 60-ies, (Grimmer, 1963), (Stidd, 1967) and (Holmström & Stokes, 1978).

Not until the early 1980-ies the method was applied directly to runoff data. Bartlein (1982) used it for studies of streamflow anomaly patterns, and Gottschalk (1985) used it as a tool for regionalization. The EOF method has previously been tested for extrapolation purposes of runoff on a monthly basis in a small study by Jutman (1985).

The search for a simple and consistent method for operational purposes initiated a project (Hisdal & Jutman, 1989) where the EOF-method was compared to regression analysis and the conceptual HBV-model. The results showed that there were no big differences between the methods in preserving the statistical characteristics of the extended series. Regression analysis and the EOF-method seemed to give better results then the HBV-model in case of large catchments and vice versa in case of small catchments. When looking at the operational use of the methods, they differ considerably. Dealing with a conceptual model the availability of precipitation and temperature data is often a critical issue. Extension of runoff series is limited to the observation period of these data. The parameters of conceptual models are often determined by visual inspection of deviations between observed and simulated runoff and from the coefficient of determination. This procedure is subjective and time consuming. It also requires a detailed knowledge of the model. Using regression analysis it is necessary to select runoff series as independent variables in the equations. This procedure too is subjective and time consuming. As shown in this paper the EOF-method is time saving and the results are consistent amongst different users. The main conclusion is that the EOF-method is to be preferred as a standard operational method. If possible, the method should be supplemented by a conceptual model in case of small catchments.

For a detailed description of the EOF-method see e.g. Essenwanger (1976) or Braud & Obled (1991). In the present description of the method attention is paid to the application of the method in KOFOT.

The EOF-method can be regarded as a further development of regression analysis. It is based on extracting information from all data sets in a region.The series contained in the analysis are mutually correlated.The principle behind the EOF-method is a linear transformation resulting in a new set of series called the EOFs, which are orthogonal and uncorrelated.

To avoid the influence of the catchment area in the EOF-analysis, a standardization giving

KOFOT

Regions in Norway

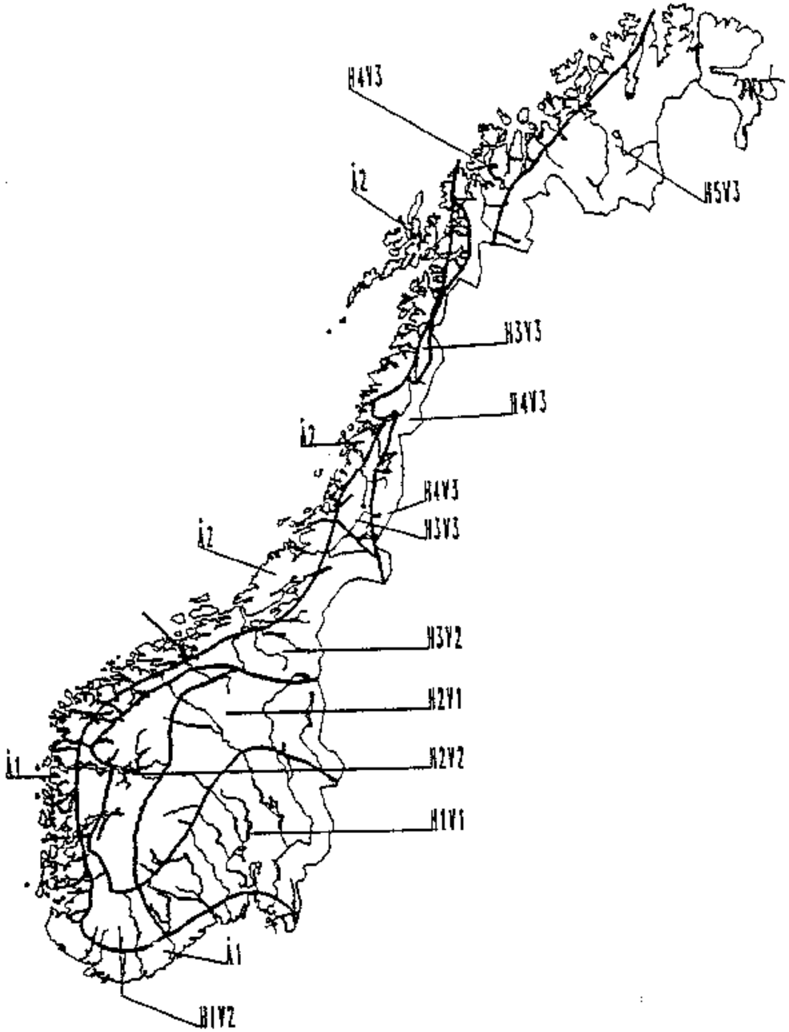

Fig. 1 Map of the regions used by the EOF-method in KOFOT

the series zero mean and standard deviation equal to unity gives the best results (Haan (1977). The standardized runoff series are denoted X(u,t). An expansion into EOFs has the form:

$$X(u,t)=\sum_{j=1}^{M} h_j(u)\,\beta_j(t) \tag{2}$$

Where:

$h_j(u)$	are weight coefficients describing the transformation
$\beta_j(t)$	are the EOFs
M	is the number of EOFs used ($M \leq N$)

The advantage of the EOFs are that they are easy to handle. They are stable and uncorrelated and each EOF contains information common to the region from which the original series are collected. They describe the runoff variations in time. A few of the EOFs will contain most of the variations in the original runoff series. They are arranged in descending order according to the proportion of variance explained by each function. Redundant information can be removed using only a few of the EOFs in the runoff simulation ($M < N$). The original runoff series are totally described if all of the EOFs ($M = N$) are used.

The weight coefficients describe the runoff variations in space. Their magnitude decide the proportion of each EOF contributing to the runoff in a specific catchment.

If the runoff pattern in the series used as input to the EOF-analysis is very different, the variance described by each EOF will be small and many EOFs are needed to describe a satisfying part of the variance. Norway has therefore been divided into geographical regions (Hisdal & Tveito, 1990), as shown in fig. 1. In addition series from catchments with more than 5% of its area covered by glaciers, form a special region. For each region an EOF-analysis is performed and a set of EOFs are established. To avoid problems of inconsistence, all series that are input in the EOF-analysis should be complete for the desired time period (in the present case daily values 1930-1985).The runoff series forming the basis of the EOFs in each specific region are described in Olaussen et.al. (1991).

In fig. 2 are shown the three first EOFs for a period of five years, given by an EOF-analysis with runoff series from region H5V3 (see fig. 1) as input. The first function describes the largest common average pattern in the runoff. The spring flood due to snowmelt can clearly be seen if the EOF is multiplied by -1, the magnitude of the first weight coefficient. The second EOF describes the time of the spring flow culmination, depending on the sign of the second weight coefficient.

The operation of extending a short runoff series by the EOF-method may be divided into two. The first part is to generate the EOFs for a region and to decide how many EOFs that are to be used for extension. This step is already performed and sets of EOFs for

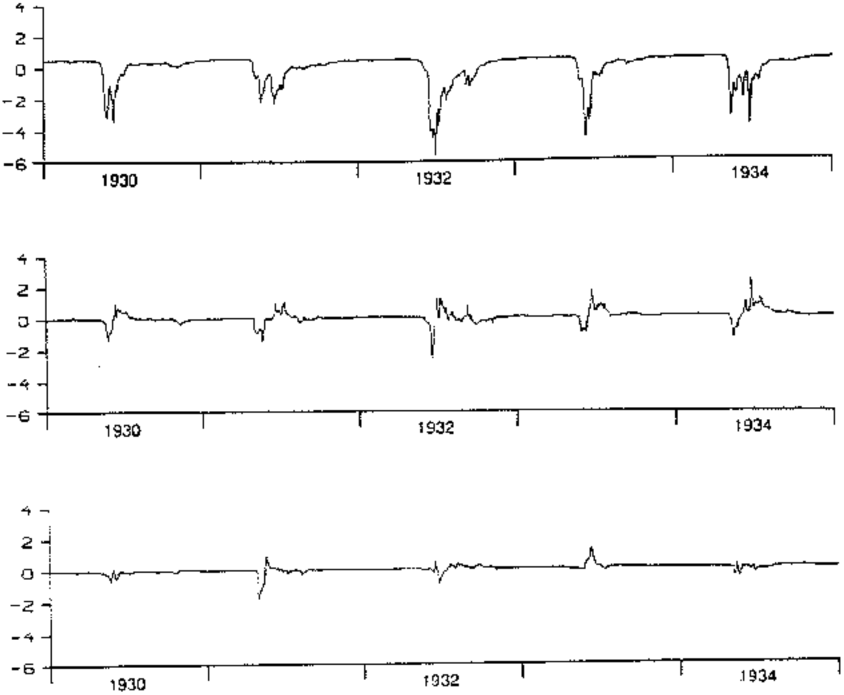

Fig. 2 First (top), second (in the middle) and third (bottom) EOF from the region H5V3 for the period 1930-1934.

each region are contained in KOFOT. The extension equation is as follows:

$$Q(u_i,t)' = \overline{Q_i'} + s'_{Q_i}\sum_{j=1}^{M} h_j(u_i)\,\beta_j(t) = \overline{Q_i'} + s'_{Q_i}\sum_{j=1}^{M} r_{ij}\,\beta_j^*(t) \tag{3}$$

Where:

$\overline{Q}_i'$ is the estimated mean value of the series to be extended
s_{Q_i}' is the estimated standard deviation of the series to be extended
r_{ij} are the estimated weight coefficients
$\beta^*(t)$ are the standardized EOFs

The second part is to calculate the mean value, the standard deviation and the weight coefficients for the series to be extended. It can be shown that the weight coefficients correspond to the correlation coefficients between the series to be extended and the EOFs.

These coefficients are calculated in KOFOT on the basis of the observed part of the series to be extended (called the calibration period). As a first estimate the mean value and standard deviation are calculated on the basis of the calibration period. These estimates deviate from those referring to the whole period of analysis. Correction factors are

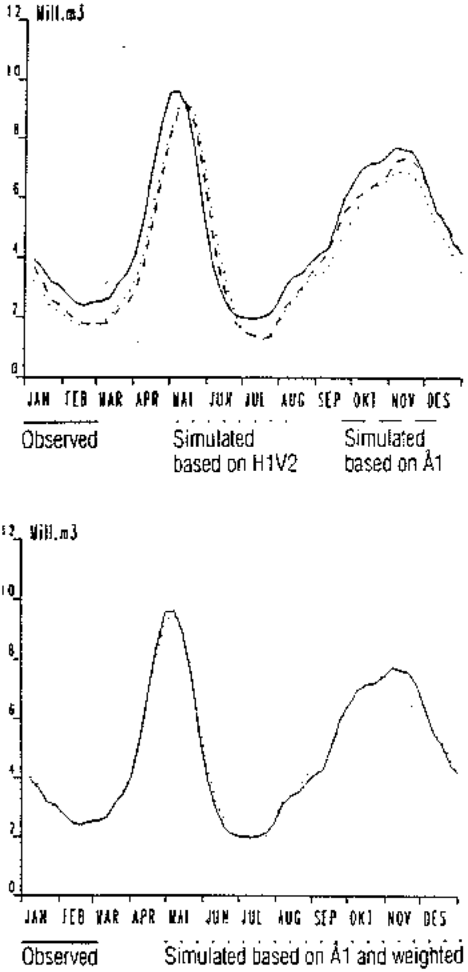

Fig. 3 Observed and simulated average weekly inflow values for the period 1951-1983 (Station 1150, Myglevatn)

calculated based on the variations in the yearly mean values and standard deviations in the runoff series contained in the EOF-analysis. Sets of correction factors for each region are incorporated in KOFOT.

The only information required to extend a series by the EOF-method in KOFOT is the region and number of the series to be extended.

As an example fig. 3 (top) shows observed and EOF-simulated series based on region Å1 and H1V2. In fig. 3 (bottom) the EOF-simulated series based on region Å1 is also weighted.

METHODS FOR QUALITY CONTROL

Trend analysis.

Trend analysis (see e.g. Hansen, 1971) is used to examine whether there are long-term trends in the inflow series. Based on a non-parametric test, counting inverse arrangements, the significance of any positive or negative trend-line is evaluated, the level of rejection being given. In KOFOT, the trend analysis is performed on accumulated yearly inflow values. The trend analysis is not meaningful with respect to the quality of a series, but a significant trend should initiate additional investigations on adjacent rivers or precipitation series for the area, to see if the trend has a logical explanation.

Double-mass analysis.

KOFOT provides the possibility to perform double-mass analysis to test inflow series against reference series for possible inhomogenities. The test is based on Searcy & Clayton (1960). It may be performed for annual or seasonal accumulated inflow.

Both the trend analysis and the double-mass analysis give results as tables, results from significance tests, and graphical plots.

Graphical analysis.

The graphical analysis provides possibilities to perform comparative plots on a yearly basis for two series, this plot also includes accumulated differences between the series. Also the annual variation of average, standard deviation and skewness may be plotted in comparative plots.

METHODS FOR COMPARATIVE STATISTICAL ANALYSIS.

Theory about the tests mentioned below can be found e.g. in Cramer (1961) or Siegel (1958).

Comparative tests for equal mean value.

This test may be performed on annual or seasonal accumulated values. KOFOT provides possibilities for as well parametrical as non-parametrical tests, dependant on whether the distributions of the inflow values may be considered as Gaussian distributed or not.

Comparative tests for equal dispersion.

This test uses a non-parametric dispersion test, and may be performed on annual or seasonal accumulated values.

Comparative tests on spring flood parameters.

There are two parameters suited for equality tests, describing the spring flood. These are:
* Starting week of the spring flood.
* Maximum relative inflow intensity (weekly).

For both these parameters are used non-parametric tests for equality.

CONCLUSION

The most important feature of KOFOT is its flexibility in use, operating against different hydrological archives, and providing various possibilities of manipulation and plotting of inflow series. Especially important is its interface to power production simulation programs, making it particularly attractive for the power production utilities.

Concerning extension methods, the time needed and consistency in the results are important factors when considering the applicability of a method. For operational use, these aspects also have to be considered together with the ability of the method to reproduce the statistical characteristics of the runoff series.

By incorporating the EOF-method in a program system like KOFOT, a rather sophisticated statistical method is transformed into a robust, consistent and quick tool for extension purposes.

KOFOT is a result of a cooperation between research institutes, water resources administrations and a group of users, the latter assuring that relatively advanced methods has been brought to common knowledge, and given the necessary practical "touch".

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LANDSAT THEMATIC MAPPER (TM) DERIVED REFLECTANCE FROM A MOUNTAINOUS WATERSHED DURING THE SNOW MELT SEASON

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ABSTRACT

Landsat-5 Thematic Mapper (TM) reflectances recorded in May 1989 from a mountainous catchment at Kvikne, Norway, are analyzed and compared with that simultaneously measured *in situ* albedo. The satellite registered shortwave snow albedo comparable to bare ground albedo and as low as 0.19 was found in areas where the snow was highly metamorphosed and heavily blackened by organic material. However, the contrast between snow and snow-free areas can be strongly improved by using a normalized TM Band 2-5 difference image. While TM Band 2 shows varying degrees of snow surface contamination within the study area, is the normalized TM Band 2-5 difference image not affected by impurities. Further, a normalized TM Band 2-4 difference image indicates that about one third of the variability in TM Band 4 is caused by effective snow grain size variations while the remaining is a result of surface contamination. Finally, the satellite reflectances have been corrected for atmospheric absorption and scattering present on the day of the satellite overpass.

1. INTRODUCTION

Information from satellite sensors, which register surface reflective characteristics, is commonly used to describe remote areas such as snow-covered mountainous terrain. Sensors with different spectral, temporal and spatial resolution are able to describe various snow properties and conditions. For example, snow storage can be estimated from the percentage of terrain that is snow-covered. Subsequently, short- or long-term forecasts of watershed runoff for the spring flood season can be outlined (Andersen, 1982; Lillesand *et al.*, 1982; Martinec, 1985).

The difference in reflective properties between snow and other surfaces is normally quite large, making it possible to distinguish and map these areas within a catchment. Nevertheless, at the end of the snow-melt season the snow-cover tends to become unevenly distributed, especially in mountainous areas. Numerous small patches of snow are surrounded by larger snow-free areas. Even inside one image pixel several surfaces with different characteristics might occur, creating mixed pixels. Under such conditions there are advantages in using satellites with high resolution to limit the number of mixed pixels. For example, one NOAA AVHRR-pixel covers an area equal to that which is covered by 1490 TM-pixels due to the different spatial resolution of the two sensors. Additionally, the snow albedo is lowered due to contamination transported from surrounding snow-free areas and from the on-going metamorphosis of the snow pack.

Better knowledge of temporal and spatial variability of albedo for both snow-covered and snow-free areas would be useful for a more accurate interpretation of satellite images, especially late in the melting season. In this study, field measurements of snow albedo, snow temperature, density and structure together with meteorological and surface observations were collected simultaneously with a Landsat-5 Thematic Mapper overpass. Albedo recordings were carried out on a wide variety of surfaces with the intention to register variability in reflectance, especially for snow. Then using field measurements, supervized image training areas were selected to include the main surface categories and subsequently analyzed and compared with *in situ* snow albedo measurements. Some typical spectral variations of snow albedo are presented. Overall, this study demonstrates some of the problems connected with the interpretation of satellite images recorded during the snow-melting season.

2. STUDY AREA AND *IN SITU* ALBEDO MEASUREMENTS

Field measurements and image analyses were executed within a 4.5 x 4.5 km segment surrounding Lake Falningsjøen at Kvikne, Norway (Figure 1). Elevations in the study area

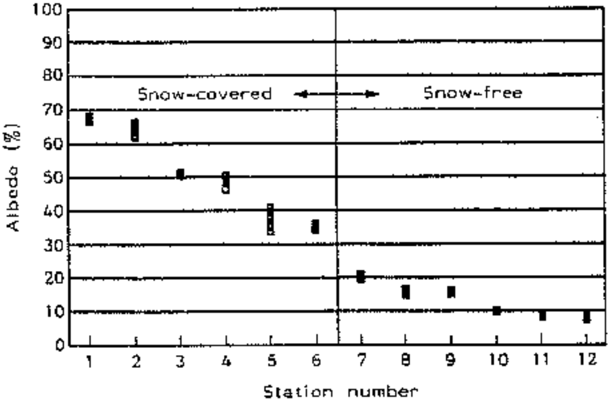

Fig. 1. *In Situ* measurements of shortwave albedo carried out on 22-24 of May 1989.

range from 843 to 1241 m.a.s.l. Lake Falningsjøen is situated at 850 m.a.s.l., while there in some areas is exposed rock, the terrain surface is mainly covered by moss, heather, bog, scrub, and low birch wood. Field measurements of albedo were collected at twelve different stations using two simultaneously logging portable Aanderaa pyranometers, one up-looking and one down-looking (Winther, 1989). The pyranometers have an effective wave length range of 300 to 2500 nm. At each station twenty consecutive albedo recordings were executed (Figure 1).

3. IMAGE ANALYSES RESULTS

Eight characteristic training areas, most of them approximately horizontal, are selected using an ERDAS software system (Table 1). The reason for selecting training areas in horizontal terrain is to minimize the effect of anisotropic snow reflection. For example, the specular reflection from sun-exposed sloping areas increases the reflectance measured by the satellite sensor. Thus, such areas appear brighter than they are.

Table 1. Characteristics of the selected training areas.

Training area	Surface type	No. of pixels	% of total area
TR 1	Snow at the Lake Falningsjøen	5847	25.6
TR 2	Blackened snow along the shore of Lake Falningsjøen	1196	5.2
TR 3	Blackened snow on land	4859	21.3
TR 4	Clean snow, relative flat terrain	3933	17.2
TR 5	Clean snow, sun exposed terrain	1855	8.1
TR 6	Moss and heather	1305	5.7
TR 7	Mainly exposed rock	2319	10.2
TR 8	Open water	68	0.3
			SUM = 93.6

The percentage covered by each training area within the study area is indicated (Table 1). Firstly, pixels are selected inside each of the eight surface categories chosen during the field measurements. The number of pixels selected by supervised classification depends on the size of the training area, ranging from about 40 (TR8 - open water) to about 1500 (TR1 - Lake Falningsjøen). Secondly, statistically similar areas are assigned to the original training areas using a maximum likelihood (Bayesian) classification method. The classification process computes the likelihood of the pixel belonging to each category. The category with the maximum likelihood is chosen as the output category. The number of pixels within each training area increased during the process of classification to include sloping areas as well. As shown, about six percent of the study region is not classified within the selected surface categories (Table 1).

3.1 Surface Albedo

Analyses of spectral variations within and among training areas were performed using TM Bands 2, 4 and 5. Results from the statistical analyses show at-satellite narrow-band albedo[1], atmospheric corrected narrow-band albedo[2] and atmospheric corrected shortwave albedo[3], respectively (Table 2).

Atmospheric corrected data are computed using the 5S computer code for the simulation of satellite signals in the solar spectrum (Tanré *et al.*, 1990). The 5S code allows estimation of solar radiation backscattered by the Earth-surface-atmosphere system, as it is observed by a satellite sensor. Calculations of atmospheric corrections due to gaseous absorption and scattering by molecules and aerosols are based on input specifications like geometrical conditions, atmospherical model (subarctic summer), aerosol characteristics (type and concentration), spectral band of observation, and the ground reflectance. For a specified ground reflectance the apparent or at-satellite reflectance is determined by the model.

3.2 Normalized TM Band Difference Images

The following two combinations of TM Bands 2, 4 and 5 have been used to obtain an improved contrast in the image and to map snow grain size variations (Dozier, 1989):

$$[\rho_p(TM2) - \rho_p(TM5)]/[\rho_p(TM2) + \rho_p(TM5)] \qquad (1)$$

$$[\rho_p(TM2) - \rho_p(TM4)]/[\rho_p(TM2) + \rho_p(TM4)] \qquad (2)$$

The normalized TM Band 2-5 difference image (Equation 1) emphasizes the contrast between snow and bare ground (Table 3), whereas the normalized TM Band 2-4 difference image (Equation 2) is sensitive with respect to grain size. High values represent large snow grains. It is clearly important to notice that the values in Table 3 are *relative* and scaled to lie within the interval 0 - 1. Consequently, they are not direct comparable with the albedo values (Table 2).

Table 2. Reflective properties of the training areas using TM Bands 2, 4 and 5.

Training area	Band	Albedo[1] and standard dev.	Albedo[2] (atm. corr.)	Albedo[3] (0.4 μm - 2.5 μm)
TR 1 (snow on the lake)	TM2	0.45 ± 0.04	0.49	0.31
	TM4	0.33 ± 0.03	0.35	
	TM5	0.01 ± 0.00	0.01	
TR 2 (blackened snow)	TM2	0.33 ± 0.05	0.35	0.19
	TM4	0.21 ± 0.04	0.22	
	TM5	0.01 ± 0.00	0.01	
TR 3 (blackened snow)	TM2	0.52 ± 0.03	0.57	0.44 (0.50)[4]
	TM4	0.46 ± 0.03	0.50	
	TM5	0.01 ± 0.00	0.01	
TR 4 (clean snow)	TM2	0.61 ± 0.03	0.67	0.52 (0.64)[4]
	TM4	0.55 ± 0.02	0.59	
	TM5	0.01 ± 0.01	0.01	
TR 5 (clean snow)	TM2	0.73 ± 0.02	0.80	0.66
	TM4	0.69 ± 0.03	0.75	
	TM5	0.02 ± 0.01	0.02	
TR 6 (moss and heather)	TM2	0.18 ± 0.07	0.18	
	TM4	0.23 ± 0.03	0.26	
	TM5	0.14 ± 0.04	0.15	
TR 7 (exposed rock)	TM2	0.15 ± 0.01	0.15	
	TM4	0.23 ± 0.02	0.26	
	TM5	0.21 ± 0.01	0.23	
TR 8 (open water)	TM2	0.11 ± 0.02	0.10	
	TM4	0.05 ± 0.02	0.05	
	TM5	0.00 ± 0.00	0.00	

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[1] Values are not corrected for gaseous absorption and molecule/aerosol scattering in the atmosphere.

[2] Atmospheric correction is executed (Tanré *et al.*, 1990)

[3] Narrow-band TM 4 albedos are converted into shortwave albedo (0.4 μm - 3.0 μm) to make comparison with field measurements (Hall *et al.*, 1989).

[4] Spectrally and geographically comparable field measurements (TR 3 and TR 4).

Table 3. Results and corresponding standard deviations from the normalized TM Bands combinations, Equations (1) and (2).

	TR 1	TR 2	TR 3	TR 4	TR 5	TR 6	TR 7	TR 8
$TM(\frac{2-4}{2+4})$	0.37±0.05	0.58±0.11	0.24±0.01	0.22±0.01	0.18±0.01	0.26±0.05	0.22±0.04	1.00±0.00
$TM(\frac{2-5}{2-5})$	0.93±0.02	0.90±0.02	0.92±0.03	0.92±0.01	0.91±0.05	0.17±0.11	0.07±0.02	0.91±0.08

Scatterplots of TM5 & TM2 and TM5 & (TM2-TM5)/(TM2+TM5), respectively, for the training areas (column 4 in Table 2) are displayed (Figure 2). The two scatterplots clearly demonstrate the improvement with respect to image contrast using the normalized TM Band 2-5 difference image. Scatterplots of TM4 & TM2 and TM4 & (TM2-TM4)/ TM2+TM4), respectively, are presented (Figure 3). TM Band 2 is mainly sensitive to impurities and is typically not highly sensitive to grain size (Dozier, 1984). Therefore training areas 1 through 5 are located along the TM2-axis (x-axis in Figure 3 a)) corresponding to their degree of surface blackening. Hence, the area at the shore of Lake Falningsjøen (TR2) is most blackened, while clean snow at higher elevations has a higher albedo (TR4 and TR5).

However, in TM Band 4 there is a contribution from variable grain size. Thus, the spreading in albedo along the TM4-axis (y-axis in Figure 3) is caused by a combination of impurities and grain size variations. The effect of impurities in TM Band 4 is lower than in TM Band 2 (Wiscombe and Warren, 1980). As there is a lack of data describing spectral snow albedo contaminated by organic material, soot contamination is used to determine the influence in TM Band 4 albedo relative to TM Band 2 (Clarke and Noone, 1985). The soot surrogate (M 71) with properties similar to those observed for atmospheric soot indicates that the radiative absorption at 0.800 µm (– TM Band 4) is 0.8 relative to the absorption at 0.525 µm (– TM Band 2). It can be calculated from the basic data that the variation in snow reflectance for TM Band 2, ΔTM_2 is 0.45, while ΔTM_4 is 0.53 (Figure 3 a)). Then, based on the assumption above, approximately two thirds (0.45 · 0.8 /0.53 = 0.68) of TM Band 4 variability is caused by surface impurities. The remaining is due to grain size variations.

According to Dozier (1989), Equation (2) is mainly a grain size index, although it is sensitive to contamination. Assuming this index is not affected by snow impurities, the spread along the x-axis contains only reflective variations caused by varying grain size (Figure 3 b)).

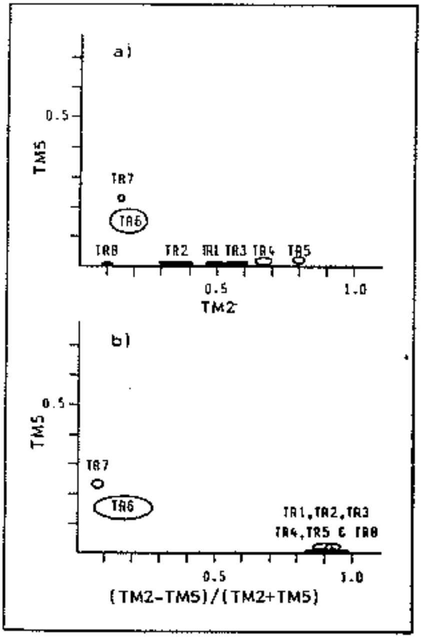

Fig. 2. Scatterplots represent combinations of respectively a) TM5 & TM2 and b) TM5 & (TM2-TM5)/(TM2+TM5). Ellipses indicate ± 1.0 σ. The separation between snow-covered areas and other surfaces is very good, the only exception being open water (TR8).

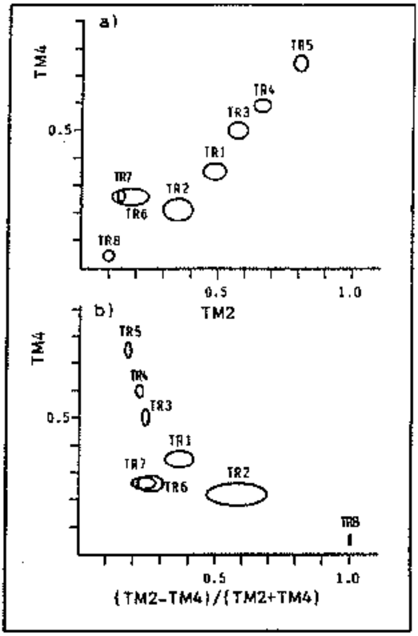

Fig. 3. TM Band 2 is insensitive to grain size. Consequently separation of training areas 1 through 5 along the x-axis in a) is mainly caused by snow surface contamination. In TM Band 4, however, there is both a contribution from variable grain size and surface contamination.

4. DISCUSSION

In this study satellite registered shortwave snow albedo is shown to vary between 0.19 and 0.66 (Table 2). Consequently, as stated earlier, these large variations in shortwave snow albedo due to surface contamination and various states of snow metamorphosis create serious problems for making high-quality estimates of snow-covered area. As an example, TM Band 4 albedo in TR 2 (snow) is lower than TM Band 4 albedo in TR 6 and TR 7 (snow-free areas) (Table 2). Thus, it seems that the separation of dirty snow from bare ground is difficult within this wavelength region. Besides, this is clearly important when snow coverage is calculated from NOAA AVHRR Channel 2 (0.72-1.10 µm). Even if the contrast is better in TM Band 2, the data suggest that multispectral analyses should be used to improve the image contrast.

snow coverage is calculated from NOAA AVHRR Channel 2 (0.72-1.10 μm). Even if the contrast is better in TM Band 2, the data suggest that multispectral analyses should be used to improve the image contrast.

Higher contrast between snow and snow-free ground is obtained using a normalized TM Band 2-5 difference image. The normalized TM Band 2-5 image is not influenced by the extreme blackening of the snow in training areas TR 2 and TR 3 (Table 3). However, it is obvious that the normalized image must be combined with a monospectral image (e.g. TM Band 2 or TM Band 4) to separate open water from snow (Figure 2). Dozier (1989) suggests a threshold value of 0.4 in Equation (1) to distinguish snow from soils. Based on this study, however, it seems like the threshold value might be increased to at least 0.7 without missing any areas covered by snow (Figure 2). Despite the fact that this contrast image might be useful for many purposes, it is not sufficient for an automatic snow mapping procedure. Firstly, a snow/cloud discrimination routine has to be applied using TM Band 5. Secondly, a criteria to distinguish snow from other surfaces in shadowed areas is necessary.

While Equation (1) aims to separate snow from other surfaces, Equation (2) detects surface properties within the snow-covered areas. Detectable snow surface properties include effective grain size and amounts of impurities. As the snow grain size increases, the snow albedo drops. The reason for this can be explained by the way electromagnetic waves (or light) is scattered in an air/ice composition such as snow. Scattering of the light, and consequently a possible escape out of the snow pack, is only feasible at an air-ice interface. Obviously, the number of possible escapes or reflection events decreases as the number of grains within an unit area decreases. Thus, growth and subsequently rounding of snow grains reduce the snow albedo. The term effective grain size is used to include the effect of liquid water in the snow pack. Liquid water simply increases the effective grain size since the refractive index contrast between water and ice is small (Warren, 1982).

Impurities influence the albedo in the TM Band 4 region, even though the effect drops quickly for wavelengths greater than 0.8 μm (Patterson, 1981; Hobbs *et al.*, 1981). With wavelengths greater than 1 μm the effect of impurities is negligible (Warren, 1982).

The above comments indicate that the portion of TM Band 4 albedo variability caused by grain size normally dominates. The situation during the field period, however, was air temperatures close to +20°C and a fully saturated and well advanced metamorphosed snow-cover. For this reason, it is supposed that variability in the degree of metamorphosis was substantially lower than surface contamination variability. Unfortunately, no measurements of grain size and shape were carried out within the training areas. Such measurements will be included in future studies.

Interestingly, if only one third of TM Band 4 variability originates from various degrees of metamorphosis, then the normalized TM Band 2-4 difference image seems to be a good grain size indicator (Figure 3 b)). It would be of great interest to apply the grain size indicator to an image consisting of a more well-defined snow metamorphosis pattern. Obviously, future studies should also aim to verify to what extent impurities influence the normalized TM Band 2-4 difference image. Such a verification would then make the surveillance and determination of contaminated snow possible, no matter the degree of snow metamorphosis. This is particularly interesting for large-scale mapping of snow pollution for instance from volcanic eruptions, desert sands, and big fires.

Finally, a comparison is shown of shortwave albedo measured from the satellite and *in situ* measurements (Table 2). Satellite-derived albedo is calculated for every pixel in the image, that means calculation of 4859 albedo values for TR 3 and 3933 albedo values for TR 4 (Table 1). Next, the albedo values are averaged within each of the training areas and presented as a single value (Table 2). Similarly, the geographically comparable albedo measured in the field is an average from 40 measurements both for TR 3 and TR 4. Only TR 3 and TR 4 are geographically comparable with field measurements, and the deviation is respectively 13.6 and 23.1 per cent. When similar measurements were carried out on a glacier in Greenland (Hall *et al.*, 1990), an average deviation of 5.0 - 6.0 % was observed. In this study, *in situ* albedo recordings are assumed to be too large. This is considered to be caused by sensor inaccuracy from the measurement arrangement. For instance, there was no horizontal screen attached to the down-looking pyranometer sensor, preventing it from being directly exposed to incoming solar radiation. Naturally, this generates too high albedo values, and is considered a major error source. Moreover, the topography affects the satellite-derived reflectance in such a way that illumination and reflectance from sloping areas deviate from the true spectral response characteristics to those areas. The geometry between the sun, the target orientation, and the sensor, might vary from one pixel to another. Therefore, this generally results in darker parts of the image facing away from the sun and the brighter areas being sun-facing slopes. The topographic effects are most pronounced at low sun elevations. The terrain in the study area is moderately rugged and the solar elevation was 45.9° during the image recording. No corrections for topograpic effects have been carried out.

5. CONCLUSIONS

Spectral and spatial resolution make the Landsat Thematic Mapper useful for detailed studies of snow. The shortwave snow albedo is highly variable in the snow melt season. This study determines that the snow albedo ranges between 0.19 and 0.66. Surface contamination, high liquid water content in the snow pack and snow metamorphosis are reasons for the extreme low albedos found in the study area. In addition, an increasing number of pixels consisting of both areas covered by snow and snow-free ground occur in the spring. This makes mono-spectral satellite registered estimates of snow-covered areas a difficult task.

Interestingly, estimates of the percentage of snow-covered area are strongly improved using a normalized TM Band 2-5 difference image. The image increases the contrast between snow and bare ground and is not affected by snow surface contamination.

Snow grain size variations were detected in the catchment area using TM Band 4. It seems like about one third of the variability in TM Band 4 reflectance is caused by effective snow grain size variations, the rest by surface impurities. However, a situation with larger spatial variations in degree of snow surface metamorphosis or a series of images recorded with different meteorological conditions during the winter would give a more complete data set for further analyses.

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PRODUCTION OF A NEW RUNOFF MAP OF SWEDEN

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ABSTRACT

A new methodology for comprehensive mapping of water resources is developed. The main aim with respect to products is to update the existing runoff map of Sweden covering the period 1931-1960 to the period 1961-1990. Manual procedures of the production of the previous runoff map is replaced by a scheme containing numerous runoff model calculations and the use of a contouring and graphical packages. Runoff calculations was performed for grid cells using a constrained version of the HBVmodel. The calculation cells correspond to the division of the country given by the topographical maps. Several parameters of the runoff model are kept constant, some are regionalized and a few are estimated on the basis of elevation and land characteristics.

INTRODUCTION

The demands for comprehensive mapping of water resources show an increasing tendency. The interest is not only in general maps for normal periods but also in maps for specific purposes, for limited regions and for specified time periods. Analyses concerning regional effects of various climatic scenarios on water resources is an important field exemplifying the extended needs.

Runoff maps for the whole of Sweden has previously been produced using manual interpretations of point measurements of precipitation and estimates of potential evapotranspiration. Adjustment of estimated runoff has been done on the basis of observed runoff from small watersheds. The runoff map of Sweden for the period 1931 - 1960 together with the production methodology is reported by Tryselius (1972).

The aim of this project is to improve efficiency of runoff map production procedures. Production time has to be shortened and costs for map production lowered. The present demand on comprehensive hydrological mapping stress the flexibility with respect to choice of region or time period studied. There is also a need for consistency between different maps. Maps of runoff for parts of a time period should be consistent with the map of the whole of the period.

The first product of the new production scheme is the runoff map of Sweden for the period 1961 - 1990. Creation of this specific map is the application underlying the development of the method and the practical example used in this paper. Specificly there is also a need for a new runoff map for presentation in the Climate, Lakes and Rivers volume of the new National Atlas of Sweden to be published in 1995.

The minimization of manual and subjective elements in the creation of the map is one basic presumption for the development of the new method. The procedure should be divided into separate modules to facilitate improvements of specific parts of the scheme and each module should be formulated in such a way that the map production will be relatively independent of subjective interpretations of the operator.

METHODOLOGY

The map production structure is based on various computer methods for runoff simulation, interpolation and graphical presentation. As far as possible existing methods have been used. Some of the methods have been developed at the institute while other parts consist of commercial software packages. The main procedural structure of the runoff map creation is given in figure 1.

The main areal units for calculation of runoff are defined by the topographical maps i.e squares of size $25*25$ km^2.

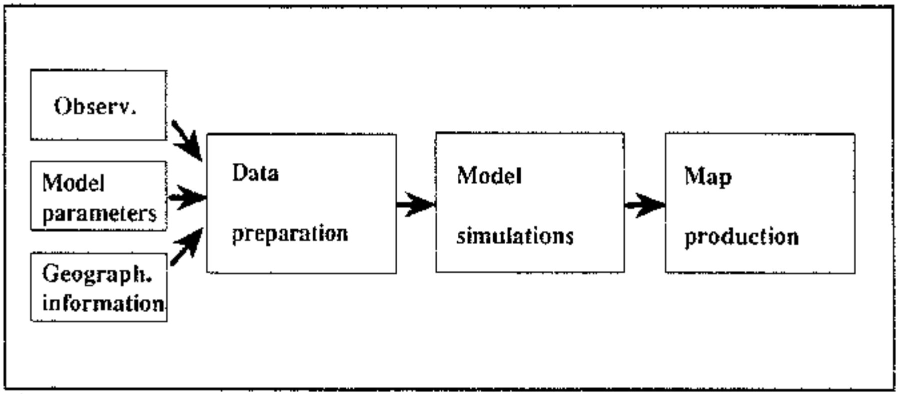

Figure 1 Map production scheme

Simulation model

The HBVmodel is used for the runoff simulations. Description of the model structure, developments and applications is given by Bergström (1992).

The model is for this mapping purpose run on a time step of 24 hours. The simulated daily values are aggregated to monthly and yearly values before statistical interpretations are applied.

The transformation part of the model is not used. This modification excludes the time lag that the model introduces between the precipitation event and the runoff output. This effect can be neglected for the relatively long time steps that are used for comprehensive mapping of water resources. The time lag introduced by the transformation routine generally do not exceed four days and is in most cases be shorter than that. Consequently the use of monthly values is reasonable with respect to this type of error.

The total number of model simulations performed as a basis for the mapping is equal to the number of topographical maps covering the country i.e. about 800.

Data preparation

The model simulations are preceded by the preparation of different categories of data sets as listed below.

* METEOROLOGICAL DATA

- Precipitation, daily values
- Temperature, daily values
- Potential evapotranspiration, monthly values

* MODEL PARAMETERS

* GEOGRAPHICAL INFORMATION

- Elevation
- Lake percentage
- Coverage of open fields and forests

Daily values of precipitation, temperature as well as monthly estimates of potential evapotranspiration for the simulations are provided by the databases at SMHI.

All precipitation stations covering the whole of the studied time period were included. Some norwegian stations were added to ensure consistency over the border. The number of available stations in regions with a sparse net could be raised by utilizing stations partly covering the time period. This option has so far not been included into the scheme.

Up to four precipitation stations are related to each calculation unit (=topographical map) together with the closest stations for temperature observations and potential evapotranspiration estimates.

The four closest precipitation stations are searched within a radius of 60 km from the centre of the calculation unit. In those cases where no station is present within this distance the closest station beyond this maximum search radius is chosen.

Model parameters are to a majority set to constant values for the whole of the country. The setting of these values has been done by experienced users of the model on the basis of previous model calibrations. A number of parameters are regionalized as described in the following chapter and a few are calculated such as weights for the precipitation stations.

Weights for precipitation stations were calculated using the inverse of the squared distance between the stations and the centre of the calculation unit. Alternate methods for calculation of weights have been discussed. It is of special interest to take into account the variation of the spatial correlation with direction. Methods exist but it has not been possible to adjust and implement them within the scope of this project.

Elevation information is used for correction of precipitation and temperature values. Elevation of a station is here compared to the average elevation of the calculation unit and corrections of observations are applied according to the factors given in the following chapter.

The information on the distribution of forests and open fields is in the model used for the determination of snowfall correction factor and within the snowmelt calculation for the two land categories.

Parameter regionalization

The HBVmodel has been applied to runoff simulation for numerous catchments in Sweden during the last two decades. Information collected from these calibrations of the model parameters in this project forms a basis for a selection of which parameters to be regionalized and which to be held constant. Those parameters that showed any regional distribution are regionalized. The other model parameters are set to an average of the estimates given by existing calibrations.

It here assumed that a regionalization of some of the model parameters is of a certain value for the spatial description of the runoff formation. There are generally many doubts risen to the relevance of regionalization of parameters of a conceptual model. In a calibration a parameter will play both the role of being an indicator of the operators ideas of the spatial variation of the corresponding physical phenomenon and the role of a tool for adjusting simulated series to the observed series. The views on the choice of parameter estimates will vary among operators giving inconsistencies between different calibrations. The combination of many spatially generalized parameters as input to the runoff model accentuate the consistency problem.

A low number of parameters showed a spatial variation that enabled a regionalization. The selected parameters mainly describe soil characteristics. The regionalized model parameters are given in Table 1 and the regions are presented in figure 2. As shown in the figure the definition of the regions is coarse. The underlying sets of model parameters gave no reason or possibility for a more detailed description of some parts of the country where a subdivision would be expected. Examples of regions that might differ are the west coast area and the neighbouring inland region as well as the inland region in northern Sweden in relation to the mountain area.

Table 1: Regionalized model parameters

Parameter	Name in model	Region no.							
		1	2	3	4	5	6	7	8
Field capacity (mm)	FC	210	210	210	180	150	150	150	150
Exponent in the soil moisture routine	BETA	3.5	3.5	3.0	2.5	2.5	2.5	2.0	1.5
Limit for potential evapotransp. (mm)	LP	180	160	160	160	160	140	140	140
Correction of precipitation with elevation(%/100m)	PCALT	10	10	10	15	15	15	15	15

In table 1 FC and BETA are parameters included in the soil routine as given by the formula below.

$$Dq = Dp * (SM/FC)^{BETA} \qquad (1)$$

where Dq is output water volume from the soil zone expressed as a part of the input water volume to the soil zone, Dp. SM is the soil water content.

The lower limit of soil water content giving potential evapotranspiration (E_{pot}) is defined LP. It controls the estimation of evapotranspiration (E) as given by equation 2.

$$E = E_{pot} * (SM/LP) \qquad \text{for } SM < LP \qquad (2)$$

otherwise $E = E_{pot}$

Temperature correction factor with respect to elevation was set to 0.6 ^{o}C/100m for the whole of the country while the precipitation correction factor was given different values for North and South Sweden respectively as given by Table 1.

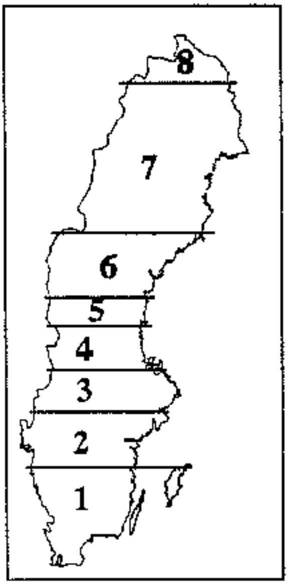

Figure 2 Regions of equal parameters

Map production

Model simulations of runoff for numerous basins each comprising a 30 year period is a heavy computational task. The simulations for the runoff map were performed on a main frame computer.

Contouring and creation of presentations were produced within the personal computer environment. Averages of annual and monthly runoff were calculated for each calculation unit serving as input to the contouring package (SURFER). Contour lines were plotted onto a digital map of Sweden and maps coded with black and white bitmap patterns or colours were created using a graphical package (DESIGNER).

Trials were done using a Geographic Information System (GIS) for contouring and map presentation. The contouring module were though found to have insufficient abilities. It is anyhow probable that this will be a major direction for improvements. Making use of a GIS normally adds versatile tools for further analyses that may be important for many applications. A GIS is in general adapted to analyses and presentations of geographically referenced phenomena and would serve as a natural basis for the production of runoff maps.

RESULTS AND CONCLUSIONS

The runoff map of Sweden for the period 1961 - 1990 produced according to the developed method is presented in figure 3. The presented version is preliminary. The main part of the analysis and verification of the map remain.

The general runoff pattern of the created map has as a first simple test been compared to the pattern of the runoff map for the previous normal period. There is a resemblance that indicates a certain reliability of the new method. The map has also been inspected against observations of runoff for a few stations with small catchments. Comparisons with additional catchments and adjustments of the map will be applied before presenting the final version.

Problems mainly occur in the mountainous region where the precipitation station net is sparse. In the part where we find the highest elevations the precipitation volumes seems to be overestimated. This is due to the too simple precipitation correction method applied here. This part of the mountain area produces the highest runoff and so the above mentioned error in the map is hidden in an open interval.

Comprehensive map production is eased with the new method. Subjective actions by the analyst at the various production steps are brought to a minimum. Production time is shortened compared to the manual methods thereby lowering costs. The method may in general serve as a flexible tool for comprehensive mapping and analysis of water resources.

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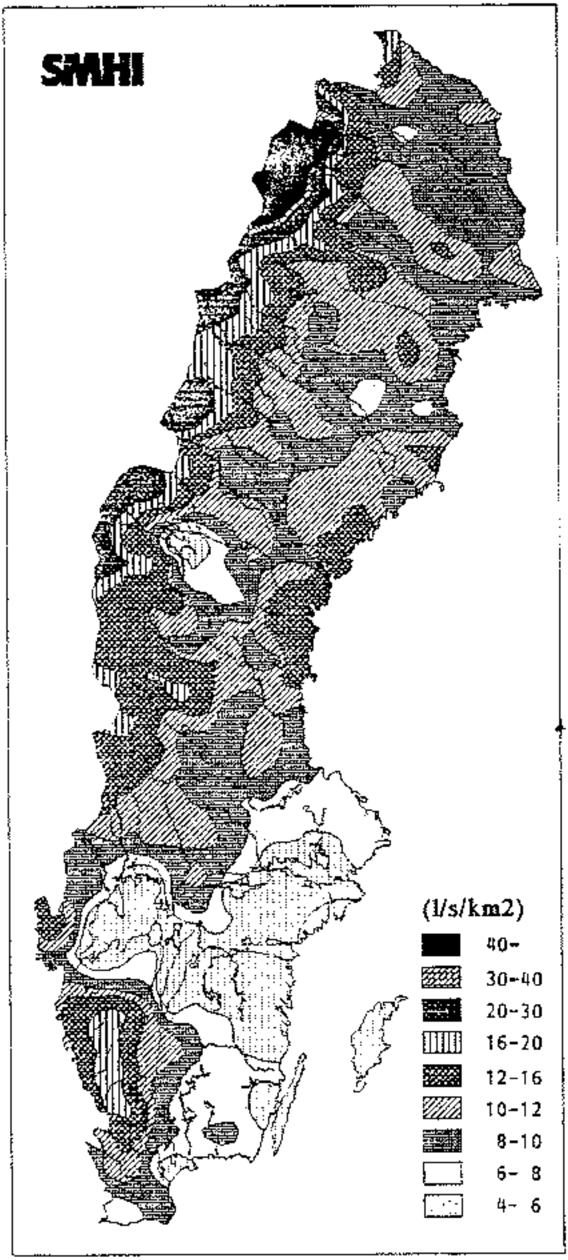

Figure 3 Runoff map of Sweden, 1961-1990.

GRUNNVANN I NORGE

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ABSTRACT

This paper is based on a short talk given at a seminar in Oslo on groundwater possibilities in Norway, in December 1991. It stresses the importance of regarding groundwater as part of the water balance. Some estimates are made of the groundwater resources of Norway. Calculations of the percentage of groundwater in the total winter runoff from some catchments in central Norway are quoted.

INNLEDNING

Grunnlaget for denne korte artikkelen er et innlegg holdt ved Vannforeningens seminar i Oslo 5. des. 1991. Samtidig er det hensikten å få gjengitt i trykt form resultatet av beregninger daværende statshydrolog Ola Gjørsvik gjorde i sitt arbeid for "Utvalget for tilsigsprognoser" (Gjørsvik m.fl., 1970). Artikkelen gir noen tanker omkring ressursen grunnvann i Norge, forhåpentligvis ikke for kontroversielle.

LITT OM VANNBALANSE OG TERMINOLOGI

Når en geohydrolog skal vurdere tilgjengelige grunnvannsressurser er det naturlig at hydrologien spiller en viktig rolle i denne vurderingen, sammen med de geologiske vurderinger. Men det bør egentlig være like naturlig for en hydrogeolog å supplere sine geologiske informasjoner med data om hydrologien. Enten vi vurderer vann på overflaten eller vann i grunnen er kjennskap til vannbalansen en forutsetning for en noenlunde riktig vurdering av ressursenes størrelse.

Så et par ord om terminologien vi bruker. Jeg vet ikke hvem som først introduserte uttrykket "selvmatende magasin", men det er et uttrykk jeg alltid har hatt problemer med å akseptere, enn si forstå. Bruken begrunnes med ønsket om å skille mellom magasiner som får vann fra oven, og de som "trekker til seg" vann fra et vassdrag (elv eller vatn). Når det gjelder den første typen magasiner er det ganske klart at disse er helt uten innflytelse på "matingen", den skjer når det regner eller snøen smelter. Her kan man i beste fall snakke om tvangsforing! Når det gjelder elvenære magasiner, derimot, så kan disse med en viss rett kalles selvmatende. I de tilfelle senkningstrakten rundt en brønn som pumpes når bort til elven, vil vann fra denne infiltrere magasinet og trekkes mot brønnen. Da får vi en selvmating. Jeg kunne derfor forstått bruken av ordet "selvmatende", hvis det bare ikke hadde vært brukt direkte omvendt.

NASJONALE MULIGHETER

Når vi skal se på hvilke muligheter for bruk av grunnvann vi har i Norge, er det innlysende at vi må se på de forskjellige bruksområder. Drikkevannsforsyning peker seg umiddelbart ut som et hovedbruksområde. På grunn av grunnvannets utvilsomme kvaliteter som drikkevannskilde er det et mål å øke grunnvannets andel av drikkevannsforsyningen fra dagens 13% til kanskje det dobbelte. Dette er det uttrykte mål bak programmet GiN, Grunnvann i Norge.

Men grunnvann har også andre bruksområder (industri, fiskeoppdrett, jordvatning m.v.). Og tilstedeværelsen av grunnvannet er jo av avgjørende betydning for jord- og skogbruk. Vi skal heller ikke glemme sammenhengen mellom vannføring i elvene og grunnvannet, spesielt i lavvannsperioder.

Avgjørende for tilgjengelige ressurser er bruken av vannet. Hvilke bruksmessige krav stilles det, bakteriologisk, fysisk og kjemisk? Hva kan gjøres for å beskytte de ressurser som idag er tilfredsstillende? Er det, eller kan det bli konflikter med andre brukere? Et nærliggende eksempel å vise til her er grunnvannsressursene på Romerike. Planlagt hovedflyplass, militær aktivitet og nåværende flyplass, store grustak, søppeldeponi og drikkevannsforsyning representerer kryssende interesser. Prioritering integrert med nøye planlegging er nødvendig.

Et kanskje litt lettvint svar på spørsmålet om nasjonale muligheter når det gjelder grunnvann til drikkevannsforsyning er følgende:

* For "småforsyninger" er det muligheter svært mange steder.
* For "store forsyninger" er det muligheter noen steder. Er mulighetene marginale kan de ofte økes kunstig.

I GiNs veilederserie har veileder nr. 8 tittelen "Grunnvannsforekomster i Norge", og behandler nettopp de nasjonale muligheter (Gaut 1992).

TILGJENGELIGE RESSURSER

Nasjonale muligheter og tilgjengelige ressurser er egentlig to sider av samme sak. I og med at de tilgjengelige grunnvannsressurser avhenger av vannbalansen vil de hydrologiske forhold gi nyttig informasjon. Selvfølgelig kan en også bruke nedbørdata ved vurderingene, men hydrologiske data har den fordel fremfor nedbørdata at de representerer arealverdier. En god, men selvsagt noe generell, oversikt over avløpsforholdene i Norge finner vi i "Avrenningskart over Norge" i målestokk 1:500 000 (NVE 1987).

Selvfølgelig kan man se bort fra hydrologi og vannbalanse, og betrakte grunnvannet på samme måte som olje og gass. Med andre ord, ta ut fra reservoaret så mye som det er teknisk mulig å få ut, inntil det i praksis er tomt. Eksempler på dette har vi bl.a. i Australia og i Nord-Afrika. I Norge er en slik driftsmåte ikke aktuell, vi ønsker å behandle grunnvannet som en fornybar ressurs.

Et lite eksempel kan illustrere nytten av en hydrologisk vurdering. Under byggingen av Borgund kraftverk i Lærdal, innerst i Sognefjorden, ble det boret en brønn i fjell til vannforsyning for noen gårder. Det ble da konflikt om grunnvannsressursen, i det det ble hevdet at den nye brønnen tok vann fra en tidligere utført boring. En geologisk vurdering av problemet ble gjort, og uttalelse avgitt. Det var i og for seg greit nok, men hydrologiske data for stedet, sammenholdt med et blikk på kartet, viste at tilsiget til grunnvannsmagasinet i tørre perioder ville være helt utilstrekkelig, selv for den opprinnelige vannforsyning. Da kom bl.a. et endret forbruksmønster inn i bildet.

MENGDER

Hvilke mengder grunnvann er tilgjengelige? Som nevnt avhenger dette av bruksmåte og kvalitetskrav.

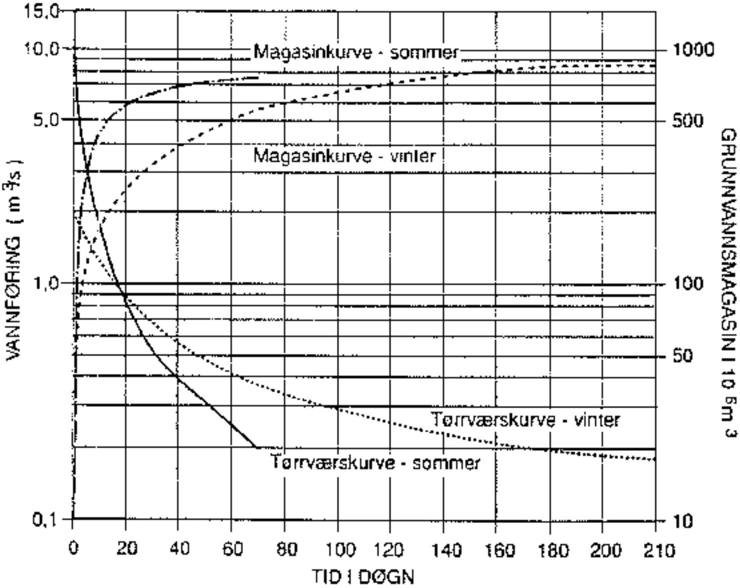
Forundersøkelser

La oss forutsette at det skal etableres en vannforsyning fra en brønn i fjell eller løsmasser. En hydrogeologisk oversikt vil da være første undersøkelse, altså en oversikt over geologi og hydrologiske forhold. For en brønn i løsmasser må vi få kjennskap til disse massene. Fra NGUs brønnboringsarkiv kan vi få verdifulle opplysninger om tidligere boringer i området, og hva vi ut fra disse kan vente. Blir en brønn satt ned vil prøvepumping gi meget verdifulle opplysninger. En kan da få en vurdering både av kvantitet og kvalitet.

Gjelder det en større vannforsyning vil det være ønskelig å skaffe nok data til kalibrering av en strømningsmodell. Derved vil det være mulig å gi en sikrere vurdering av de muligheter for vannforsyning fra akviferen som foreligger.

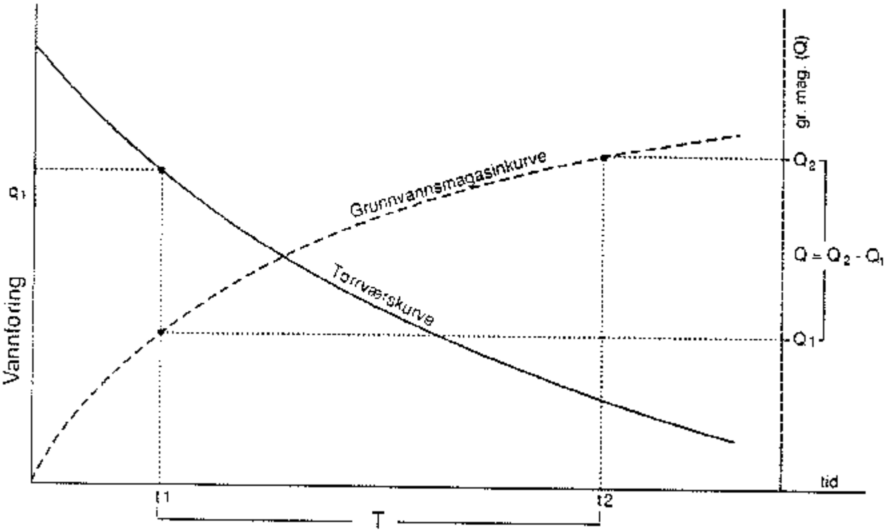
Beregning av grunnvannsmagasinet

Beregning av grunnvannsmagasinet i et nedbørfelt av begrenset størrelse kan gjøres, basert på hydrologiske observasjoner. Dersom avløpet fra feltet er observert i en elv eller bekk over en lengre periode, så vil avløpet i tørrværsperioder kunne skilles ut. For disse periodene tegnes avløpskurvene opp. Disse vil ha mer eller mindre samme form, og kan uttrykkes ved en kurve vi kaller tørrværskurven (eller resesjonskurven).



Figur 1. *Tørrværskurver og grunnvannsmagasinkurver for Narsjø vannmerke. Nedbørfelt 117 km².*

Kurver tegnet for vinterforhold og for sommerforhold vil vanligvis være forskjellige. Disse avløpskurvene representerer det avløpet vassdraget får fra grunnvannsmagasinet. Det betyr at om vi integrerer en slik kurve, så får vi direkte den mengde grunnvann som er rent ut fra magasinet i feltet i løpet av tiden vi har integrert over. Vi får altså et direkte mål på den aktive del av grunnvannsmagasinet.



Figur 2. *Prinsippskisse for beregning av total grunnvannsmengde Q i en periode T.*

Ola Gjørsvik gjorde i sin tid noen slike beregninger. På det grunnlaget kunne han regne ut hvor stor del av vinteravløpet som var direkte grunnvannsbidrag i noen tilfeldig valgte vassdrag. Andelen var uventet høy. Tallene gjengis i tab.1. (Gjørsvik m.fl. 1970).

Tabell 1. *Grunnvannsandelen av vinteravløpet.*

Avløp i %	Aursund 830 km^2	Atna 400 km^2	Femund 1723 km^2	Narsjø 117 km^2	Groset 6 km^2
Grunnvann	55	88	63	82	59
Nat.sjømag.	23	2	20	7	
Overfl.avløp	22	10	17	11	

Det finnes også alternative beregningsmåter for å finne grunnvannsandelen av avløpet i et vassdrag. Hans Holtan har f.eks. sett på den kjemiske sammensetning av elvevannet (Holtan

1971). I Sverige er det ved to studier brukt henholdsvis mengden av en oksygenisotop og den elektriske ledningsevnen, med ganske forskjellig resultat (Rohde 1981, Calles 1985). I England har man brukt metoder basert på tørrværsavrenning, slik Gjørsvik gjorde (Ineson og Downing 1964).

Et enkelt spørsmål er hvor meget grunnvann det finnes i Norge? Det er like enkelt å stille som det er vanskelig å svare på. I det foregående er det referert til noen beregninger av grunnvannsavløp. Disse, og enkelte andre, kan gi grunnlag for å anslå grunnvannsdelen av totalavløpet til kanskje 40%. Jeg presiserer at dette er et anslag forbundet med meget stor usikkerhet, men jeg tar det med for at vi skal ha et grunnlag å regne på. Midlere overflateavløp i Norge er beregnet til 383 km^3 pr. år, og følgelig skulle andelen grunnvann utgjøre ca 150 km^3. Underlagsdata til denne og de følgende beregninger er hentet fra "Hydrologi i praksis" (Otnes og Ræstad 1978).

Det vi hittil har sett på er den aktive delen av grunnvannsmagasinet. Total mengde grunnvann vil utgjøre et større volum. Ser vi på arealet av landet vårt (324000 km^2), antar en midlere dybde av grunnvannsakviferen på 50 m, og med stort mot anslår porøsiteten til 0,02 i middel, så ender vi opp med en grunnvannsmengde på 324 km^3.

Det er også andre måter å nærme seg problemet på. Anslått grunnvannsforråd i verden er 10,5x10^6 km^3. Fordeles dette i forhold til Norges del av verdens landarealer blir Norges grunnvannsandel 30x10^3 km^3.

Grunnvann i % av verdens ferskvann er 30,15, mens overflatevann utgjør 0,34%. Da er alle breer regnet med. Hvis vi forutsetter at forholdet mellom grunnvann og overflatevann også er det samme i Norge, og vi i mangel av bedre kunnskap sier at mengden vann på overflaten av Norge tilsvarer årsavløpet, så har vi drøyt 30x10^3 km^3 grunnvann.

Det er som det går fram store sprik i resultatene, og det er ikke vanskelig å komme med vektige innvendinger mot betraktningene som ligger til grunn. Konstruktive bidrag til å belyse problemstillingene mottas derfor med takk.

LOKALISERING

Det er ikke mulig å gi detaljkunnskap om lokalisering i en generell oversikt. Svært kort kan man imidlertid si:

Hydrologien og geologien bestemmer de grove trekk (bakgrunnen).

Geologien bestemmer detaljene. Fjell, løsmasser, kvartærgeologi.

AVSLUTNING

Det er gjort en lang rekke antakelser i det foregående, tildels av svært usikker karakter. Det er også tildels store sprik mellom de resultater ulike forskere er kommet fram til, via forskjellige metoder. Noen klar og entydig konklusjon er det derfor ikke mulig å komme med. Med et unntak, nemlig det at grunnvannet er en del av vannbalansen. Og det er ment å være hovedbudskapet i dette innlegget.

For ordens skyld gjøres det oppmerksom på at den oversikt som her er gitt ikke gjør krav på å være fullstendig. Det er ingen tvil om at det finnes andre arbeider det med fordel kunne vært referert til.

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FRESH-WATER-RUNOFF TO THE BALTIC SEA FROM SURROUNDING LAND-AREAS

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ABSTRACT

Since 1990 SMHI is taking part in a research-programme named "Large-scale Environmental Effects and Ecological Processes in the Baltic Sea". The programme is granted by the Swedish Environmental Protection Agency. The objective of the programme is to strengthen the scientific base for international negotiations concerning the protection of our marine environment. One part of SMHI's work within this project is to calculate and prepare data-files of the total runoff to the Baltic Sea and its sub-basins. The calculations, monthly means, will cover the time-period 1950 to 1994. The coasts of Sweden, Finland and Denmark are divided into small segments of some ten kilometers. The runoff from the other countries is dominated by the discharge from very big rivers and smaller basins in between.

In this paper the total runoff to the Baltic and its sub-basins is presented and the results are compared with calculations of Mikulski (1986). The influence of geography and climate on the runoff in different parts of the area is also discussed.

INLEDNING

Presentation av projektet

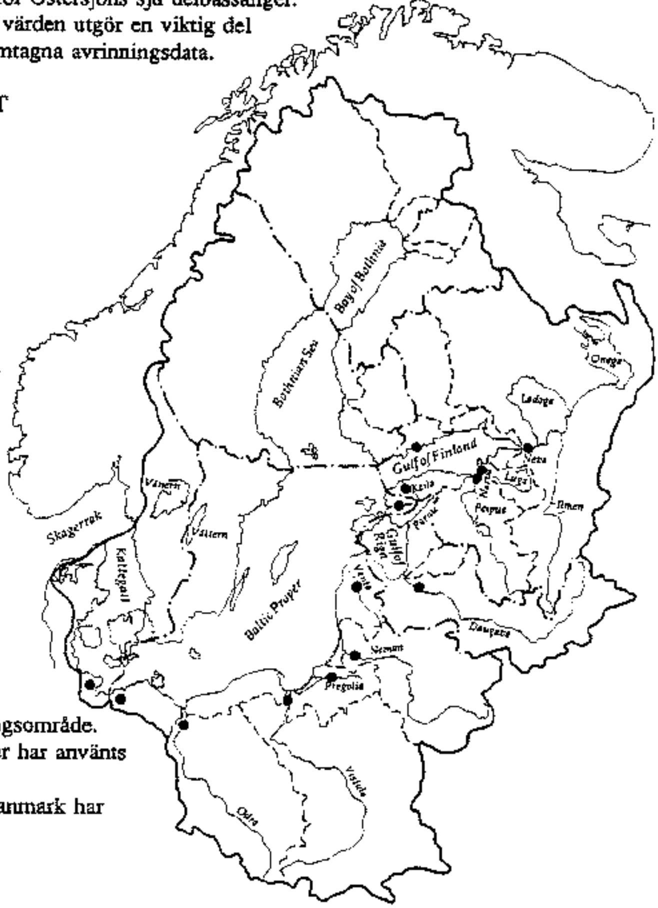
Under de senaste årtiondena har Östersjöns eutrofiering och förändringar p g a giftiga utsläpp m m blivit alltmer påtaglig. Allt oftare återkommande algblommningar och kraftiga fluktuationer i växt och djurpopulationer är tydliga bevis på detta. För att få ett grepp om dessa storskaliga processer initierade Statens Naturvårdsverk (SNV) 1989 ett tvärvetenskapligt forskningsprogram under rubriken "Large-scale Environmental Effcts and Ecological Processes in the Baltic Sea" (SNV 1990). Det övergripande målet är att skapa en modell där de storskaliga processernas långsiktiga inverkan på Östersjön beskrivs. Förutom processer, fysikaliska, kemiska och biologiska, i själva Östersjön omfattar programmet därför också belastningsstudier, närsalter, metaller, gifter mm, relaterade till meteorologi och hydrologi. I programmet ingår forskargrupper från ett flertal universitet och institutioner i Sverige.

Det här presenterade materialet, sötvattentillrinningen till Östersjön, utgör en del av SMHI's bidrag till nämnda program.

Tidigare mätningar

Den mest omfattande sammanställning av tillrinningsdata för Östersjön som tidigare gjorts omfattar åren 1920-1976 (HELCOM 1986) och har gjorts av Dr. Z Mikulski. Beräkningarna bygger på månatliga värden från de 17 största floderna inom det ca 1.700.000 km^2 stora avrinningsområdet. Dessa 17 floder representerar ca 63% av avrinningsområdet. Resultatet har sammanställts bassängsvis för Östersjöns sju delbassänger.
Jämförelser med Mikulskis värden utgör en viktig del vid granskningen av nu framtagna avrinningsdata.

AVRINNINGSOMRÅDET



Figur 1. Östersjöns avrinningsområde. Med (●) markerade stationer har använts vid beräkningarna.
För Sverige, Finland och Danmark har större delen av det kustnära stationsnätet utnyttjats.

Inom Östersjöns avrinningsområde bor en befolkning på ca 90 miljoner. Hela området, exklusive själva Östersjön, har en yta på ca 1,7 miljoner km^2. Östersjöns yta är ca 415 000 km^2. Inom detta stora område finns stora hydrologiska skillnader. Klimat och topografi är de faktorer som betyder mest. Skandinavien ligger i en övergångszon mellan maritimt klimat i väster och sydväst och kontinentalt klimat i öster. Nederbörden i de dominerande västliga vindarna faller till stor del över den Skandinaviska fjällkedjan. En kraftig väst-ostlig nederbördsgradient finns i fjälltrakterna på den Svenska sidan. Årsnederbörd i fjällen på över 1500 mm är ej ovanligt, medan normalvärdet i norra norrland i övrigt ligger på 400-600 mm/år och i södra norrland på 500-800 mm/år. Nederbördsmängder av denna storleksordning, 500-800 mm/år, är det normala i nästan hela övriga delen av avrinningsområdet. Undantag utgör t ex norra Finland, som liksom norra Sverige har något mindre nederbörd, 400-600 mm/år. Områden med mindre nederbörd finns även på det Polska låglandet samt t ex den Svenska ostkusten. Områden med förhöjd nederbörd finns bl a längs den Svenska västkusten, samt Polska och Baltiska kusterna.

Avdunstningen kan i stort sett sägas öka från norr till söder. Årsvärden för den potentiella avdunstningen är i de norra delarna ca 400 mm/år, i mellansverige ned till norra Polen 500-600 mm/år och i de sydligaste delarna av avrinningsområdet ca 700 mm/år.

Det kalla klimatet i norr gör att nederbörden här till stor del faller som snö. Snötäcket ligger i runda tal ca 200 dagar om året. I Oders och Wistulas avrinningsområden är antalet dagar med snötäckt mark av storleksordningen 20-50 dagar per år.

DATABASEN

Materialet, månadsmedelvärden i m^3/s, bygger på data, som erhållits från respektive lands nationella databas. Tidsperioden är ca 1950-1990. Arealuppgifterna är från officiell arealstatistik så långt detta är möjligt, dvs i allmänhet de stora flodernas arealer. Mellanliggande kustområden har för Sverige och Danmark beräknats av respektive lands hydrologiska institut. För övriga östersjöländer finns ännu inga officiella siffror utan de kustnära områdenas arealer har beräknats inom detta projekt. Som kartunderlag har för Finlands del använts den officiella kartan över avrinningsområden i skala 1:1 000 000. För övriga länder har avrinningsområdena beräknats från sattelitbaserade kartor i skala 1:500 000. De här redovisade egna arealberäkningarna är inte officiella och kan komma att justeras något vid senare omräkningar.

Sverige

För att beräkna den totala avrinningen från Sverige har en uppdelning av den Svenska kusten i delsträckor gjorts (Ehlert 1987). Varje kuststräcka har satts till ca 50 km, vilket innebär 40 delsträckor från Finska till Norska gränsen. Gränserna mellan kustavsnintten har valts så att de är geografiskt väldefinierade, t ex uddar, näs o s v, samt sammanfaller med vattendelare. Till kustavsnitt 1 har förts hela Torneälvens avrinningsområde, alltså även den del som ligger på finskt område. Av Sveriges ca 469 800 km^2 är vattenföringen uppmätt för ca 402 300 km^2, dvs 86%. Osäkerheten vid beräkningen av återstående 14% har satts till mellan 20% och 50% vilket innebär att till osäkerheten i uppmätt vattenföring skall läggas mellan 3% och 7%. Beräkningarna har av SMHI ställts till Östersjöprojektets förfogande.

Danmark

Avrinningen från Danmark bygger på ett arbete av (Höybye 1990). Beräkningarna har föregåtts av omfattande statistiska metodundersökningar. Vid beräkningarna har det danska landet och öarna delats in i 9 delområden. Avrinningen från 7 av dessa, nr 3-9, sker till Kattegatt och sunden. Arealen för dessa 7 områden är 31 055 km^2 varav 9 190 km^2, eller 30%, omfattas av uppmätt vattenföring medan resten är beräknad.

Osäkerheten anges till ca 5% för årsmedelvärden och till ca 15% för månadsmedelvärden. Beräkningarna har av Det Danske Hedeselskabet ställts till Östersjöprojektets förfogande.

Finland

Några officiella beräkningar på den samlade avrinningen från Finland finns ännu inte (1991). Avrinningen från Finland till Bottenviken, Bottenhavet och Finska Viken har inom Östersjöprojektet beräknats utgående från 30 vattenföringsstationer. Långa mätserier och var stationer för vattenkvalitet finns har givet urvalet.

Enligt Finska vattendragsregistret avvattnar kustnära stationer sammanlagt 216 063 km^2 till Östersjön och Finska viken. Finska avrinningsområdet nr 67 Torne älv, kustnära områden samt de delar av Finland som avvattnas via Ryssland ingår inte i denna areal. Inkluderas de inom detta projekt beräknade kustnära områdena, men ej Torne älv, blir den totala arean för Finland 230 800 km^2. Perioden 1970-90 täcks 88% av denna areal av utnyttjade mätningar. Ett lika omfattande stationsnät fanns ej tillgängligt perioden 1950-70.

Ryssland och de Baltiska staterna

Från State Hydrological Institute i S:t Petersburg har erhållits månadsvattenföringar i stationer som framgår av karta på figur 1. Tidsperioderna är i allmänhet från 1950 och fram till 1987-88. Vattenföringsuppgifter har också erhållits från universiteten i Tartu och Riga.

Polen och Tyskland

Kartan på figur 1 visar de platser från vilka vattenföringar erhållits från Meteorologiska Institutet i Warszawa och Bundesanstalt fur Gewässerkunde. Som framgår täcks nästan hela Polen av stationerna Gozdowice, 109 729 km^2, i Oder och Tczew, 194.376 km^2, i Wistula. Tillsammans avvattnas således 304 105 km^2, 91%, vid dessa två stationer. Längs den polska kusten återstår 28 650 km^2, lika med 9%. Detta kustnära område kommer att kompletteras med ytterligare stationer. I här redovisade beräkningar representeras det av Oder och Wistula.

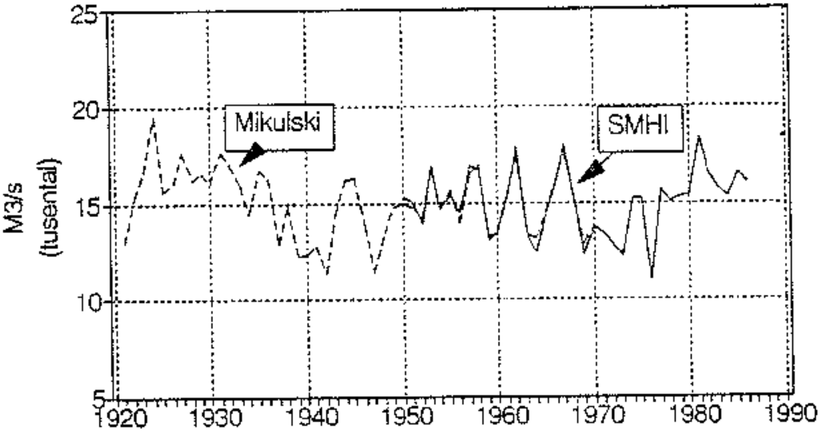
Tyskland representeras av stationerna Warnov i floden Trave och Sehmsdorf i Gross Görnov. Området är 24 000 km^2 och täckningsgraden endast 6%.

JÄMFÖRELSER MED MIKULSKIS MATERIAL

I nedanstående sammanställning jämförs de arealberäknigar som nu gjorts med Mikulskis arealberäknigar (HELCOM 1986)). Dessa senare bygger på avrinningen från endast 17 floder. Procent inom parentes anger täckningsgrad för de använda Finska Q-stationerna 1950-70.

	SMHI			Mikulski	
	area (km²)	%	%	area (km²)	%
Bay of Bothnia	261 140	87	(72)	269 950	30
Bothnian Sea	229 560	84	(81)	229 700	36
Gulf of Finland	421 380	93		419 200	89
Gulf of Riga	132 060	66		127 400	65
Baltic Proper	584 610	80		568 973	75
Danish straits and Kattegatt	101 260	96		106 010	64
Total	1 730 010	86	(83)	1 721 233	63

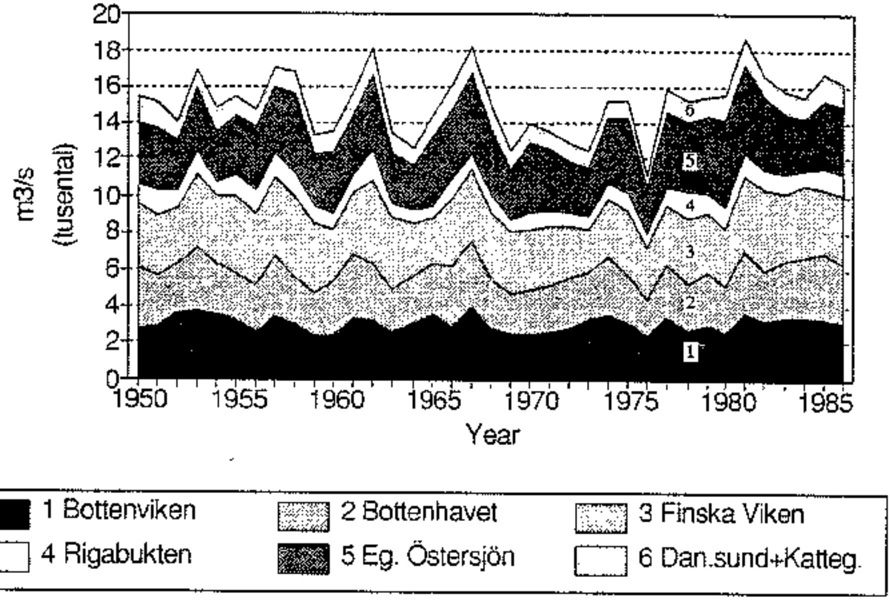
Som framgår av tabellen är alla arealskillnader små och torde ligga inom de använda beräkningsmetodernas felmarginaler. Eventuella flödesskillnader går därför inte att hänföra till olika stora areor. Den huvudsakliga skillnaden består i den högre täckningsgrad som erhållits för Bottenviken (från 30 % till 87 %) och Bottenhavet (från 36 % till 84 %) i och med att praktiskt taget alla Svenska och Finska kustnära stationer utnyttjats. Mikulski redovisar tillrinningen till Östersjön från 1921 till 1950. Om vi kombinerar denna serie med den nu framräknade får vi den samlade tillrinningen till Östersjön från 1921 till 1988, figur 2. Årsmedeltillrinningen har under nästan alla dessa år legat mellan 12 000 m^3/s och 18 000 m^3/s. Höga värden förekom 1924 (19 500 m^3/s) samt 1962, 1967 och 1981. Låga värden förekom 1942, 1947 samt, allra lägst, 1976 (11 000 m^3/s).



Figur 2. Totala tillrinningen till Östersjön 1921-86. Årsmedelvärden, m^3/s.

Studerar man enbart tiden från ca 1970 och framåt tycks en fortgående ökning i sötvattentillförseln till Östersjön äga rum. Ökad vattenföring från 1970 och framåt förekommer även i en del floder från öster t ex Neva och Daugava. I det längre tidsperspektivet är denna ökning ej exceptionell.

Den totala tillrinningen till Östersjön uppdelad på de olika delbassängerna visas i figur 3. Som synes ligger flödena från fyra av de sex delarna tämligen lika runt 3 000 m^3/s. Flödena till Rigabukten och till Danska sunden och Kattegatt ligger runt 1 000 m^3/s.



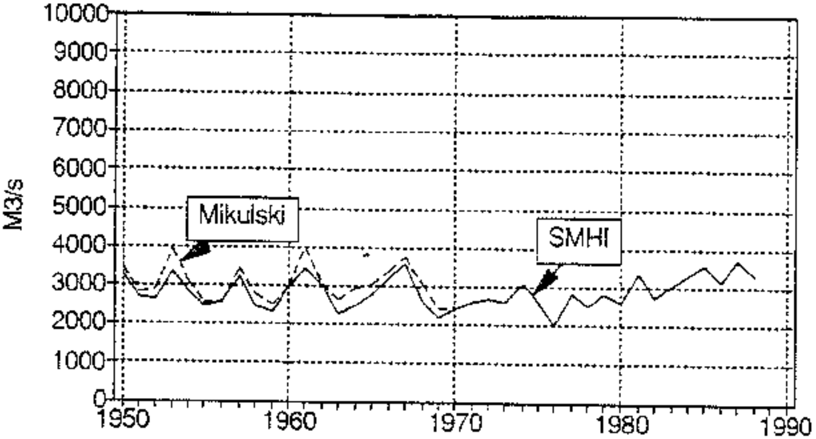
Figur 3. Totala tillrinningen till Östersjön 1950-86, uppdelad på delbassänger, m3/s.

Någon större skillnad vad gäller det årliga flödet till Östersjön totalt får man således inte med den ökade stationstätheten, figur 2. Om man däremot studerar endast de norra delarna, Bottenviken och Bottenhavet framträder vissa skillnader. Som exempel väljs här Bottenhavet, figur 4. Åren 1950-70 var tillrinningen enligt de egna beräkningarna lägre än enligt Mikulskis. Mikulskis beräkningar bygger på endast tre floder, Dalälven, Ume älv och Kokemäenjoki, och de nyare på nästan alla Svenska kustnära stationer inom området samt tre Finska. I genomsnitt var den årliga skillnaden för perioden 235 m^3/s (2790 m^3/s och 3025 m^3/s resp.).

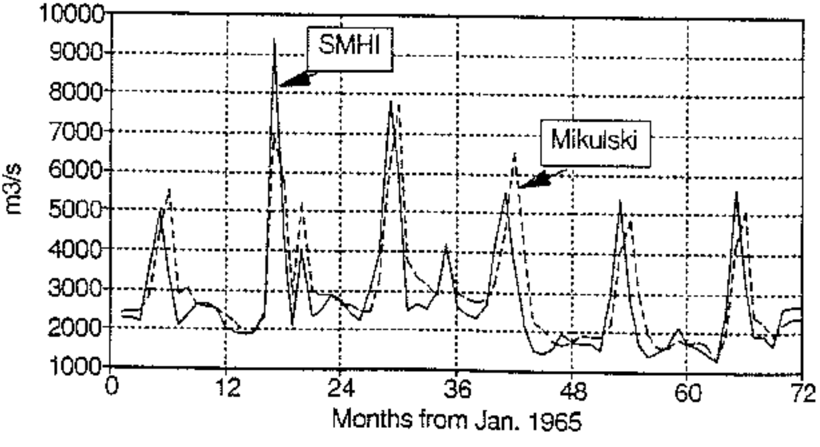
Vid plottning av månadsmedelvärden framträder ytterligare en viktig skillnad, figur 5. Vårflödena infaller enligt de nya beräkningar nästan varje år 1965-70 ca en månad tidigare, vilket beror på att snösmältningen infaller något tidigare på den Svenska sidan av Bottenhavet än på den Finska. Sverige dominerar volymsmässigt sett flödena till Bottenhavet, arealförhållande 5:1.

HYDROLOGISKA REGIONER

Inledningsvis berördes i korthet klimatets och topografins effekter på avrinningsbilden. För dynamiken under året har dessutom regleringarna stor betydelse. Utgående från figur 6, som visar regleringarnas inverkan på Lule älv, samt figurerna 7 och 8, vilka visar den specifika avrinningen fördelad månadsvis och areellt, diskuteras dessa faktorer nedan.

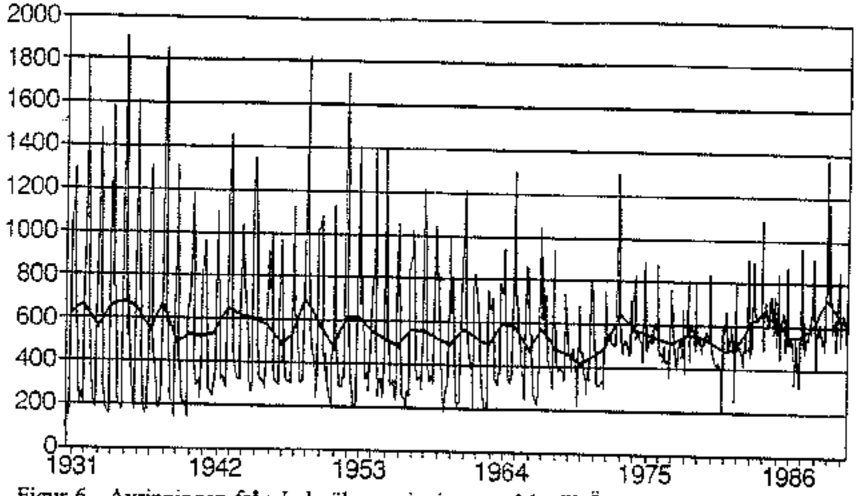


Figur 4. Tillrinningen till Bottenhavet 1950-88. Årsmedelvärden, m^3/s.



Figur 5. Tillrinningen till Bottenhavet 1965-70. Månadsmedelvärden, m^3/s.

Torne älv, figur 7, är exempel på en oreglerad älv från den nordligaste regionen. Karakteristisk är den kraftiga vårfloden i samband med snösmältningen i maj-juni på över 30 l/skm^2. Också sommarvattenföringarna är höga på grund av den låga avdunstningen sommartid. Samma uttalade vårflöde skulle även alla andra stora norrlandsälvar, t ex Lule älv, ha haft om de inte i så hög grad varit reglerade.



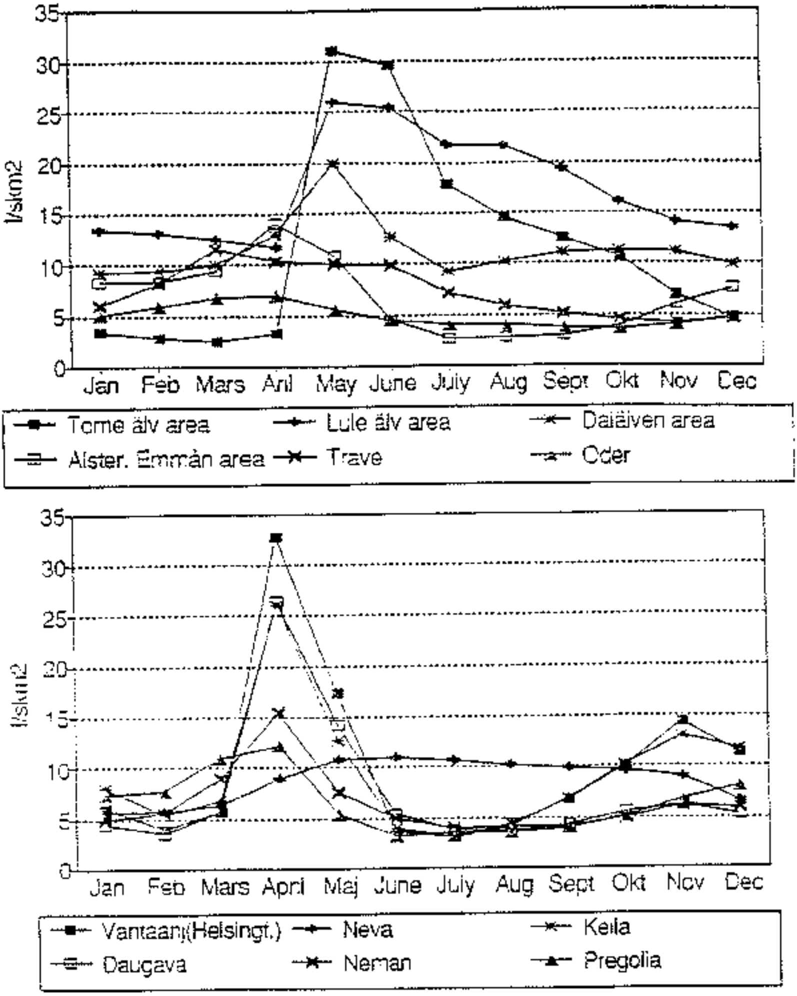
Figur 6. Avrinningen från Lule älvs avrinningsområde till Östersjön 1931-90. Månads- och årsmedelvärden, m^3/s.

Effekten på månadsvattenföringarna av utbyggnaden av Lule älv tar sig framför allt uttryck i minskade säsongsvariationer. Figuren 6 visar avrinningen från ett område, som till 80 % utgörs av Lule älv. Av årsvärdena kan utläsas att någon förändring av det totala flödet knappast skett sedan 1931, men de månadsvisa svängningarna har drastiskt minskat i takt med utbyggnaden. Magasinen fylls med vårfloden och därefter sker i princip en successiv avtappning till nästa vårflod eller nederbördstillfälle. Avrinningen ligger vintertid på 13-14 l/skm^2 jämfört med Torneälvens 3-4 l/skm^2.

De Svenska och Finska skogsälvarna har i stort sett samma avrinningsförlopp som de nordliga Lule och Torne älvar, men skulle, om de varit oreglerade, haft en mera utpräglad vårflodstopp än vad som framgår av figur 7. De sydligaste av de stora svenska älvarna inom denna region är Dalälven och den i Vänern norrifrån mynnande Klarälven.

Då vi förflyttar oss ytterligare något söderut kommer vi in i en annan hydrologisk regim. Söder om en linje dragen ca genom Norges sydspets, tvärs över Sverige, genom sydligaste Finland och vidare österut kommer de atlantiska vädersystemen att kunna påverka hydrologin på ett helt annat sätt än bakom den skyddande Skandinaviska bergskedjan. I den östligaste delen av detta område finns hela tillrinningsområdets största sjö, Ladoga, som tillsammans med regleringar vid utloppet i Finska Viken vid S:t Petersburg helt bestämmer avrinningsbilden för Neva, figur 7. Neva har en genomsnittlig vattenföring på ca 2 400 m^3/s. I samma figur har medtagits det enda vattendrag, Alsterån/Emmån, som i Mikulskis beräkningar ensamt fått bestämma hela avrinningen från Svenska ostkusten till Östersjön. Den Svenska ostkusten karakteriseras av liten nederbörd och förhållandevis hög avdunstning, därav den mycket låga specifika avrinningen sommartid, 2-3 l/skm^2.

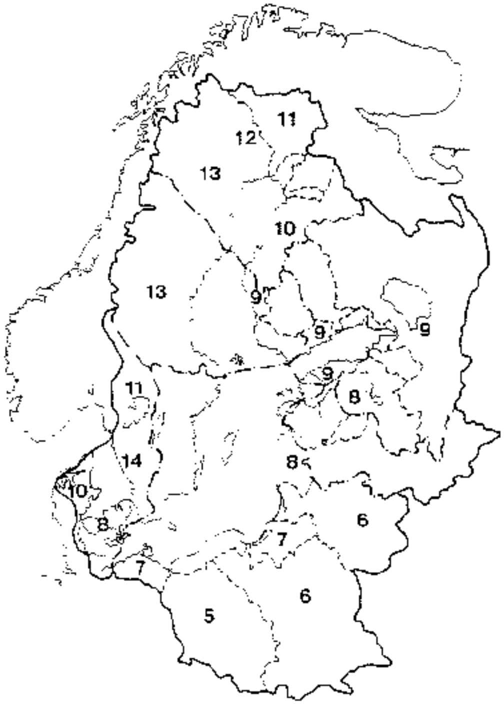
Tillrinningen till Östersjön söderifrån domineras fullständigt av de två stora floderna Oder och Wistula på tillsammans över 500 000 km^2. De har sin upprinnelse nära Alpernas nordsluttningar och avvattnar hela Nordeuropas slättland. Detta enorma område har en kraftigt



Figur 7. Specifika avrinningen för floder mynnande i Östersjön, l/skm^2.

utjämnande effekt på avrinningen. Specifika avrinningen för Oder varierar mellan endast ca 4 l/skm^2 under sommaren och ca 7 l/skm^2 under mars-april. Medelvattenföringen för Oder är 540 m^3/s och för Wistula ca 1100 m^3/s. (1950-88).

De flesta av de stora floderna som från öster rinner ut i Östersjön är mer eller mindre reglerade. Regleringsgraden är svårt att få grepp om. De här redovisade månatliga specifika avrinningarna måste därför tas för vad de representerar, nämligen ett resultat av en delvis reglerad men till största delen naturlig vattenföring. Alla floderna utom Neva i figur 7 visar det genomgående mönstret att ju längre söderut man kommer ju mindre utpräglad blir vårfloden. De två små floderna Vantaanjoki (mynnar vid Helsingfors) och Keila (Estland) vid Finska Viken uppvisar ett på höstregn beroende maxima under november.



Figur 8. Specifika avrinningen för avrinningsområden och enskilda floder, l/skm^2.

En översiktlig bild av specifika avrinningens fördelning över hela området ges i figur 8. Siffrorna där representerar dels regioner (Sverige, Danmark, Finland) och dels enskilda floder (Ryssland, Baltiska staterna, Polen och Tyskland).

SLUTORD

Ett tack till alla institutioner och enskilda runt hela Östersjön som välvilligt ställt avrinningsdata till förfogande för uppbyggnaden av denna databas.

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NEDBØRENS VARIATION PÅ FÆRØERNE.

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ABSTRACT.

Since 1987 precipitation registrations have been carried out with 22 raingauges located in different heights above sea level. In 1991 the recording program was escalated, also to include 7 especially designed self-recording raingauges.

The main purpose for this program is to investigate the variation in precipitation in mountain areas, and to correlate these variations with different meteorological parameters and topography.

The project is the NHP-project nr. 2: "Nedbørens højdegradient", and the first results are reported in a paper precented at the NHK-conference in Rovaniemi in 1988. Results are also reported in "Vannet i Norden", Nr. 2, 1990.

Preliminary results from the selfrecording raingauges show very great variations over short distances, and because the time resolution is very good, it is expected, that the final results will be of wide interest for people working with problems related to both meteorological and hydrological processes.

INDLEDNING

Anledningen til iværksættelse af dette NHP-projekt var, et ønske fra både de færøske myndigheder og det færøske elkraftselskab om et bedre kendskab til vandmængder i åer og vandløb, når både vandkraft- og fiskeopdrætsprojekter skulle vurderes.

I forbindelse med myndighedsbehandlingen af vandkraftudbygningen på Eysturoy kontaktede man Det Norske Meteorologiske Institutt, og Bjørn Aune og Eirik J. Førland analyserede nedbørsforholdene i området omkring vandkraftverket ved Eiði på den nordlige Eysturoy. Der blev udarbejdet en rapport (B. Aune og E. J. Førland, 1986), som indeholder en vurdering af nedbørsmængdens variation med højden over havet på grundlag af nedbør- og afløbsdata. Rapporten konkluderer imidlertid, at denne vurdering er ret usikker, dels på grund af det tynde stationsnet, og dels som følge af, at der kun findes enkelte stationer i højereliggende områder.

I 1987 etablerede Danmarks Meteorologiske Institut nogle permanente nedbørststioner for at sikre et tættere stationsnet. Endvidere oprettede elkraftselskabet midlertidige stationer, i to profiler tværs over den nordlige del af Eysturoy, for at undersøge nedbørens variation med terrænhøjden. De første resultater blev analyseret og præsenteret af E. Davidsen (1988) på NHK 88 i Rovaniemi. Senere er resultater fra projektet publiceret i Vannet i Norden nr. 2, 1990 (Davidsen, Førland og Madsen, 1990). De første resultater viste store variationer i nedbørsmængden over korte afstande, og at terrænhøjden var en afgørende parameter, men resultaterne viste også, at i de enkelte nedbørsituationer, har den aktuelle vindretning også meget stor indflydelse på nedbørsfordelingen. Alle nedbørsdata var fra manuelle nedbørsmålere, og det var svært at tyde højdens og vindretningens indflydelse på nedbøren, på grund af den dårlige tidsopløsning. Automatiske nedbørsmålere med god tidsopløsning var derfor ønskelige.

I løbet af 1990 blev derfor en billig automatisk nedbørsmåler designet og afprøvet, og i 1991 blev 7 nedbørsmålere af denne type sat ud i fjeldområder i et profil tværs over Eysturoy. Nedenfor gøres rede for disse målere og de første resultater fra måleperioden i 1991.

INSTRUMENTER

Kravene til den automatiske nedbørsmåler var, at den skulle være billig, og kunne køre på batterier og have lavt strømforbrug.

Nedbørsmåleren er af typen "tipping bucket". Den nedbørsopsamlende del er en tro kopi af Hellman-måleren, og nedenunder åbningen sidder en ske, der vipper for hver 0,5 mm nedbør. Hvert vip aktiverer en "read switch", der giver en impuls til dataloggeren.' Måleren er lavet i plastik og produceres af Pronamic i Danmark.

Dataloggeren er en Psion Organiser, der er programmeret således, at for hver impuls fra nedbørsmåleren gemmes tidspunktet. Dataloggeren er også programeret således, at når tidspunktet er gemt går loggeren i dvale og strømforbruget er næsten nul.

Dataloggeren kan opbevare 2000 tidsregistreringer der svarer til 1000 mm nedbør. Batterikapaciteten er til ca. 6 måneders drift.

I starten var der problemer med nedbørsmåleren i frostsituationer, idet skeen frøs fast i åben tilstand, og dataloggeren fik uafbrudt impulser og således brugte hele sin hukommelse til fejlmålinger. Dataloggeren blev derfor omprogrammeret således, at for hver impuls testes om skeen er kommet på plads igen.

Psion Organiseren er en meget billig datalogger, og kan ikke anvendes ubeskyttet mod vand og fugt. Derfor er den sammen med to små opladelige 6V akkumulatorer indbygget i en vandtæt plastboks. Dataloggerens funktion ved minus-grader er tvivlsom, men målerne har været udsat for -10°C uden problemer.

STATIONSNET

På grund af meget kraftige vindforhold på Færøerne valgte man at placere nedbørsmålerne plant med terrænet. I terrænet blev gravet et hul til dataloggerboksen, og græstørv lagt ovenpå, for at beskytte dataloggeren i eventuelle frostsituationer.

Målerne blev placeret i et profil tværs over øen Eysturoy ved Norðskála, som vist på kort nr. 1, og 2. Højdeforholdene fremgår af nævnte kort.

Følgende tabel viser målestationernes navn og i hvilken højde over havet de var placeret.

Tabel nr. 1: Målestationernes navn og koter.

Navn:	NESV	ETV	NS280	NS400	FF400	FF280	FF20
Kote: (m over havet)	8	190	290	385	390	275	20

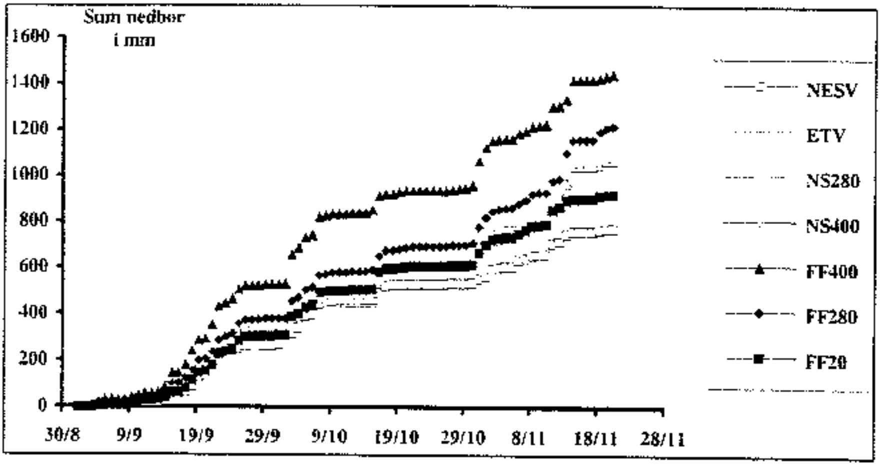
RESULTATER

De første målestationer blev etablerede i januar 1991, men først efter at vinteren var overstået, blev resten af stationerne oprettet, og fra 1. juni til 19. november 1991 findes måleresultater fra alle målerne. Alle data bliver analyseret, og kommer til at blive præsenteret i en særskilt rapport, men i dette paper vises kun resultater fra de sidste tre måneder af måleperioden, og nogle typiske situationer analyseres og kommenteres.

Tabel nr. 2 viser nedbørsmængderne i sept., okt. og nov. 1991. Figur nr. 1 viser den akkumulerede nedbørs forløb i det samme tidsrum.

Tabel nr. 2: Nedbørsmængder i sept., okt. og nov. 1991.

	NESV	ETV	NS280	NS400	FF400	FF280	FF20
Sept.	266,5	289,0	348,0	352,5	529,0	381,5	305,5
Okt.	288,5	361,0	348,5	350,0	536,5	397,5	361,5
Nov.	218,5	277,5	318,5	364,5	375,0	437,5	253,5
Ialt	773,5	927,5	1015,0	1067,0	1440,5	1216,5	920,5



Figur nr. 1: Måleresultater fra sept., okt. og nov. 1991.

Ved at sammenligne disse nedbørsmængder med samtidige målinger i Vestmanna, er nedbørsmængderne omregnet til årsnedbør.

Tabel nr. 3: Nedbørsmængder omregnet til årsnedbør.

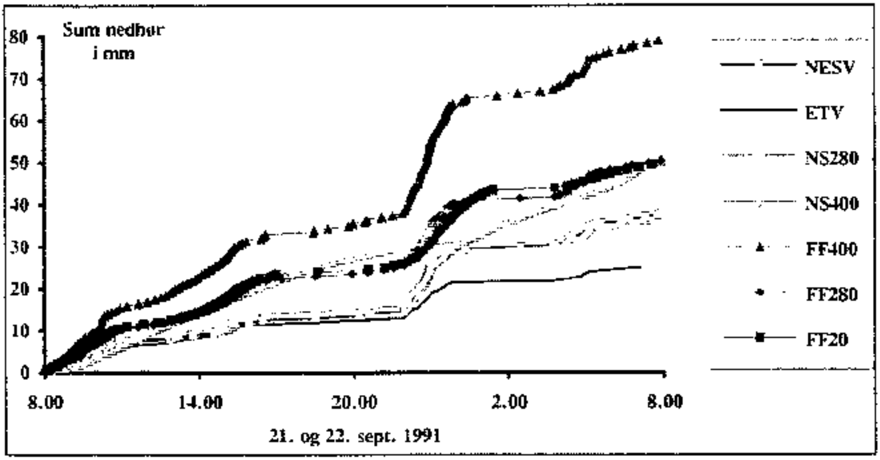
	NESV	ETV	NS280	NS400	FF400	FF280	FF20
Årsnedbør	2240	2686	2940	3090	4172	3523	2666

Måleresultaterne viser meget stor forskel i nedbøren fra sted til sted, og en afgørende faktor synes at være stedets højde over havet, men denne forskel er ikke konstant over tid. I de forskellige nedbørssituationer synes det som om, at stedets placering i terrænet i forhold til den aktuelle vindretning er en anden meget afgørende parameter.

For at illustrere vindretningens indflydelse på nedbørsfordelingen, er der udvalgt tre vejrsituationer med hver sin specielle vindretning. I alle tre tilfælde er nedbøren faldet inden for ét døgn, og i hvert tilfælde har vindens retning, der er målt ved to klimastationer på Sandur og Nólsoy Fyr, maksimalt ændret sig 45° inden for det tidsrum, hvor nedbøren er faldet. Herved er det muligt at undersøge effekteken af en speciel vindretning der, i forbindelse med terrænet, bevirker en bestemt nedbørsfordeling. Selv ved relativ små ændringer af vindretningen under nedbør, sker der nemlig samtidig ændringer af nedbørsmønstret. I denne forbindelse kan nævnes, at i forbindelse med den endelige dataanalyse vil data fra to automatiske klimastationer, der indeholder oplysninger om vinden helt ned til 10 minutters værdier, blive inddraget i analysen, hvorved en mere detaljeret analyse af forholdene omkring nedbørens fordeling kan foretages.

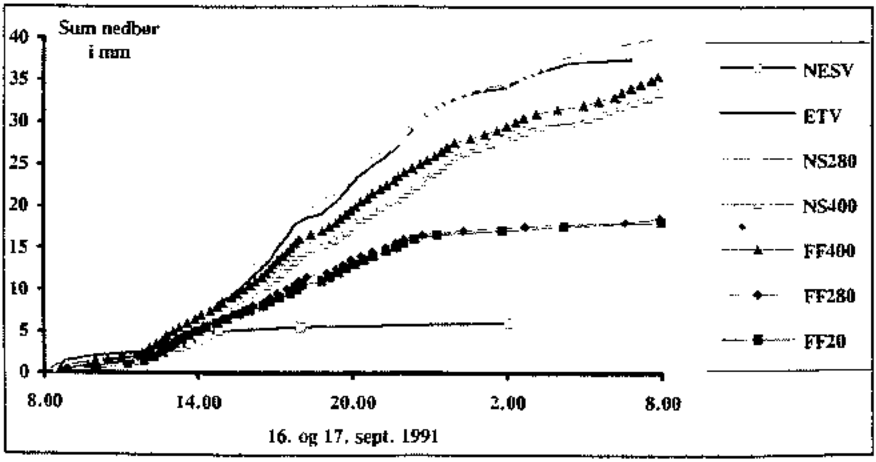
De hyppigste vindretninger under nedbør er fra S og SV, og et eksempel herpå indtraf den 21. og 22. sept. 1991. Vindretningen var 205°, d.v.s. parallel med stationsprofilet og vindhastigheden var 13 m/s.

Figur nr. 2 viser måleresultater fra den 21. og 22. sept. 1991.



Figur nr. 2: Måleresultater fra 21. og 22. sept. 1991.

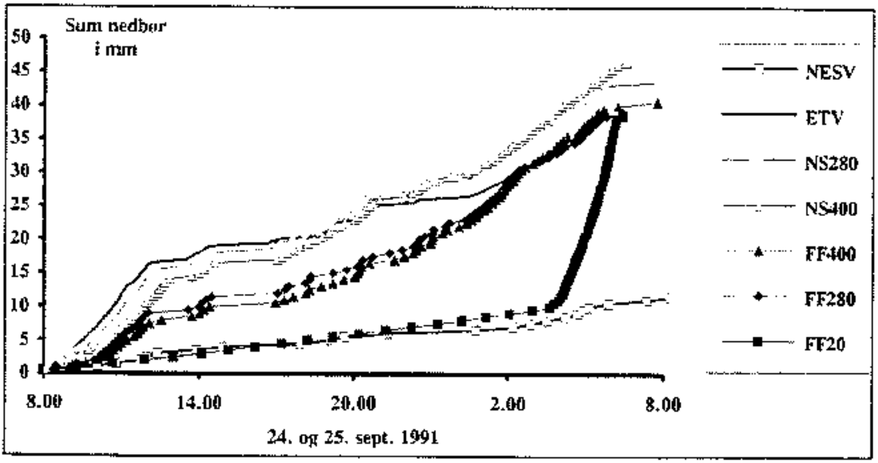
Nedbørsmængden vokser langs med profilet i vindens retning og øges med terrænhøjden. Nedbørmaksimum findes ved FF400 lidt forskudt i vindens retning i forhold til terrænhøjden, hvilket især skyldes den såkaldte "spill over"-effekt (B.Aune og E.J. Førland, 1986 og E. Davidsen, E.J. Førland og H. Madsen, 1990)



Figur nr. 3: Måleresultater fra den 16. og 17. sept. 1991.

Den 16. og 17. sept. 1991 havde vi vind fra øst, og figur nr. 3 viser denne nedbørssituation. Ved Sandur og Nólsoy Fyr var vindretningen 95° og vindhastigheden 17 m/s. Her bemærkes det, at nedbørsmaksimum nu optræder på vestsiden af terrænmaksimum, og ligesom før forskudt i vindens retning.

I det sidste eksempel har vinden været mellem nord og nordvest, eller vinkelret på stationsprofilet og parallel med fjordene og fjeldryggene. Denne situation indtraf den 25. sept. 1991 og ved Sandur og Nólsoy Fyr var vindretninen 345° og vindhastigheden 7 m/s. Nedbørsmålingerne viser (se figur nr. 4), at nedbørsmængden varierer tilfældigt langs profilet.



Figur nr. 4: Måleresultater fra 24. og 25. sept. 1991.

NEDBØRSFORDELINGEN OVER FÆRØERNE

I forsøg på at give et lidt mere generelt billede af nedbørsfordelingen over Færøerne er der, på kort nr. 1 vist de normaliserede årsnedbørsværdier for et antal stationer incl. de 7 målestationer ved Norðskála. Nedbørsværdierne er fremkommet ved at bruge samtidige målinger i Vestmanna og langtidsnormalen for samme sted som basis for normaliseringen.

Selv om de viste værdier er behæftet med en relativ stor usikkerhed, tyder de f. eks. på , at årsnedbøren i punkt FF400 er ca. 2,9 gange større end i Tórshavn. Også kan bemærkes, at den estimerede årsnedbør på ca. 4200 mm ved punkt FF400 er blandt de højeste, der er registreret i Norden.

AFSLUTTENDE BEMÆRKNINGER

Som nævnt indeholder dataserierne fra klimastationerne 10-min's værdier for vindhastighed og -retning. Det er hensigten at anvende dette materiale for at analysere vindens og terrænets indflydelse på nedbørfordelingen i mere detaljeret form. Sammen med data fra de manuelle nedbørstationer, samt afstrømningsmålinger fra udvalgte felt, vil resultaterne blive brugt til at lave et isohyetkort for normal årsnedbør over Færøerne.

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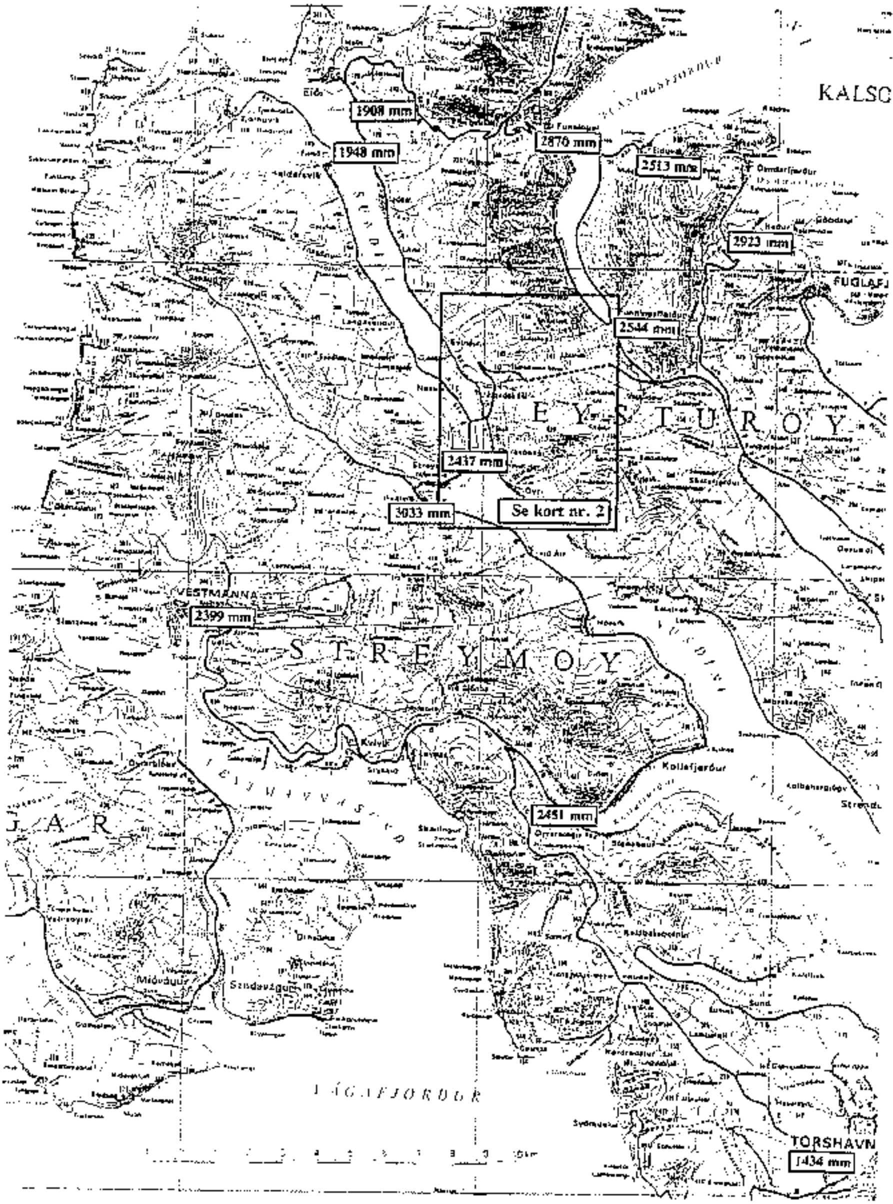
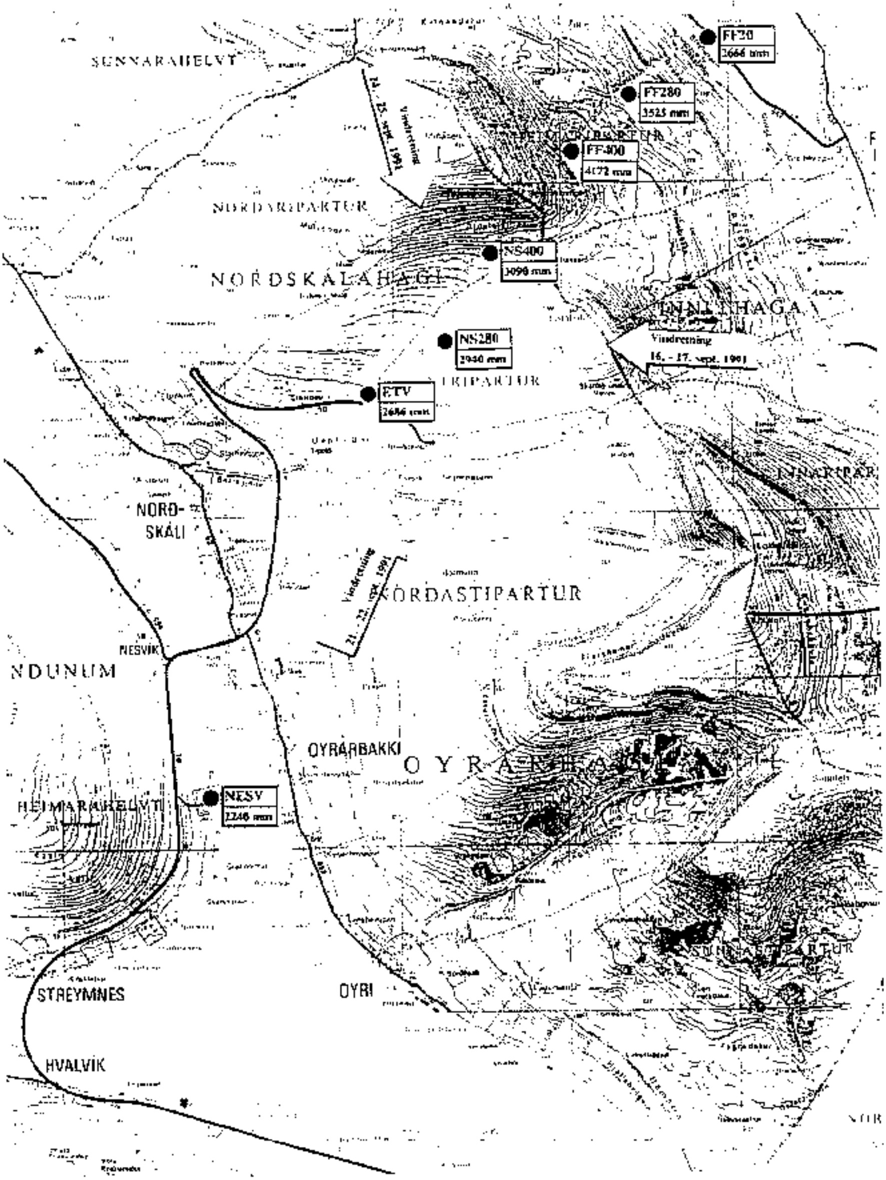

1908 mm
1948 mm
2870 mm
2513 mm
2923 mm
2544 mm
EYSTUROY
2437 mm
3033 mm
Se kort nr. 2
VESTMANNA
2399 mm
STREYMOY
Kvívík
Kollafjørður
2451 mm
Miðvágur
Sandavágur
LÁGAFJØRÐUR
TORSHAVN
1434 mm

Kort nr. 1


SUNNARAHELVT
FF20
2666 mm
FF280
3525 mm
FF400
4072 mm
Vindretning
24. - 25. sept. 1991
NORDARIPARTUR
NS400
3098 mm
NORÐSKÁLAHAGI
INNI Í HAGA
Vindretning
16. - 17. sept. 1991
NS280
2940 mm
ETV
2686 mm
NORÐ-
SKÁLI
Vindretning
21. - 22. sept. 1991
NORÐASTIPARTUR
NESVÍK
NDUNUM
OYRARBAKKI
NESV
2246 mm
HEIMARAHELVT
STREYMNES
OYRI
SUNNASTIPARTUR
HVALVÍK

Kort nr. 2

DEN AREELA NEDERBÖRDSFÖRDELNINGENS BEROENDE AV ATMOSFÄRISK CIRKULATION ANALYSERAT MED ETT TÄTT STATIONSNÄT I SKÅNE.

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ABSTRACT

The dependence of areal precipitation distribution on atmospheric circulation analysed by using a dense precipitation network in Scania, Southern Sweden. – Output from various general circulation models (GCM) are partly contradictory and not enough detailed to allow a closer analysis of the regional rainfall distribution. However, modelled atmospheric circulation patterns are much more consistent and robust with respect to small scale processes. Thus, an alternative approach could be to study how present day mesoscale precipitation distribution varies according to atmospheric circulation patterns.This is the aim of a recently started project focussing on precipitation patterns in Scania, Southern Sweden.The analyses will make use of 30 years of data from a mesoscale network comprising up to 200 stations.

INLEDNING

Med allmänna cirkulationsmodeller (GCM) kan en eventuell klimatförändring orsakad av en ökning av växthusgaserna beskrivas. Resultatet från olika modelleringar är emellertid delvis motsägelsefulla och alltför generella med avseende på nederbördsfördelningen. Vad gäller den atmosfäriska cirkulationen överensstämmer modellerna betydligt bättre. Ett alternativt sätt angripa problemet är därför att studera av hur dagens mesoskaliga nederbördsfördelning varierar med den atmosfäriska cirkulationen. På så sätt skulle information om regional nederbördsfördelning kunna uppskattas ur klimatmodellerna. I tidigare studier har klassifikationer av den atmosfäriska cirkulationen i Europa och USA använts (se Lamb, 1972; Baur et al., 1944; McCabe, 1989). Genom olika statistiska utvärderingar av dessa har samband mellan nederbörd och atmosfärisk cirkulation kunnat fastställas (Briffa et al., 1990; Bardossy och Plate, 1991; Hay och McCabe, 1992, Wilson and Lettenmaier, 1992). Inom ett nyligen påbörjat projekt studeras hur dagens mesoskaliga nederbördsfördelning varierar med den atmosfäriska cirkulationen med hjälp av 30 års data från ett mycket tätt nät av nederbördsstationer i Skåne. Preliminära resultat och ytterligare beskrivning av projektet presenteras på poster under konferensen.

DATA

Det aktuella stationsnätet har sin upprinnelse i ett forskningsprojekt rörande Kristianstadslättens hydrologi som startade i slutet av 1950-talet. Projektet avslutades och rapporterades i slutet av 1960-talet (SKH, 1969), men nederbördsmätningarna fortsattes och utvidgades successivt till allt flera skånska stationer (figur 1). Mätningarna pågår forfarande och omfattar som mest 200 stationer. Alla stationer följer SMHIs standardtid och standardinstrument. Genom en samordning av projekt vid Naturgeografiska institutionen och Institutionen för teknisk vattenresurslära, Lund, har originalprotokollen införskaffats och överförts till datormedium. Materialet har noggrannt kvalitetskontrollerats och läggs på databas.

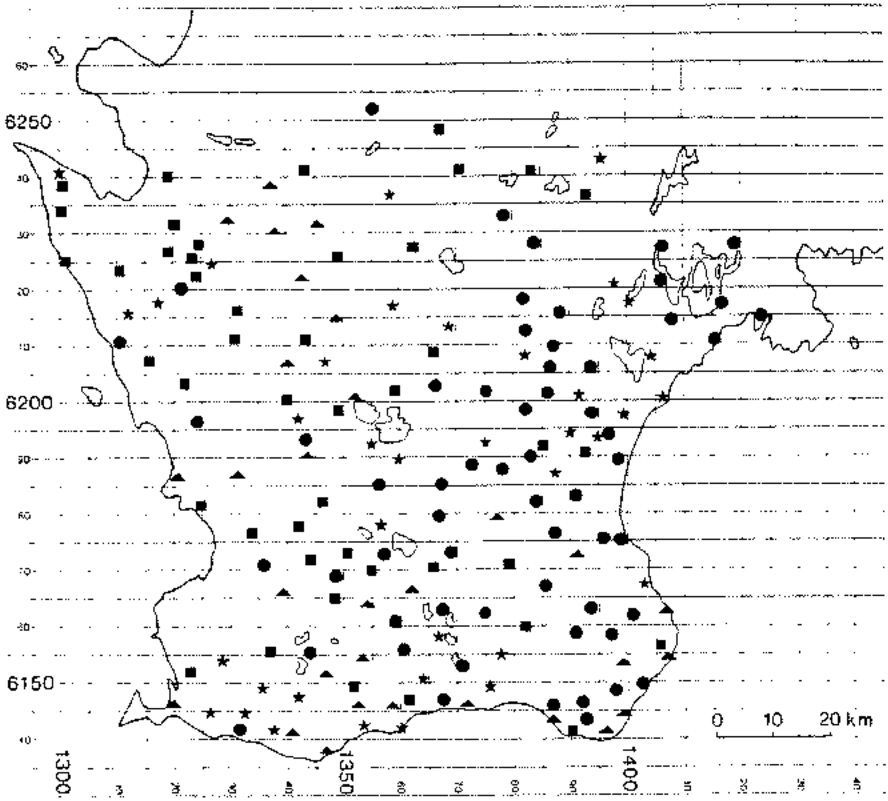

Figure 1: Map showing location of the stations in the dense network. Circle (●) = start before 1966, totally 62 stations, of which 43 started before 1962. Square (■) = start 1966-1975, totally 43 stations. Triangel (▲) = start 1976-1980, totally 31 stations. Star (★) = stations that either ended in 1986, started after 1980 or where the series is interrupted for more than 6 years. Totally 48 stations, of which 25 is continuous for at least 10 years.

TVÅ TYPSITUATIONER.

Figurerna 2 och 3 visar exempel på nederbördsfördelningen vid två helt olika vädersituationer under några dagar i augusti 1985. Under dagen den 13 augusti bildas lokala konvektiva celler som lokalt ger ca 20 mm nederbörd. Över sydöstra delen av Skåne ger ett mer vidsträckt konvektivt område 5-10 mm nederbörd. Följande dygn, under natten den 14 till 15 augusti passerar en kallfront, vilket medför stora nederbördsmänder. Mönstret antyder att en kraftig nederbördscell passerat i nordostlig riktning över Romeleåsen och Linderödsåsen upp mot norra Blekinge.

Det täta nätet har applikationer inom en rad klimatologiska och hydrologiska problemställningar. Studier av extrem arealnederbörd bedrivs som ett samarbetsprojekt mellan Naturgeografiska institutionen och Institutionen för Teknisk Vattenresurslära. Andra projekt, med tillämpningar inom skogs och lantbruk, gällande odlingslokalisering samt spridning och effekter av luftföroreningarär för närvarande under slutförande.

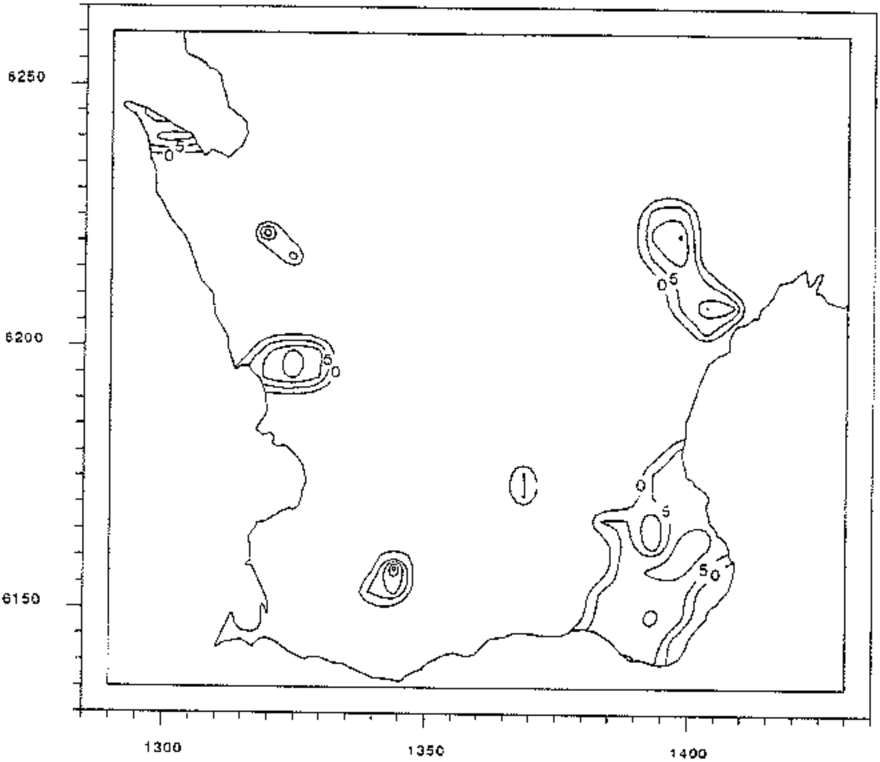

Figure 2: Precipitation pattern from convectional precipitation during the 14 of August 1985. Contour interval is 5 mm.

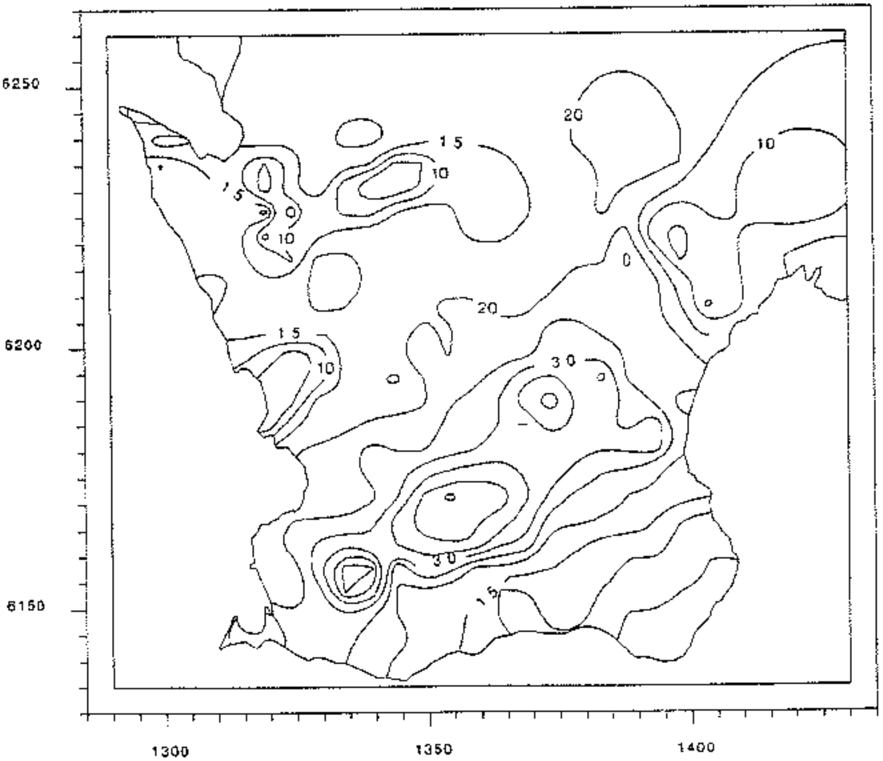

Figure 3: Precipitation distribution from a cold front passing from SE, the night between the 14 and 15 of August 1985. Contour interval is 5 mm.

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GLACIER HYDROLOGY IN A CHANGING CLIMATE

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ABSTRACT

Glacier variations are a primary cause of hydrological variability in Iceland and the same is true for Greenland, Svalbard and some areas in Norway. Glacier variations associated with an enhanced greenhouse effect and global warming are therefore an important subject for research on global change in the Nordic countries. Apart from being practical for the Nordic countries themselves, such research is a significant contribution of the Nordic countries to international research on climate change. Information on glacier variations comes from relatively few countries in the world, as few nations live in close proximity to glaciers. The large amount of glaciological data gathered on glaciers in the Nordic countries is especially valuable for that reason.

Records of glacier variations in Iceland show a clear relationship with climate and such records have been used as an indicator of historical climatic variations, before regular weather monitoring was started in Iceland around the middle of the nineteenth century. During the twentieth century, the warm years between 1930 and 1940 were associated with pronounced glacier retreat, but the cold years following 1960 lead to stagnation and later to readvance of many glaciers.

The response of glaciers to changes in climate is a consequence of the weather over a region and thus provides complementary information to most other meteorological data which consist of point measurements. Identifying climate trends from data on the advance and retreat of glaciers is problematic, because the response of the glaciers is a function of the climate over a relatively long time period. Hydrological measurements of glacial rivers can be used to circumvent this problem as the cumulative yearly discharge is primarily a function of the temperature over the area covered by the glacier during the year in question. Data on changes in the discharge of rivers from heavily glaciated areas are therefore a suitable climate indicator for identifying climate trends.

Glaciological research in the Nordic countries has gained new importance both for the Nordic countries and in the international scientific community because of rapidly increasing interest in the greenhouse effect and global warming. Combined with hydrological measurements such research can provide data about climate trends with substantial area coverage, which provide a valuable addition to traditional meteorological data.

INTRODUCTION

It is estimated that during the next decades the mean surface air temperature of the Earth will rise at a rate on the order of 0.3 °C per decade due to increasing concentration of CO_2 and other trace gasses in the atmosphere (IPCC, 1990). This rate of warming will have pronounced effects on glaciers and ice caps and lead to large runoff changes in glaciated areas.

Fig. 1. Sólheimajökull, S-Iceland. Photo Oddur Sigurðsson, 30. October 1985.

Ice caps and glaciers cover more than 10% of the area of Iceland and they receive on the order of 20% of the total precipitation that falls on Iceland. When the glaciers are close to a steady state, they therefore contribute on the order of 20% to river runoff and infiltration to groundwater aquifers in Iceland. The relative importance of glacier runoff is greater in highland areas, which are most important for hydropower purposes. Therefore, the relative importance of glacier runoff for the hydropower industry is even larger than for the country as a whole. Climatic warming on the order of 1-1.5 °C can temporarily increase glacier runoff from some Icelandic ice caps and glaciers by on the order of 50% (*cf.* Jóhannesson, 1991). A study of the potential effects of global warming on the hydropower industry in Iceland indicates that increased glacier river discharge due to climatic warming might permit a significant delay in the installation of new hydropower capacity and thus have large economic consequences (Elíasson and Sigurðsson, 1992).

Advance and retreat of glaciers is an indicator of climate changes and reconstructions of past variations of glaciers from geological evidence or historical observations is an important tool for deductions about past climate. Information about many past climate changes has in part been deduced from records of glacier variations. Future climate changes will be monitored instrumentally and this will of course give much more quantitative information about the changes than is available about past climate changes. Nevertheless, it is important to monitor glacier variations associated with future climate changes. The climatic signal contained in records of glacier variations has a large area coverage whereas most meteorological data consists of point measurements. Moreover, the glacier records document climate changes that occur in relatively high mountain areas which are often poorly represented in the meteorological data. Finally, it is important for the interpretation of past records of glacier variations to obtain good data on glacier variations associated with climate changes which are well defined by measurements.

The interpretation of climate from records of glacier variations is problematic in a number of ways. The advance and retreat of surging glaciers is unrelated to climate and records from

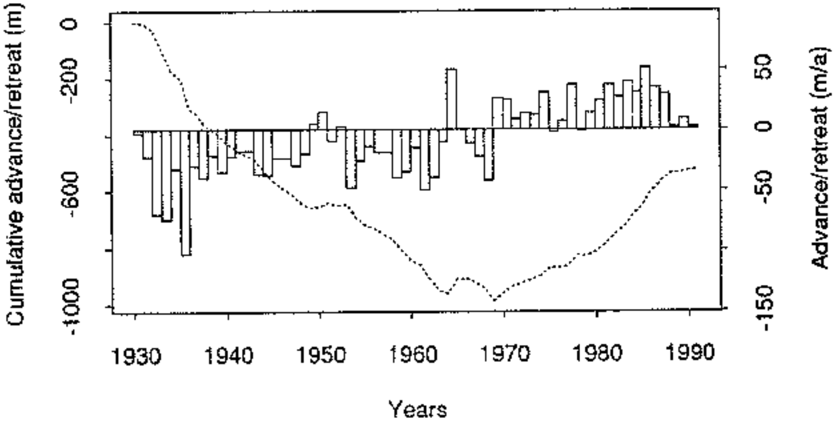

Fig. 2. Yearly advance and retreat of Sólheimajökull from 1930/31 to 1990/91 (histogram) and the cumulative advance/retreat of the glacier since 1930 (dashed curve). The ticks on the x-axis indicate the beginning/end of the measurement intervals (*i.e.* the tick marked 1960 is at the end of the interval 1959/60 and at the beginning of the interval 1960/61 which is in the fall of 1960).

such glaciers must be eliminated from a data set that is to be used for deductions about climate. The response of non-surging glaciers to climate changes is influenced by the response time of the glaciers, which leads to a delay between a climate change and the associated response of the glacier terminus (*e.g.* Jóhannesson and others, 1989a,b).

Data on discharge fluctuations of glacier rivers are a more direct indicator of the climate on the glacier than data on the advance and retreat of the terminus. Fluctuations in the yearly discharge are an indicator of climate changes and they are not affected by the time lag associated with the flow of the glacier. This even applies to surging glaciers, except during the first few years immediately following a surge, if proper account is taken of changes in the area covered by the glacier,

GLACIER VARIATIONS IN ICELAND SINCE 1930

Glaciers in Iceland started retreating from their Little Ice Age maximum between 1850 and 1900 and the rate of retreat became quite rapid after 1930. As the climate became cooler after 1960, the retreat of the glaciers slowed down and many glaciers started advancing, especially after 1970 (Thórarinsson, 1974; Björnsson, 1979). After about 1985 the climate has become warmer and many glaciers have started retreating again.

Figure 1 shows a photograph of the outlet glacier Sólheimajökull from the ice cap Mýrdalsjökull, S-Iceland, and Figure 2 shows the advance and retreat of Sólheimajökull from 1930/31 to 1990/91 (Sigurðsson, 1990). Figure 2 shows a rapid retreat between 1930 and 1960 followed by an advance which has slowed down in recent years.

Figure 3 shows the relative number of advancing and retreating glacier termini in Iceland from 1930/31 to 1990/91. The figure is based on measurements at only 20 (non-surging)

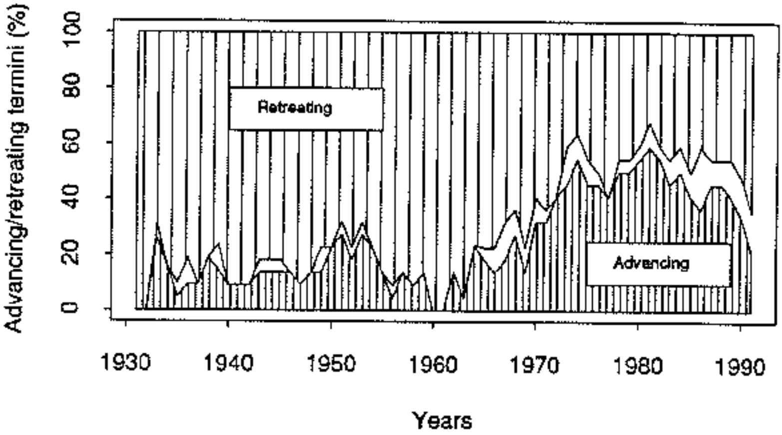

Fig. 3. Percentage of advancing (dense shading) and retreating (less dense shading) termini of non-surging, Icelandic glaciers as a function of time from 1930/31 to 1990/91. No shading indicates stationary termini. Over most of the time period shown, the figure is based on measurements at 22 locations at 20 termini (somewhat fewer termini in the years 1931, 1932 and 1991). The figure is based on measurements of the variations glaciers in Iceland which are published annually in the journal Jökull (*cf.* Sigurðsson, 1990) with some corrections (for more information, see the Appendix at the end of the paper).

glaciers and therefore it may not give a correct picture for all non-surging glaciers in Iceland. The figure shows that between 80 and 90% of the termini were retreating in the time period 1931 to 1960. Although between 10 and 20% of the glacier termini were advancing each year in this period, all the termini, without exception, had retreated from their 1930 positions by 1960. After 1960 the fraction of advancing termini started to rise, but after 1980 more glacier have started advancing again. The fluctuations of the Icelandic glaciers are similar to glacier fluctuations in the Alps (VAW, 1991; Aramando, 1992), but glacier fluctuations from other parts of the world can be quite different. For example, the retreat rate of glaciers in the Tianshan Mountains in China did not slow down or reverse around 1960 as was the case in Iceland and in the Alps (Chaohai, 1992).

Figure 4 shows summer temperature (May to September) and yearly precipitation (October previous year to September) in Reykjavík from 1931 to 1991. Variations in glacier ablation are primarily related to variations in the summer temperature, whereas changes in the accumulation may be expected to correlate with variations in the precipitation record. There is good correlation between temperature measurements at different meteorological stations in Iceland (Einarsson, 1989), and thus the temperature record from Reykjavík gives an estimate of temperature variations that occurred on Icelandic glaciers in this time period. The figure shows that the temperature was relatively high from 1931 to 1960, especially in the years 1931 to 1940. After 1960 the climate started to cool relatively rapidly. The temperature reached a minimum around 1980 and the climate has been warming since then. There are no similar systematic trends in the precipitation record in spite of large short term fluctuations (note the shifted precipitation scale in Fig. 4).

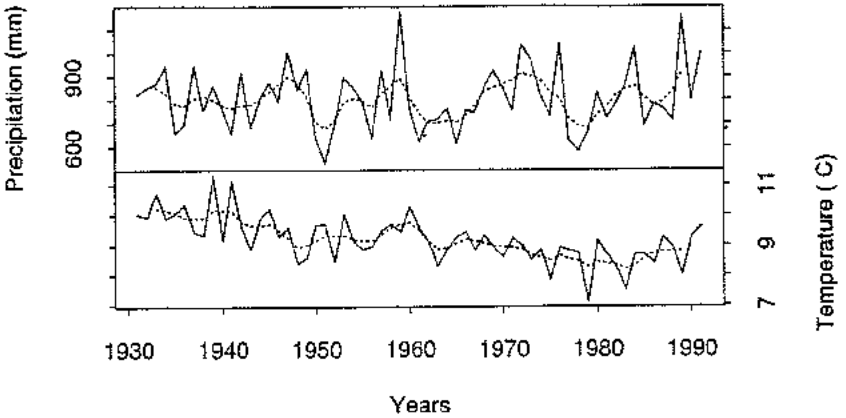

Fig. 4. Summer temperature (May to September) and precipitation (October previous year to September) in Reykjavík from 1931 to 1991 (solid curves). Dashed curves are weighted, running 5 year means using the weights (1/9,2/9,3/9,2/9,1/9) centered about each year.

The temperature and precipitation records in Figure 4 indicate that glacier fluctuations in Iceland (*cf.* Fig. 3) were primarily controlled by variations in the summer temperature. The rapid glacier retreat from 1931 to 1960 is related to high summer temperatures in this period. The glacier retreat slowed down and turned to advance after 1960 when the climate became cooler and the fraction of advancing glaciers reached it's maximum around 1980 when the summer temperature was at a minimum.

In spite of the strong correlation between glacier variations and summer temperature, which is apparent from figures 3 and 4, the figures show that the relationship between glaciers and climate is not simple. The decade from 1931 to 1940 is the warmest decade in the instrumental record in Iceland. In spite of this, between 10 and 20% of the glacier termini were advancing in this period, and more than 50% of the termini were still retreating during the very cold summers from 1970 to 1980. Moreover, Figure 3 excludes surging glaciers. Most of the larger outlet glaciers from the Icelandic ice caps are surging glaciers and records of their fluctuations have little or no climatic significance.

GLACIER MASS BALANCE AND CLIMATE

Climate changes affect glaciers through their effect on glacier mass balance. Therefore, quantitative estimates of mass balance variations associated with climate changes are of primary importance for understanding the effect of climate changes on glaciers. The summer temperature appears to be the most important of the climatic parameters that affect glacier variations, according to the discussion above.

A simple approach to this problem is to compute mass balance variations caused by temperature changes by raising or lowering the equilibrium line of the glacier, while keeping the mass balance gradient with elevation constant. The change in the elevation of the equilibrium line is then assumed to be linearly related to changes in the temperature with a constant

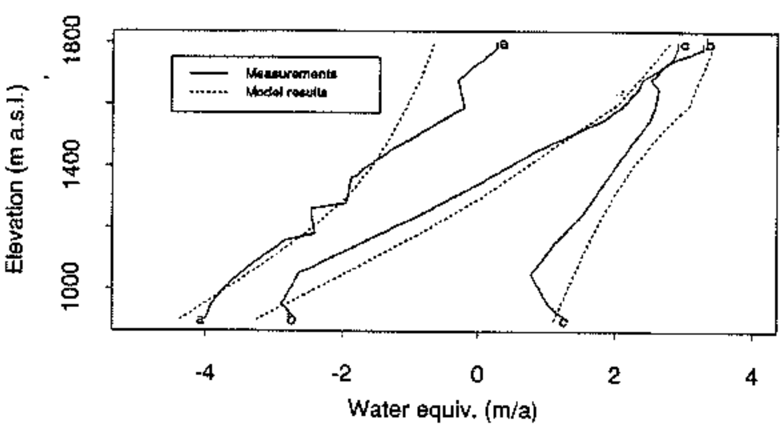

Fig. 5. Measured (1988-91 mean) and computed accumulation ("c"), ablation ("a") and mass balance ("b") on Sátujökull as a function of altitude (for explanation, see text).

of proportionality approximately equal to 100 m per 0.5-0.75 °C. This approach was used by Jóhannesson (1991) for computing the response of the Hofsjökull ice cap, Central Iceland, to climatic warming.

A more rigorous approach is to compute glacier accumulation and ablation from measured or synthetic time series of temperature and precipitation. A relatively simple glacier mass balance model based on degree-day computations has been adjusted to mass balance measurements on the outlet glacier Sátujökull from the Hofsjökull ice cap. The model is described by Reeh (1991) and Laumann and Reeh (in preparation). Below, this model will be used to estimate the effect of climatic warming on the mass balance of Hofsjökull.

Figure 5 shows the measured and computed accumulation, ablation and mass balance as a function of altitude. The measurements are the average of the four available years of measurements, 1988 to 1991 (Sigurðsson, 1989) The temperature and precipitation data required for the computations are taken from the meteorological station Hveravellir, which is in the neighbourhood of the glacier (data from the Icelandic Meteorological Office). The precipitation was adjusted by 63% (Sigurðsson, F.H., 1990) to compensate for an underestimate by the precipitation gauges. The model computations are based on a lapse rate of temperature with elevation equal to 0.6 °C/100 m; a precipitation gradient with elevation equal to 16% per 100 m; degree-day factors 0.008 and 0.006 m/°C/day for ice and snow; respectively; and the standard deviation of temperature fluctuations from a sinusoidal variation through the year was 3.8 °C. Four year averages of the temperature and precipitation data from the years 1988 to 1991 were used to estimate the average precipitation and an average sinusoidal variation of the temperature through the year (for a detailed description of the model, see Reeh (1991)).

The measurements and the model computations in Figure 5 are not strictly comparable, as the measured accumulation is actually the winter balance and the measured ablation is the summer balance (which becomes positive in the highest elevations), whereas the computed accumulation and ablation are yearly values. This difference accounts for a part of the discrepancy between the measured and computed accumulation and ablation curves in the highest elevations. The accumulation is somewhat overpredicted by the model, especially in the elevation range 1000-1200 m. This is partly due to drifting of snow from a convex part of

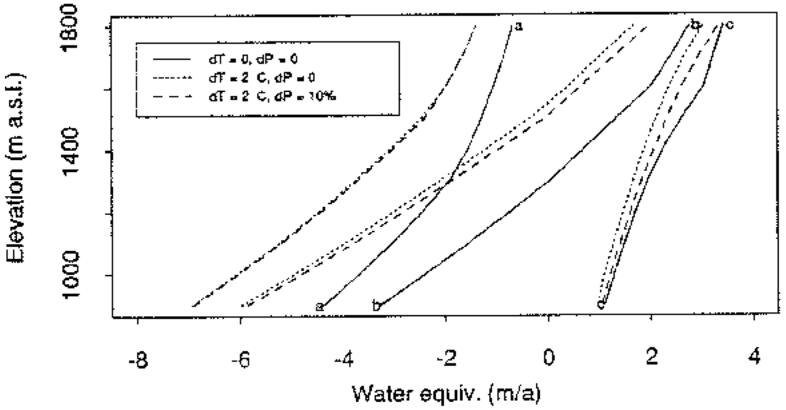

Fig. 6. Computed accumulation ("c"), ablation ("a") and mass balance ("b") on Sátujökull as a function of altitude. The solid curves are the same as the computed curves in Figure 5. The dashed curves correspond to a warming of 2 °C, with unchanged precipitation (short dashes) and with a 10% increase in the precipitation (long dashes), respectively (for explanation, see text).

the glacier surface. In the adaptation of the model to Sátujökull, refreezing of meltwater in the snow pack was not specified and this leads to an overprediction of the ablation in the higher altitudes. The overprediction of the ablation is nevertheless not as great as it appears in the figure, because the measured ablation in the higher altitudes is reduced by a significant amount through snowfall in the summer, but snowfall during the summer is included in the model accumulations as mentioned above. In spite of the abovementioned discrepancy between the measured and computed profiles, the most important features of the measurements (the gradients of ablation and accumulation with altitude) are reproduced by the computations. Since the reduction of the ablation with elevation, which is mostly caused by the fall of summer temperature with increasing elevation, is realistic in the model computations, one may expect that predicted ablation changes due to higher summer temperatures, will be realistic too.

Figure 6 compares the accumulation, ablation and mass balance computed by the model for current climate (solid curves) with the model results for higher temperature (dashed curves). The temperature increase is chosen to be 2 °C, which is in the lower range of predicted warming due to a doubling in the effective CO_2 content of the atmosphere (IPCC, 1990). Recent GCM computations with a transient increase in the effective CO_2 content of the atmosphere (*e.g.* Manabe and others, 1992), indicate that the warming may be less in the N-Atlantic region than elsewhere in the same latitude in the Northern Hemisphere. A warming of 2 °C is not inconsistent with Manabe's results, for the N-Atlantic region for the time period 60 to 80 years after the start of the transient computations, when the effective CO_2 content of the atmosphere has been approximately doubled.

The short dashed curves in Figure 6 show the model results for Sátujökull when the temperature is raised by 2 °C and the precipitation is not changed. It is seen that accumulation is lowered by a small amount (because more precipitation falls as rain), but the ablation is increased substantially, *i.e.* by more than 2 m/a in the lowest elevations. This leads to a raising of the equilibrium line by about 250 m (from approximately 1300 m a.s.l. to 1550 m a.s.l.)

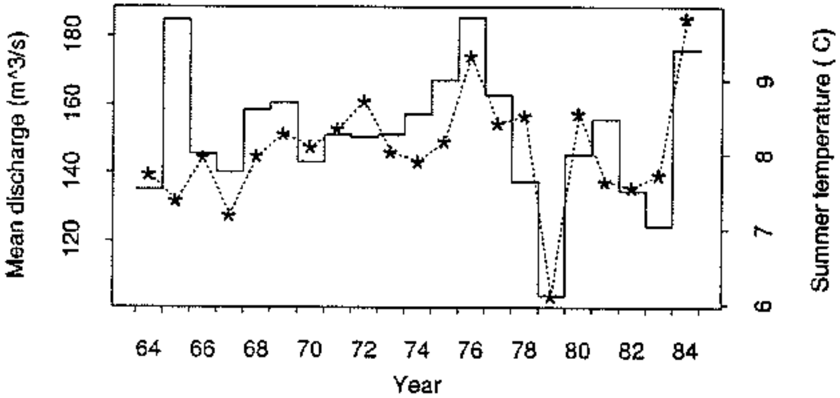

Fig. 7. Mean yearly discharge of Jökulsá á Dal (stair-step curve) and mean summer temperature (May to September) at Hallormstaður (dashed curve) from 1964 to 1984. The temperature means are plotted in the middle of each year.

This corresponds to 100 m per 0.8 °C, which is slightly higher than the values used by Jóhannesson (1991), that were mentioned above.

In general, GCM computations indicate that precipitation will increase with increasing global temperature, although this prediction is highly uncertain. An increase in the precipitation may be expected to increase the accumulation on ice caps and glaciers and it could therefore to some extent compensate for the increased ablation caused by a rise in the temperature. In Manabe's computations the average precipitation for the time period 60 to 80 years after the start of the transient computations is increased by approximately 10% in the latitude of Iceland. The long dashed curves in Figure 7 show the model results for Sátujökull when the temperature is raised by 2 °C and the precipitation is increased by 10%. The figure shows that the accumulation is raised by a small amount compared to the computations without an increase in the precipitation, but it is still lower that the accumulation computed for the current climate. The ablation, on the other hand, is hardly changed at all. Thus, the predicted mass balance and equilibrium line altitude are similar to the previous results for no increase in the precipitation (short-dashed curves).

The above results indicate that a climatic warming of 2 °C will lead to a large change in the mass balance of Icelandic glaciers, relatively independent of changes in the precipitation (as long as they are on the order of 10%). The predicted mass balance change is on the order of 1-2 m/a. Such a change in the mass balance will lead to a rapid retreat of glaciers in Iceland and a significant increase in the discharge of glacier rivers. The transient response of Hofsjökull to climatic warming and the associated distribution with time of the discharge increase in the rivers issuing from the ice cap are discussed in Jóhannesson (1991).

EFFECT OF GLACIERS ON RIVER DISCHARGE

As discussed in the introduction it may be expected that time series of the discharge of glacier rivers are a better indicator of climate change than variations in the position of glacier termini. Figure 7 shows the mean yearly discharge of river Jökulsá á Dal at Hjarðarhagi in NE-

Iceland from 1964 to 1984 (data from the National Energy Authority). There are problems in the discharge data during the winter time in the first half of the time period shown in the figure, but they are unlikely to affect the estimated mean yearly discharge significantly, because the winter discharge is very low compared to the mean yearly discharge (Snorrason, personal communication). The figure also shows the mean summer temperature (May to September) at a neighbouring meteorological station at Hallormstaður (data from the Icelandic Meteorological Office). Jökulsá á Dal is a glacier river that originates from the Brúarjökull outlet glacier from the Vatnajökull ice cap. The Brúarjökull glacier surged in 1963/64 (Thórarinsson, 1969). Abnormal discharge was recorded in Jökulsá á Dal during the years following the surge and hydrological modelling based on degree-days (Snorrason, 1986) indicates that the relation between river discharge and degree-days (*i.e.* temperature) is affected by the surge for a few years after the surge.

The correlation coefficient of the 21 years of discharge and temperature measurements in Figure 7 is 0.63. If the years 1964 and 1965 are excluded because of the surge in 1963/64 the correlation coefficient for the 19 remaining years is found to be 0.79. The excellent correlation between the discharge of Jökulsá á Dal and the summer temperature at Hallormstaður shows that a strong climatic signal is contained in the river discharge time series. Thus, discharge measurements in Jökulsá á Dal may be used to estimate temperature variations over the large ablation area of Brúarjökull.

CONCLUSIONS

Glacier variations in Iceland from 1930/31 show a clear relationship with variations in summer temperature. Climatic warming due to an increase in the greenhouse effect in the Earth's atmosphere during the next decades may lead to a substantial increase in glacier ablation in Iceland. This will increase the discharge of glacier rivers and have a significant impact on the hydropower industry in Iceland. The effect of climatic warming on glacier ablation is likely to be much more significant for the mass balance of Icelandic glaciers and ice caps than the increase in precipitation which is predicted to be accompanied by the warming by GCM computations. Monitoring of the discharge of glacier rivers is an important part of the instrumental monitoring of climate change.

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APPENDIX:

Figure 3 is based on measurements at 22 locations at 20 glacier termini in Iceland. Measurements of the variations of glaciers in Iceland are published annually in the journal Jökull (*cf.* Sigurðsson, 1990). The figure includes previously unpublished data from 1991 and a few corrections of the previously published data.

The figure is based on data from the following glaciers:

Outlet glaciers from Öræfajökull, SE-Iceland: Kvíárjökull, Svínafellsjökull, Virkisjökull.

Outlet glaciers from Vatnajökull, SE-Iceland: Breiðamerkurjökull (two locations), Brókarjökull, Fláajökull, Heinabergsjökull, Hoffellsjökull, Svínafellsjökull in Hornafjörður, Morsárjökull, Skaftafellsjökull, Skálafellsjökull.

Outlet glaciers from Drangajökull, NW-Iceland: Kaldalónsjökull, Leirufjarðarjökull, Reykjarfjarðarjökull.

Others glaciers: Gígjökull in Eyjafjallajökull (S-Iceland), Gljúfurárjökull (N-Iceland), Hyrningsjökull in Snæfellsjökull (W-Iceland), Nauthagajökull in Hofsjökull (Central Iceland), Sólheimajökull in Mýrdalsjökull (S-Iceland, two locations).

Only termini which have been measured since about 1930 are included in the figure. Measurements from glaciers which are known to surge are not included because terminus variations of surging glaciers are typically not controlled by climate changes. Data from Skeiðarárjökull in Vatnajökull are not included for this reason.

A number of the time series do not start until 1932 or 1933 and data from 1991 are not available from all the locations. The figure is therefore based on fewer time series in 1931 (9 series), 1932 (13 series) and 1991 (14 series) than in the others years (at least 19 series).

POLAR HYDROLOGI:
NORSK HYDROLOGISK FORSKNINGSAKTIVITET PÅ SVALBARD

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ABSTRACT

Since 1987 polar hydrology has been a slowly icreasing field of research for Norwegian hydrologists. This field is considered important both from aspects like local water supply and more large scal aspects like understanding of hydrological processes in arctic ecosystems. This paper describes hydrological research activities in Svalbard during the period 1987-92 sponsored by the Norwegian National Committee for Hydrology. Also a new researh program named "Polar hydrology Svalbard" is briefly outlined. This program is intended to take place during the period 1993-95.

INNLEDNING

Polar hydrologi har vært et gryende aktivitetsområde innen norsk hydrologi siden 1987. Norsk hydrologisk komite (NHK) fikk polar hydrologi inn på sitt FoU-program både for periodene 1987-89 og 1990-92. Nylig har NHK også vedtatt å gå inn for en økt innsats innenfor polar hydrologi i og med vedtaket om å iverksette et eget FoU-program i polar hydrologi for perioden 1993-95.

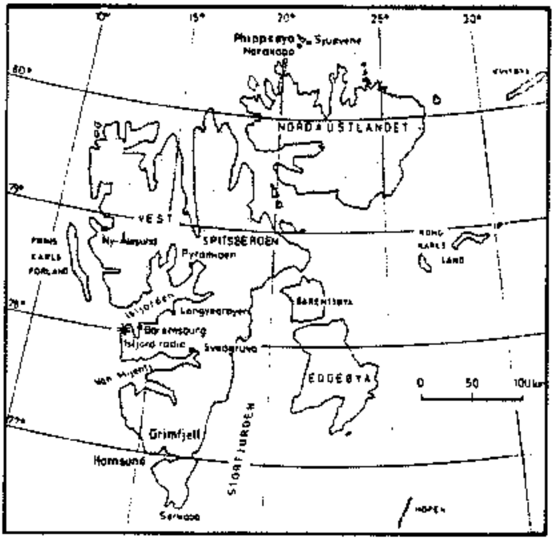
Polar hydrologi har blitt definert som hydrologi i områder hvor permafrost har betydning for de hydrologiske prosessene (Hagen m.fl., 1992). For Norge vil dette i praksis bety hydrologi på Svalbard. Her er samtidig snø og is de dominerende elementer i vannbalansen og frysing og smelting er de dominerende hydrologiske prosessene.

Dette paper er et oversikt over norsk hydrologisk forskningsaktivitet på Svalbard.

SVALBARD - EN FORSKNINGSARENA I ARKTIS

Svalbard er navnet på øygruppen beliggende mellom breddegrad 76° og 81°N og lengdegrad 10° og 35°E i norsk arktis (figur 1). Av et totalt areal på ca 63 000 km^2 er 60 % dekket av breer. Isfrie landområder har kontinuerlig permafrost og permafrostdybden variere fra mindre enn 100 m ved kysten til mer enn 500 m i høyereliggende fjellområder (Liestøl, 1977). Temperaturene er høye, breddegraden tatt i betraktning. Dette skyldes først og fremst milde havstrømmer som kommer opp langs vestkysten av Spitsbergen. Middeltemperaturer for Isfjord Radio er for kaldeste og varmeste måned (henholdsvis mars og juli) -11.7°C og +4.7°C. Gjennomsnittlig årsnedbør er i underkant av 400 mm langs vestkysten av Spitsbergen, denne er imidlertid økende østover. Polare ørkenområder finnes på den nordøstre delen av øya (Hisdal, 1985).

Administrasjonen av Svalbard er nedfelt i Svalbardtraktaten fra 1920, Norge ble da tildelt suverenitet over øygruppa. Svalbardtraktaten er idag undertegnet av 35 nasjoner. I henhold til traktaten har alle nasjoner som har undertegnet like rettigheter til utnyttelse av øygruppas naturressurser. Idag driver Norge og Russland utvinning av kull på Svalbard. Norge, Russland, Tyskland og Polen har permanente, helårsbemannede forskningsstasjoner. Et stort antall nasjoner driver sesongbasert forskning over hele Svalbard.



Figur 1. Svalbard

HYDROLOGISK FORSKNING PÅ SVALBARD FRAM TIL IDAG

Det første omfattende hydrologiske forskningsarbeid på Svalbard ble utført i Bayelva, Ny-Ålesund i årene 1973-78 (Repp, 1979). Før dette er bare enkelte mindre hydrologiske forskningsarbeider utført på Svalbard. Repp(1979) beskrev hydrologiske prosesser i Bayelvas tilsigsfelt og Brøggerbreene med hovedvekt på breerosjon, brehydrologi og sedimenttransport.

Fra og med 1987, når NHK tok "polar hydrologi" inn i sitt FoU-program, har antallet forskningsprosjekter på Svalbard økt. Flere sentrale forskningsmiljøer i Norge har engasjert seg innen dette fagfeltet. I de følgende avsnitt gis en kort beskrivelse av endel av de prosjektene hvor NHK har vært en viktig sponsor.

Forskningsinnsatsen på Svalbard er hittil prioritert i 3 forskjellige tilsigsfelter: Bayelva ved Ny-Ålesund, DeGeer-elva og Endalselva/Isdammen. Disse feltene er valgt av ulike årsaker: Bayelva var det eneste feltet hvor det allerede forelå et hydrologisk datamateriale av særlig størrelse og varighet (Repp, 1979). DeGeer ble valgt pga. at denne elva var en av de meget få på Svalbard som har et naturlig stabilt måleprofil, dessuten er feltet interessant pga liten bredekning (ca 15 %) (Hagen m.fl.,1987). Endalselva/Isdammen utgjør vannforsyningskilde til gruvesamfunnet Longyearbyen (ca 1000 innbyggere) feltet ble valgt ut fra den avgjørende betydning dette vassdraget har for lokalsamfunnet Longyearbyen.

Avløp

Mesteparten av innsatsen i den første FoU-perioden ble lagt i å opprette avløpsmålestasjoner. En permanent måledam ble bygd i Bayelva og en limnigrafstasjon ble bygd i DeGeer-elva. Disse stasjonene drives nå av Norges vassdrags- og energiverk (NVE). I Isdammen som utgjør vannforsyningsreservoir for Longyearbyen omfatter målingene både en overføring inn i magasinet, tapping, vannstand og overløp.

I løpet av 1992 vil det foreligge avløpsdata for tilsammen 9 år for Bayelva og 2 år for DeGeer. I Isdammen ble målingene i satt regulær drift først i 1992.

Vannbalanse

Vannbalansens enkelte ledd har vært relativt dårlig kjent både regional og lokalt på Svalbard pga. manglende datamateriale.

I årene 1991-92 har det vært utført et prosjekt "Vannbalanse Svalbard" som primært tar sikte på å vurdere betydningen av de enkelte leddene i vannbalansen samt utarbeide måleopplegg for observasjon av de viktigste parametrene. I prosjektet er det etablert et observasjonsnett for sommernedbør med sikte på å kartlegge nedbørfordeling i de tre nevnte forsøksfeltene. I tillegg gjennomføres målinger av snøakkumulasjon, snøfordeling og fordamping fra fri vannflate. Ved oppsetting av vannbalansen blir det også benyttet data som framskaffes via andre prosjekter, som massebalanse av breer, fritt vann i aktivt lag og grunnvannsbalanse.

Et prosjekt "Vannbalanse Tvilligvatn" har som mål å estimere de enkelte leddene i den lokale vannbalansen for Tvillingvatn. Tvillingvatn er vannforsyningsmagasin til Ny-Ålesund. Sannsynligvis utgjør subpermafrost eller intrapermafrost grunnvann en vesentlig del av balansen.

Brehydrologi

På Brøggerbreene (i Bayelvas tilsigsfelt) er det utført undersøkelser (tracerforsøk) for å kartlegge dreneringssystemer i og under breene.

I tillegg til de nevnte prosjektene utføres det også prosjekter innenfor **sedimenttransport**, hydrologiske prosesser i **aktivt lag**, og **grunnvann** innenfor tilsigsområdet til Bayelva.

ANDRE FORSKNINGSAKTIVITETER MED RELASJONER TIL HYDROLOGI

Foruten de hydrologiske forskningsaktiviteter på Svalbard foregår en vesentlig forskningsaktivitet innen fag som er viktige støttefag for hydrologi:

Meteorologi

Det norske meteorologiske institutt (DNMI) opererer idag 5 synoptiske meteorologiske stasjoner på øygruppen. I tillegg har DNMI 4 automatstasjoner. En kontinuerlig temperaturserie er tilgjengelig fra 1911 til idag.

Permafrost

En permanent stasjon for permafrostforskning drives i Svea av Norges Geotekniske Institutt (NGI). Her observeres meteorologiske data, jordtemperaturer og varmeflukser i bakken av et automatisk datainnsamlingssystem. I tillegg gjøres manuelle målinger av tinedybde, grunnvannsnivå, tørrskorpetykkelse, jordfuktighet, snødybde og snøtetthet (Bakkehøi, 1982).

Glasiologi

Massebalansemålinger blir utført på utvalgte breer på Svalbard.

I tilsigsfeltet til Bayelva har Norsk polarinstitutt utført massebalansemålinger på Austre og Vestre Brøggerbre siden 1966 (Hagen og Liestøl, 1990).

Atmosfærens sammensetning

Norsk institutt for luftforskning (NILU) har driver en ny luftforskningsstasjon på Zeppelinerfjellet 475 m.o.h. og 2.1 km fra Ny-Ålesund. Stasjonen inngår i flere internasjonale forsknings- og overvåkningsprogram for bl.a. transport av luftforurensninger, drivhusgasser, ozon og KFK-forbindelser.

Terrestrisk økologi

I 1992 har Norges Almennvitenskapelige Forskningsråd (NAVF) startet et fireårig forskningsprogram innen terrestrisk økologi på Svalbard.

NORSK NASJONALT FOU-PROGRAM: "POLAR HYDROLOGI SVALBARD"

Bakgrunn

Hittil har hydrologi i polare områder vært et lite prioritert innsatsområde i norsk forskning. NOU 1989:9 "Norsk Polarforskning" fastslår at "breer og hydrologi er kanskje det fagområdet innen naturvitenskapen hvor det er størst misforhold mellom de uttrykte behov og innsats". Beklageligvis ser dette fortsatt ut til å være tilfelle. Hittil har forskningsaktivitetene på Svalbard vært meget begrenset pga. små ressurser.

Norsk hydrologisk komite har for perioden 1993-95 utarbeidet et nytt FoU-program "Polar hydrologi Svalbard" (Hagen m.fl., 1992). Dette FoU-programmet representerer en vesentlig økning av ambisjonene for hydrologisk forskningsvirksomhet på Svalbard.

Iverksettelsen av et nytt norsk FoU-program i polar hydrologi blir begrunnet ut fra at:

- det er viktig å forstå basale hydrologiske prosesser for å kunne vurdere konsekvenser av inngrep og ulike påvirkninger. Ferskvannstilførsel og sedimenttransport er hovedtransportører av næringsstoffer og eventuelle forurensninger til fjorder og kystnære områder. Dette har også stor betydning for biologisk produksjon i omkringliggende havområder.

- forståelsen av arktiske økosystemer er viktig, ikke bare med tanke på forvaltningen av Arktis, men også fordi vi her har viktige indikatorer på både regionale og globale endringer.

- ferskvannstilgangen til bosetningene på Svalbard et stort problem lokalt. Her har det imidlertid aldri vært utført grunnleggende undersøkelser for å skaffe bosetningene en god og stabil vannforsyning.

Målsetting

Programmet har som erklært hovedmålsetning "å skaffe forvaltning og næringsinteresser på Svalbard oversikt over vannressurser og sikre hydrologisk kompetanse og prosessforståelse for å bidra til en god miljøforvaltning og en forsvarlig næringsutvikling".

Konkret skal dette hovedmålet bidra til å:

- skaffe norsk kompetanse innen polar hydrologi på Svalbard en internasjonalt sett sentral og koordinerende posisjon.
- utnytte kunnskapsnivået om hydrologiske prosesser i permafrostområder for å styrke en bærekraftig utvikling og gi bedre konsekvensvurderinger av naturinngrep i Arktis.
- ivareta Norges internasjonale ansvar for overvåkning av Arktis.
- fremme næringsvirksomhet med varige arbeidsplasser på Svalbard.

Målsettingen tenkes nådd gjennom etablering av et nett av hydrologiske målestasjoner i typeområder på Svalbard, gjennomføring av et datainnsamlingsprogram for hydrologiske basisdata samt gjennomføring av forskningsprogrammer innenfor følgende utvalgte tema:

1. Vannforsyning på Svalbard
2. Erosjon og forurensning
3. Hydrologiske konsekvenser av klimaendring

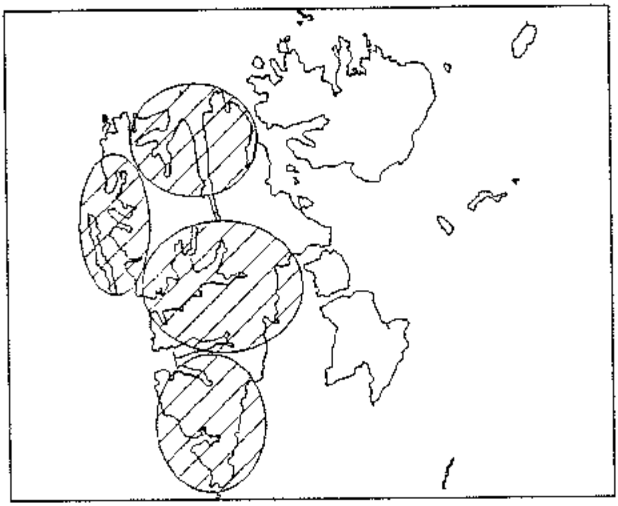
Hydrologiske basisdata.

På Svalbard som i mange andre polare områder mangler i stor grad både grunnleggende data prosessforståelse. Mange forskningsoppgaver både innenfor vannbalanse- og prosessstudier vil være vanskelig å gjennomføre uten en grunnmur av basisdata. Innsamling av basisdata vil derfor bli gitt høy prioritet i kommende FoU-periode.

Behovet for basisdata er så stort at det må etableres et nett av midlertidige målestasjoner fordelt over ulike typeområder på Svalbard. Det foreslås opptil 10 midlertidige stasjoner som skal måle **avløp, sedimenttransport, hydrokjemiske, biologiske og klimatologiske** parametre. Disse stasjonene bør drives over en treårsperiode. Ved utløpet av treårsperioden må datafangsten gjennomgå en totalvurdering for å kartlegge om det er ønskelig å drive et antall stasjoner videre på permanent basis.

Driften av et midlertidig stasjonsnett vil være en omfattende oppgave som vil kreve et tett samarbeid mellom mange institusjoner i Norge. Det vil være nødvendig å få etablert et samarbeid med Norsk polarinstitutts sommerekspedisjoner og få muligheter til å benytte NP's logistikktjenester.

Det antas at målestasjonene kan drives av fire feltpartier som vil operere innenfor hver sine områder av Svalbard, se figur 2. Feltpartiene må være ute i perioden juni til medio september, endel steder til medio oktober. Det foreslås bygd opp et vannfaglig laboratorium i Ny-Ålesund eller Longyearbyen som kan foreta kjemiske, biologiske og sedimentologiske analyser.



Figur 2 Foreslåtte operasjonsområder for feltpartiene

Ekstreme klimaforhold kan medføre nye behov mht. måleteknikker og -utstyr. Prosjekter som har som formål å spesielt tilpasse metoder og måleteknologi til bruk i kaldt klima bør prioriteres. I denne sammenheng er det også foreslått å kartlegge muligheter og begrensninger ved bruk av fjenmålte data.

Forskningsprogram

De temaene som skal prioriteres innenfor programmet er:

1. Vannforsyning på Svalbard
2. Erosjon og forurensning
3. Hydrologiske konsekvenser av klimaendringer

Vannforsyning:

Det hydrologiske datagrunnlaget for vannforsyning på Svalbard er dårlig. Dette kan legge uønsket begrensning på framtidig aktivitet på øygruppen. Det er sterkt ønskelig å få dokumentert hvilke vannressurser en rår over og hvilke tiltak som er nødvendig for å få en tilfredsstillende vannforsyning til alle bosetninger. Dette gjelder både vannets kvantitet og kvalitet.

Vannforsyning i permafrostområder byr på spesielle problemer. Gode naturlige reservoarer er mangelvare og det særegne hydrologiske regimet gir ytterligere usikker manøvrering av de reservoarer som finnes.Faktisk størrelse på de enkelte vannkildene og -ressursene er lite kjent. Økt kunnskap om vannbalanse og dens enkelte ledd er derfor nødvendig. Ikke minst er dette aksentuert av ønsket/behovet for økt virksomhet (gruveindustri, turisme, vannforsyning til fiskeflåte og andre fartøy, ny næringsvirksomhet) på øygruppen.

De eksempler vi kjenner fra vannforsyning til bosetningene på Svalbard viser klart at vannforsyning i permafrostområder ofte er lite tilfredsstillende og i mange tilfeller meget sårbare.

Erosjon og forurensning:

For å kunne forutsi konsekvenser av ulike påvirkninger i naturen og endringer i de ytre betingelser er det nødvendig å forstå de prosesser som er aktuelle i den enkelte problemstilling. Rennende vann og breer er de viktigste eroderende og transporterende agenser i et polart klima. Under arktiske forhold kan terrengskader stå i lang tid og i verste fall initiere akselerert jorderosjon av særlig destruktiv karakter. Det rennende vanns rolle har vært for lite påaktet i denne sammenheng. Skadeomfang av erosjon på Svalbard er hittil bare blitt kartlagt ved fly- eller satelittfotografering eller ved bakkeregistreringer. En skikkelig konskvensanalyse krever imidlertid en dypere prosessforståelse av overflateavløp og erosjon. Direkte prosessundersøkelser og erosjonsmålinger vil derfor være en prioritert oppgave.

Transportprosesser i rennende vann sørger for spredning av erodert materiale og forurensninger både på land og ut til de kystnære farvann. Sedimentpartiklenes rolle som bærere av partikkelbundet forurensning og naturlige sporstoffer er kjent fra andre breddegrader. Radioaktivt nedfall er en høyaktuell problemstilling i Arktis; radioaktivt nedfall etter Tsjernobyl-ulykken har vært registrert over hele Svalbard.

Den biologiske aktiviteten og de økologiske forholdene i de kystnære farvann rundt Svalbard er også knyttet til tilførselen av ferskvann, tilførselen av suspendert materiale, kjemisk oppløst stoff og partikkelbundne stoffer.

Størrelsesorden på materialtilførselen fra subaerile erosjonsprosesser i permafrostområder er lite kjent. For å kunne vurdere sediment- og stofftilførselen til kystnære farvann er det derfor viktig å kunne vurdere disse ulike prosessene opp mot hverandre.

Hydrologiske konsekvenser av klimaendringer:

Klimascenarier indikerer temperaturøkning og økning i nedbør og fordampning pga. drivhuseffekten. Det antas også at klimaendringer vil bli vesentlig større i polarområdene enn i andre deler av kloden. Disse effektene vil bidra til å endre energibalansen mellom land og atmosfære. Man ser idag konturene av hydrologiske konsekvenser av klimaendringer som f.eks.:

- avsmelting av snø- og isdekkede områder med påfølgende endring i energibalansen mellom land og atmosfære
- endret massebalanse av breer
- økt snøakkumulasjon, tidligere snøsmelting, kortere snødekt periode
- reduksjon i utbredelse av permafrost
- dypere aktivt lag
- utvidelse eller sammentrekning av innsjøer
- økt karstaktivitet
- ustabilitet i elveskråninger og strandsoner, høyere erosjonspotensiale
- større fornying og avrenning av grunnvann

De mange potensielle effekter av klimaendringer i polarområdene medfører at vi her finner mange sensitive klimaindikatorer som kan brukes i overvåkning av klimautviklingen.

Det bør prioriteres å arbeide med analyser av konsekvenser for vannbalanse, energibalanse og konsekvenser av et dypere aktivt lag.

Budsjett

FoU-programmet "Polar hydrologi Svalbard" representerer et løft innen norsk hydrologisk forskning. Dette vil kreve støtte fra nasjonale myndigheter i tillegg til de ressurser NHK rår over.

Gjennomføring av basisundersøkelser og datainnsamling er kostnadsberegnet til ca 16.5 mill. kr. over en treårsperiode. Til gjennomføring av prioriterte FoU-prosjekter er foreslått ca. 5 mill. kr pr. år i 3 år.

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VARIATIONS OF CLIMATE AND GLACIER MASS BALANCE, SVARTISEN, NORWAY

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ABSTRACT

During the last hundred years, most of the glaciers of Svartisen, northern Norway's largest ice-covered area, have changed in response to climatic conditions. In some cases, however, loss of ice by calving into marginal lakes has dominated the mass balance. At one glacier, Engabreen, records of the changes of length since the late 1860s have been supplemented by annual mass balance observations carried out by the Norwegian Water Resources and Energy Administration since 1969. A simple mass balance model, based on summer temperature and winter precipitation data from a meteorological station at Glomfjord permits extrapolation of the mass balance record back to 1945. Because the model does not take into account changes of the glacier's area x altitude distribution, it is not appropriate to extend its application back to the early part of the twentieth century. Aerial photographs of the whole of Svartisen taken in 1945, 1968 and 1985, and terrestrial photogrammetry at several glaciers during the last two decades, provide much information about recent changes. Small glaciers terminating at relatively-high altitude appear to be more responsive to slight climatic fluctuations than are the major glaciers of the area. Climatic conditions at Svartisen have changed significantly since 1945: the duration of the accumulation and ablation seasons has varied. In attempting to relate glacier change to climatic conditions, it is necessary to consider those aspects of climate which are related to atmospheric circulation patterns, as well as the monthly records of air temperature and precipitation.

INTRODUCTION

The West and East Svartisen ice caps, situated between 66°30'N and 66°50'N, are separated by a narrow valley, Glomdalen (known as Vesterdalen in its northern part). On the basis of aerial photographs taken in 1968, Østrem and others (1973), who calculated that West Svartisen covered 221.45 km^2 and East Svartisen 147.89 km^2, identified sixty glaciers at Svartisen. A few of the small ones terminate at relatively-high altitude and some of the larger ones descend to low altitudes, but about sixty per cent have lower limits between 1000 m and 700 m. Most of the glaciers in Vesterdalen are short, and many head in cirque-like basins above hanging valleys; the divides which separate them from the accumulation areas of the adjacent glaciers are largely subglacial.

TWENTIETH-CENTURY GLACIER CHANGE

One hundred years ago, many of the glaciers of the Svartisen area were close to their maximum Neoglacial size. The changes which they have experienced since then have resulted in a significant reduction in the volume of water stored as snow, firn and glacier ice (Theakstone, 1988). Differing glacier geometries influence patterns of behaviour (Theakstone, 1990).

Most of the outlet glaciers of the West and East Svartisen ice caps end on land, and their changes of size primarily are a response to climatic conditions. Whilst the best-documented record is that from Engabreen, the largest glacier of West Svartisen, a wealth of information about the changes of many glaciers is provided by aerial photographic cover of the entire Svartisen area from 1945, 1968 and 1985, and by observations made both between those dates and more recently by the authors and others (Theakstone, 1988; Knudsen and others, this volume).

The changes of length of several glaciers have been influenced strongly by the calving of ice into proglacial lakes: five of the seven largest glaciers of Svartisen terminate in lakes, or have done so in the course of their retreat. Throughout the last four decades, calving has dominated the mass balance of Austerdalsisen, Svartisen's largest glacier (Knudsen and Theakstone, 1981; Theakstone and Knudsen, 1986; Theakstone, 1989).

Calving also has played a significant role in the changes of Flatisen, the principal eastward-flowing outlet of West Svartisen, which has retreated more than 2 km since 1945. In 1890, Flatisen extended across Glomdalen, and the river Glomåga flowed beneath the glacier (Rekstad, 1893). Twenty years later, the glacier had begun to calve into a small lake which had formed at its northern margin (Marstrander, 1911). Flatisen lost contact with the eastern side of Glomdalen between 1922 and 1925, when the Glomåga flowed past the steep glacier front (Rygh, 1935). In 1931, Flatisen was calving into the river (Aigner, 1938), but four years later it ended in a lake about mid-way across Glomdalen (Granlund and Lundqvist, 1936). By 1945, the front had retreated to a point about 1 km from the eastern shore of the lake, by 1957 the distance had increased to around 1.5 km (Theakstone, 1965), by 1968 to more than 2.2 km, and by 1985 to more than 3 km.

In 1910, several of the short, steep glaciers in Vesterdalen extended to the valley floor (Marstrander, 1911). In the next 35 years, they all underwent marked retreat. Subsequently, some continued to retreat until the mid-1960s, but the net change of position of the terminus of others was slight, especially between 1945 and 1965. Since 1965, retreat has been limited: most of these small glaciers were larger in 1985 than in 1965. This behaviour contrasts with that of the longer glaciers discharging from the East Svartisen ice cap.

VARIATIONS OF ENGABREEN: CHANGES OF POSITION OF THE GLACIER FRONT

When Geikie (1866) made the first detailed study of Engabreen in 1865, the glacier was more than 2 km longer than it was to be in 1965. Part of the change was associated with calving into a lake. In 1883, the lake, said by a local farmer to have existed for only thirty or forty years, was 900-1000 m long (Rabot, 1899). Two years later, it was larger, but its surface level lower; glacier retreat had been particularly pronounced at the southern side of the valley, beyond the lake's outlet.

In 1890, Engabreen almost filled the small proglacial lake, suggesting that the glacier had advanced during the 1880s (Rekstad, 1893). In 1896, all of the low part of the glacier which had bordered the lake eleven years before had disappeared, although the eastern part still ended in the lake (Rabot, 1899). A net retreat of 60-80 m was noted between 1889 and 1898.

In 1905, Engabreen advanced across a long-used path, destroying a cairn built in 1898. The advance changed the course of the glacier river, and resulted in sedimentation within the proglacial lake basin. Rekstad (1912) suggested that the advance started in 1903. By 1909, when annual measurements of changes of position of the front were started, the basin was almost full of sediment, and the glacier terminus was 18 m in front of its 1898 position, indicating an advance of about 100 m since 1903.

In 1910, a flat plain occupied the former site of the proglacial lake. Although retreat was under way in 1911, annual changes were slight for several years. A new lake, Engabrevatnet, formed and, in the autumn of 1931, the end of the glacier, then 69 m behind its 1909 position, began to break up by calving; between 1931 and 1934, the centre of the tongue retreated 612 m (Faegri, 1935). In 1932, the glacier's position was similar to that of 1865.

Engabreen retreated from Engabrevatnet in 1944. In September 1945, its sharply-pointed tongue ended about 70 m from the lake. In the next five years, retreat totalled some 100m. By 1965, the glacier ended more than 300 m from the lake, but retreat then ceased.

Annual changes of position of the glacier front have been recorded by Norges Vassdrags- og Elektristetsverket since 1965. In 1968, Engabreen terminated 230 m behind its 1945 position, but 37 m in front of that of 1965. Advance has occurred through much of the last quarter-century, with interruptions in the early-1970s and early-1980s. In 1985, the glacier ended within 150 m of Engabrevatnet, some 160 m beyond the position occupied by the front in 1965.

VARIATIONS OF ENGABREEN: MASS BALANCE MODELLING

Annual mass balance measurements at Engabreen have revealed a net gain equivalent to >12 m of water over the entire glacier since 1969-70. During the 1970s, accumulation values were high: seven of the nine years in which the mean winter balance exceeded 3 m were in the period 1971-79. Between 1976 and 1980, however, there was a period of near-equilibrium, with three unusually-large annual net ablation values compensating for high accumulation.

Using linear regression, the winter balance (b_w) and summer balance (b_s) at Engabreen can be related to winter (October-May) precipitation (p_w) and summer (June-September) temperature (t_s) at Glomfjord, a meteorological station at 39 m above sea level, some 16 km north-west of the glacier: $b_s = 0.556t_s - 3.77$; $b_w = 1.978p_w + 0.237$. This net mass balance model has been used to synthesise data for Engabreen. Both this synthetic record and the actual mass balance values can be compared with data from other glaciers in a large part of Scandinavia.

The mean net mass balance for the decade 1970/71-1979/80 was determined for Engabreen and for each of seven other Scandinavian glaciers. Annual deviations from this mean, calculated for periods ranging from 18 to 41 years, show similar directions of change from one year to the next (Figure 1). The annual deviations tend to be higher for maritime glaciers, such as Engabreen and Ålfotbreen, than for more-continental ones, such as Storbreen and Storglaciären. Comparison of the synthetic Engabreen record for the period 1945/46-1986/87 with the actual records of Storglaciären, Sweden (the longest existing mass balance series) and Storbreen suggests that, at least from the late 1950s, the predicted pattern of annual variations at Engabreen is realistic (Figure 1, bottom).

The same model has been used to extend the Engabreen mass balance record back to 1916, when the Glomfjord station was brought into operation. Cumulative net balance values derived in this way suggest a pattern of glacier variations which departs markedly from the known changes of length. Even when allowance is made for calving, the model is not satisfactory. Undoubtedly, one cause of the poor 'prediction' is the considerable change of geometry of the glacier between 1916 and the late 1950s: the model is based on the 1968 area x altitude distribution, with only 0.31 km^2 (<1% of the glacier's total surface area) below 200 m. Between the 1920s and the 1940s, a larger proportion of the glacier, and a substantially-bigger area, was within this zone. Another weakness of the model is that no allowance is made for changes in the relative duration of the accumulation and ablation seasons. Examination of mean monthly data has shown that both May and October temperatures have changed considerably during the last seventy years (Theakstone, 1990).

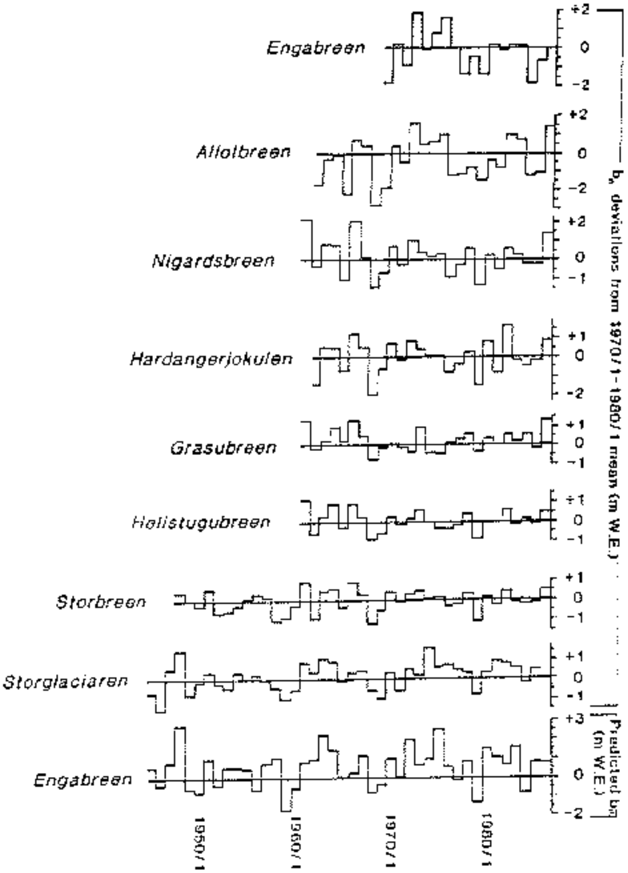

Figure 1. Annual variations of mass balance of Scandinavian glaciers, with values predicted by a simple model of Engabreen.

THE RELATIONSHIP BETWEEN CLIMATE AND GLACIER CHANGE

Over extensive areas, the relationship between climate and glacier change is dominated by synoptic conditions (Hoinkes 1968, Yarnal 1984, Letrequilly and Reynaud, 1989). It is this which causes the patterns of annual deviation of net mass balance from the decadal mean to be similar for a variety of Scandinavian glaciers. Despite this regional identity of behaviour, however, the response of individual glaciers to climatic variations is not synchronous: within a particular area, such as Svartisen, glacier responses vary because local conditions, especially topography, determine the reaction to external conditions. Adjacent glaciers which have different area x altitude distributions are likely to display different behaviour (Furbish and Andrews 1984, Kuhn and others, 1985; Theakstone, 1990).

Conclusions drawn from mass balance reconstructions based on temperature and precipitation data may be over-generalised, and even misleading. Although elements of the surface energy balance, including turbulent heat flux and incident long-wave radiation, **are** related to temperature, glacier mass balance is responsive to patterns of atmospheric circulation, which may be poorly represented by temperature and precipitation data alone. Long-term glacier change is best investigated with reference to data relating to wind, cloud and atmospheric pressure. During the winters of the 1970s, the proportion of winds with a westerly, rather than an easterly, component was unusually high at Bodø, some 70 km north of Svartisen. The increased frequency of depressions and associated frontal conditions indicated by the wind data is the most likely cause of the high accumulation recorded at Engabreen in the 1970s.

Where trends of glacier variation are both long-term and widespread, major climatic change associated with shifts of the atmospheric and/or oceanic polar fronts, and the associated changes of atmospheric circulation, may be responsible. Major alterations of the frequency of blocking anticyclones or of frontal systems crossing a region significantly affect the amount and duration of the snow cover, both on glaciers and on surrounding ice-free areas. An increase of summer insolation, associated with a reduction of the mean cloud cover, will cause increased melting of glacier ice already at the melting-point.

CONCLUSIONS

A simple model of glacier mass balance, based on summer temperature and winter precipitation, is capable of simulating changes of Engabreen during a period of a few decades. The model is inappropriate for extension to periods in which the area x altitude distribution of the glacier surface and/or the relative duration of the accumulation and ablation seasons differed significantly from the present. The role of general synoptic conditions in determining year-to-year changes of glaciers over a wide area is significant. Such conditions are better exemplified by data relating to wind, cloud and air pressure than by temperature and precipitation data alone. Because the arctic is particularly sensitive to climatic change, and may act as an indicator of fluctuations over a much wider region (Kelly and others, 1982), studies of climate-glacier relations in the Svartisen area should be continued.

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THE ESTABLISHMENT OF GAUGING STATIONS UNDER ARCTIC CONDITIONS

- The Svalbard Experience -

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ABSTRACT

In the polar regions of Svalbard, an attempt has been made by the Hydrology Department of the Norwegian Water Resources and Energy Administration (NVE), to establish three permanent gauging stations. One major concrete weir at Bayelva and one small light weir at Tvillingvatn, both near Ny-Ålesund, and one natural profile station at DeGeerdalen near Longyearbyen. An overview of the main problems encountered is presented together with an assessment of performance.

BACKGROUND AND STRATEGY

As part of a national effort to better the knowledge of the hydrological regime of Svalbard (Spitsbergen), the Hydrology Division of the Norwegian Water Resources and Energy Administration (NVE) -have established three permanent gauging stations on the archipelago.This is by no means an adequat number to aquire a satisfactory knowledge of the hydrological regime and the spatial runoff distribution in Svalbard. As station establishment as well as operation under the laborious and often hazardous field conditions, economic limits of the works enforce priority to a network made up of a few, but well maintained permanent stations in preferance to a network made up of a larger number of stations of lesser quality. When considering the station network at Svalbard, an absolute minimum initial requirement was considered to be one station in a glacial river and one in a non-glacial river.

Although the hydrometric station network on mainland Norway contains a large number of gauging stations exposed to extreme winter conditions, the experience with establishing and running gauging stations under the arctic conditions of Svalbard are limited. A fact seamingly sheared by others as there is hardly any information to be found on the matter when searching through the relevant literature prior to commencing at Svalbard.

In the following the problems and considerations encountered in establishing the permanent hydrometric gauging stations at

Svalbard, are described. These, however, are not considered to typify just the region of Svalbard, but to apply to arctic conditions at large.

A major problem in flow monitoring at Svalbard is the lack of defined water courses and stable riverbed profiles. Numerous braided streams flowing across a sandour is a commen feature. In addition there is the problem of ice and frost and the general hazardous and remoteness of the area. A gauging station will be frozen solid for most of the year. The runoff or melting season being from early June til late September. Recordings from the early and late parts of the season may well be hampered by the formation of bottom ice as well as the formation of superimposed ice. This necessitates the use of ice reduction curves together with the standard rating curves, all in all a very cumbersome and unsatisfactory way of recording runoff on a permant basis.

In brief, the major points of consideration to be considered in gauging station establishment at Svalbard, may be summarized thus:

Difficult accessebility, laborious and expensive

Glacial rivers, glacier mass balance studies necessary to avaluate glacial influence

Shifting bedloads, causes damage to stations and unstable profiles

Changing ice conditions, problem made more pronounced by permafrost condition

Braided streams

Frozen stations

Varying catchment reaction, alters through the season with the thickness of the active layer

As accessebility is a major consern in station establishment at Svalbard -especially if there is any major costruction work involved- the regions around Ny-Ålesund and Longyearbyen were considered the most desirable areas in which to establish the planned gauging stations. Several sites were considered with the following three chosen:

<u>DeGeerdalen</u>, situated some 20 kilometres near the coast north east of Longyearbyen. and easely accessible by helicopter, snow scooter or by boat. The catchment is approximately 70 km2 with only about 13% glaziers.The station utilizes a part of the river with a natural stable rock channel and control section - a rare feature

at Svalbard. The station is built as a conventional gauging station with a 200 mm stilling pipe bolted to the 12 m high rock face. The submerged part of the stilling pipe is filled with liquid parafine to enable an early season operation. The recording system is an all electronoc data logger of type PDL 10 as described in more detail later in the paper. The station seem to have performed satisfactory under the circumstances with relible recordings for the major part of the season. There have been ice problems, however, especially in the early parts of the season with bottom ice building up periodically. The logging system has worked well with the recording logger started the autumn before and run all through the winter and thus catching the first floods.

Tvillingvatn, situated within walking distance from Ny-Ålesund. Tvillingvatn, a small shallow lake acting as the water supply of Ny-Ålesund, is partly fed by temperate springs and hence, does not bottom freeze in the winter. Attempts has been made to establish a V-shaped weir as well as a prefabricated Crump weir at the small rock fill dam barraging the outlet. Both attempts have been unsuccessfull, however, due to major frost heaving of the constructions. To overcome the stability problem, an attempt will be made to pile the structure in to the permafrost. This might solve the stability problem, but may create a future leakage problem.

Bayelva, approximately 3km from Ny-Ålesund, drains a catchment of approximately 30km2 with just over 50% glaziers. The gauging station is situated about 300m from the river mouth where the river passes through a rock ridge. Bayelva as the major hydrometric station at Svalbard, will be described in more detail in the following and be the basis for the rest of the paper.

WEIR DESIGN AND CONSTRUCTION

The design and building of a weir structure at Svalbard raised a number of questions pertinent to the area:

- previous experience
- construction (flow interference, stability, durability)
- material availability
- cost
- protected area
- early phase recording
- data logging equipment
- control and maintenance

Regarding the first point, ie. previous experience with the design and construction of a concrete weir under arctic conditions, the literature gave no indication to any such work to be performed prior to this. Thus, the weir design at Ny-Ålesund had to be based on the general rules of arctic construction and the standard hydraulics of weir construction. In this respect, the main problens to be encountered were the stability and durability of the weir, influence of ice, permafrost protection and the large sediment transport of the river (max 3,80 mg/l). Further, the very short seasonal construction period available had to be taken into consideration.

In the case of the Bayelva gauging station, a two dimensional triangular profile compound weir structure (Crump weir) 15m wide, with of a middle third section of crest height 0,35m and the two outer thirds of crest height 0,50m, was built. Total length is 10m and side wall height 1,50m. This gives a maximum capacity of approximately 32 cumecs. As crest tapping is impossible under arctic conditions due to repeated sub-zero conditions in the runoff season, this feature was omitted and hence, the weir was designed to operate in the modular range only. To prevent the active layer to develop underneath the weir, a 0.3m layer of expanded polystyrene was applied as insulation between the concrete and the foundation or the backfill.

During construction, special attention was paid to ensure there were no voids between the foundation, the insulation and the concrete, as bad contact would allow seapage, piping, possible leakage and a consequent possible failure of the weir (as indeed happened at Ny-Ålesund). Further, the local aggregate had to be tested for durability as much of the local sand is prone to be from easily erodible rock, and hence, of poor quality.
During constuction in 1988, bad weather in September forced the works to a halt before backfilling behind the abutments were completed. This hindered an active layer to develop underneath part of the construction, with subsequent leaking the following summer, resulting in instabillity and severe damage to part of the construction. The weir is now complete and operational except for some preventive piling work to ensure the total stability of the weir.

The recording system at Bayelva is an optical encoder system transferring the water level to an all electronic data logger type PDL 10 from Solutions fro Technology, Ltd. UK. The PDL is purpose designed for hydrological data collection, and has proved its suitability in other similar conditions. The instrument hut is placed on top of the stilling well. The stilling well may be heated prior to the spring melting by conection to a mobile external power supply, thus ensuring recordings from the first flood.

The Crump weir was chosen for its robustness, stability, relativ constuctural simplicity, self cleansing capacity and last, but not least, ability to performe under sub-zero conditions. The latter phenomena is proven when applied under extreme winter conditiions in Norway.

Construction Summary

Regarding the construction and maintenance of hydrometric structures for the arctic, it may be said in conclusion:

Principle of permanently water retaining embankments to be applied, ie. full ground insulation.

Full advance site inspection for channel suitability to comply with hydraulic requirements for weir installations and the ground conditions on site. Special attention being paid to susceptibility to upstream or downstream jamming.

Advance testing of local aggregate.

Apply a free-flow self cleansing long based weir operating in the modular range only.

Double reinforced walls and floor to sustain reverse acting forces from water and ice.

Close distribution steel to prevent surface cracing.

Steel capped crest

Carefully compacted backfill protected by rock laid in a rip-rap fashion.

Full site controll during construction

Suitable designed and fully proven electronic logging equipment.

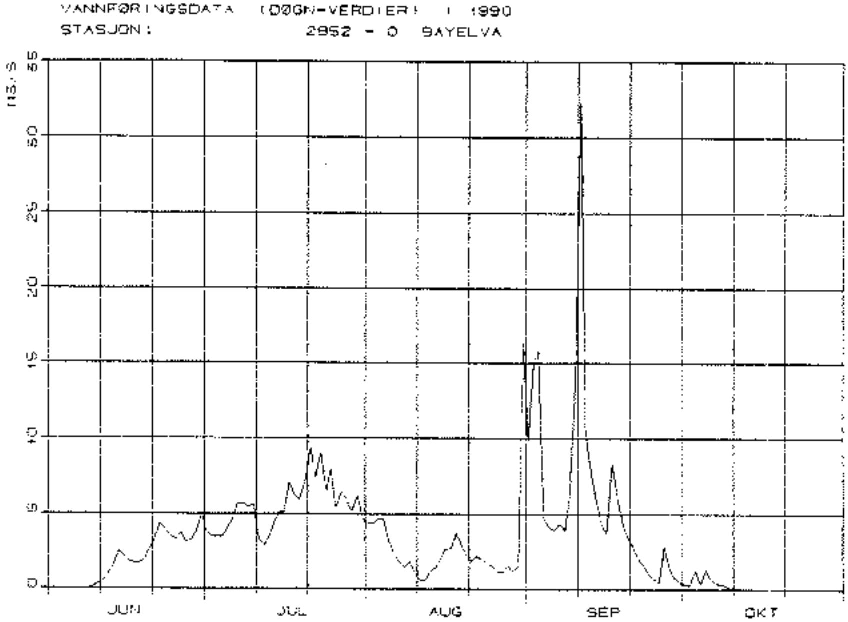
Possibility of access during the winter.

CONCLUDING REMARKS

The establishment of permanent gauging station in the arctic regions of Svalbard have proven to be more demanding than anticipated. Part of the reason being lack of experience and the underestimate of the permafrost influence on the controlling section with regard to ice as well as instabillity. However, the experience gained by the works is considerable and most valuable and must be sustained for future hydrometric projects in the polar regions.

The Crump weir at Bayelva has been in operation for three seasons. Although the construction suffered major leakage problems its first season with subsequent major repair works, this now seems rectified. In this context it seems only fair to point out that the main reason for the initial troubles was lack of site control. This type of work under these conditions require constant control by qualified engineers to ensure the neccessary quality control and on the spot tackling of any unforseen problems emerging.

Although the Crump weir has tilted slightly from true horizontal, it still performs satisfactory. Spot controls by current meter measurements gives values well within acceptable tolerances (less than 5% deviation). Hydraulically, the weir conforms well with the design spesifications, ie. stable head, good self cleansing ability and minimized ice and frost problems.



The chart above shows the daily runoff for the 1990 season. As shown, an exceptional flood occured early September that year with a peak of 32,5m3/s. The corresponding rainfall in the area was at a 100 year frequency combined with relatively high temperatures. The weir suffered no damage from the event thus indicating the rehabilitation works to be successful as well as proving the stability and performance of the structure under these conditions.

It is to early to give a verdict as to the performance of the DeGeer station with its natural section and hence, also to compare the performance of the two stations. One obvious advantage of the purpose built Crump weir is that it comes with a known rating curve. With the sort of conditions experienced in these parts of the world, that alone may be a decising factor in choosing station type.

TIME SERIES ANALYSES OF RADIATION, TEMPERATURE AND DISCHARGE AT AUSTRE OKSTINDBREEN, NORDLAND, NORWAY

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ABSTRACT

During three ablation periods in 1988, 1989 and 1990, measurements of radiation, temperature and discharge were made on a 20-minute basis. Subsequently, the measurements were analysed using spectral analysis, to stipulate the relation between the time- and frequency domain, and determine the auto- and crosscorrelation functions. The calculations were made using a Fast Fourier Transformation. Subsequently, the relations upon filtering procedures were used to calculate a theoretical weighted discharge from temperature and radiation. The assessment of the results indicates that it is possible to determine the delay of water release from the glacier, both on a daily and a longer term basis. Further it was observed that the results were different during the periods selected, possibly as a result of variation in development of the internal drainage system during individual years, reflecting the weather conditions through the summer.

INTRODUCTION

Glacier river discharge receives contributions from ice meltwater, snow meltwater, rainfall and groundwater. These vary with time. As a result, the volume of water leaving the glacier fluctuates in response to variations in source input. As the presence, distribution and movement of water within the glacier is difficult to determine directly, much effort has been made to interpret the relation between the input from various sources and the conditions governing meltwater release.

A model of reservoir conditions within a glacier through the ablation period, based on the relation between meteorologically determined water input and the measured discharge, was originally suggested by Stenborg (1970). Later, the model was demonstrated at several locations (Tangborn et al. 1975, Oestling and Hooke 1986).

Hydrological models relating meteorological observations and water discharge in glacier rivers mainly on adaily basis were reviewed by Fountain and Tangborn (1985).Besides description of several models, calculated or predicted runoff was compared with the measured value. Most often, essential parameters in the models are temperature and precipitation, measured at a lowland weather station. The discharge is explained using linear regression models.

Conditions governing daily variations in discharge through the ablation period have been described at many glacier, as in the Alps (Elliston 1973, Lang 1973, Collins 1979).

Linear models of the relationships between meteorological observations and the discharge of meltwater from a section of Vatnajøkull were investigated by means of spectral analysis and estimation of the impulse response (Gudmundsson and Sigbjarnarson 1972). They conclude that the relations are by no means linear, because hydrological conditions vary as a result of variation in the exhaustion of snow cover for runoff generation and the release of snow melt. Further, conditions change between years, as do conditions if the glacier is in a state of retreat or advance.

The purpose of this paper is to present the results of time series analysis using spectral analyses of meteorological observations of radiation, temperature and precipitation and their relation with meltwater discharge at Austre Okstindbreen during three ablation periods in 1988, 1989 and 1990.

THE AREA

Austre Okstindbreen, the largest glacier of the Okstindan area, covers about 14 km². The accumulation area covers about 10 km² between about 1700 m and 1200 m, most of which lies below 1500 m. The ablation area, about 4 km², lies between 1200 and 730 m, where the glacier terminates in a proglacial lake that covers about 0.1 km² (Fig. 1). A limnigraph is installed at the outlet of the lake. A lake, Kalvtjørna, dammed by the western margin of the glacier, is situated in a narrow valley between Nordre Okskalven and Kjensvasshammeren. During several summers the lake drained beneath the glacier (Knudsen & Theakstone 1988). During the years 1988-90, the lake has remained empty. Generally, the glacier has retreated about 20 m y^{-1} during the last 20 years. During the period 1985-91, the mass balance of the glacier in total has been slightly positive. Meteorological observations have been measured at a station at about 825 m just outside the northern glacier margin.

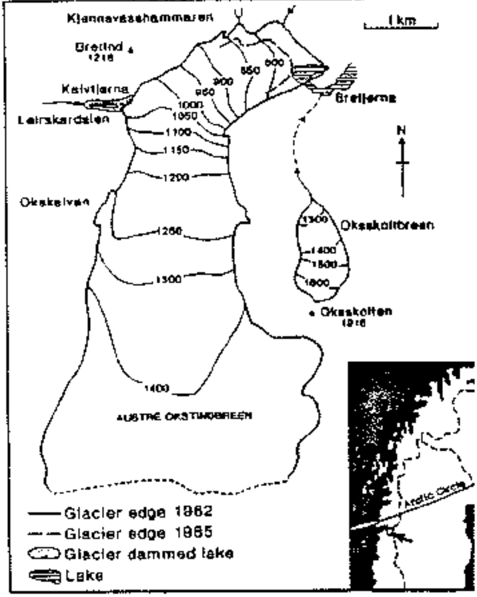

Fig. 1. The location of Austre Okstindbreen, Okstindan, Norway.

Methods

The water level was measured at the outlet of the proglacial lake with a 20-minute interval using a datalogger. Using the established Q_h relation determined from measurements at the outlet, the discharge was calculated through the periods of observation.

Temperature was measured at about 800 m using a datalogger at a station on the glacier in 1988 and 1989 with 10-minute interval. In 1990, temperature was measured with a thermohygrograph at a station outside the glacier margin. The observations were digitized with a 20-minute interval.

Net radiation was measured using a datalogger system in 1988 and 1989 at the same site where temperature was observed.

Precipitation was measured on a daily basis at a station outside the glacier margin at about 850 m.

Observations of discharge, radiation and temperature were stored on file with a chosen interval of 20 minutes. An example of observations and periods used in calculations is shown in fig. 2.

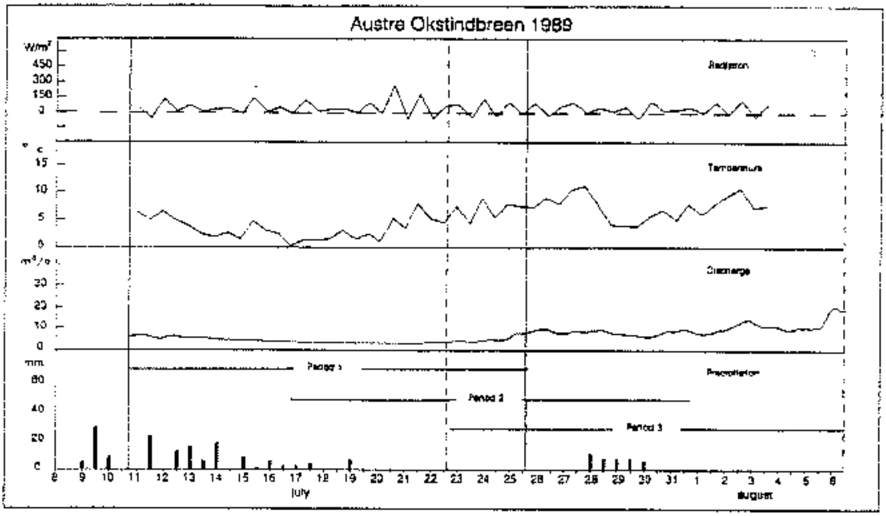

Fig.2 Observations of radiation, temperature, discharge and precipitation at Austre Okstindbreen in 1989. The periods used in calculations are shown.

In all calculations only the deviations from the mean value for each data set were used. Subsequently an examination of which frequencies x(t) and their magnitude, using a FFT-procedure, was made. The formulas used in the FFT-procedure were

$$f_t = \frac{1}{N}\sum_n F_n \exp\left(2i\pi\frac{n}{N}t\right)$$ Time domain

$$F_n = \sum_t f_t \exp\left(-2i\pi\frac{n}{N}t\right)$$ Frequency domain

that can be applied to a sampled periodic function f^t , where t is an integer with the period N. It is anticipated that a given discharge is explained by periodic events (temperature and radiation), single events (precipitation), trend and noise, as indicated in fig 3.

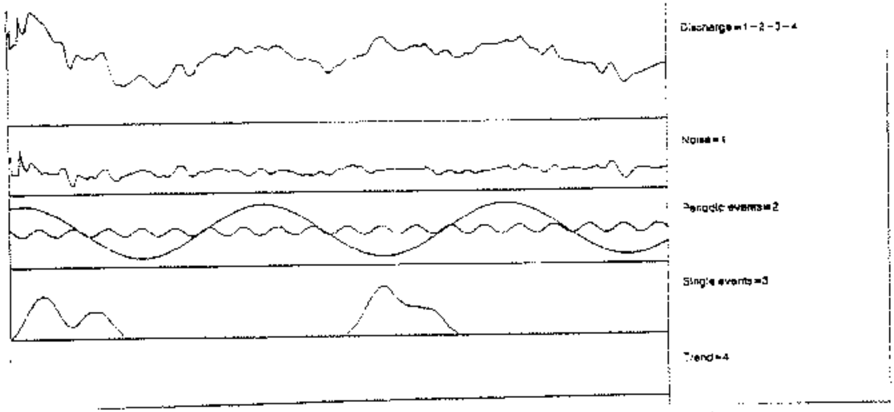

Fig.3 The discharge consists of periodic events, single events, trends and noise.

The program Onedim calculates the fourier-transforms using a maximum number of observational sets of 2048. To avoid discontinuities a window-function is applied towards the ends of the observations.

The auto and cross correlation functions of the observations are given by

$$\Phi_{n,xy} = \overline{F}_{n,x}\cdot F_{n,y}$$ Power spectrum

$$\phi_t = \frac{1}{N}\sum_n \Phi_{n,xy} \exp\left(2i\pi\frac{n}{N}t\right)$$ Crosscorrelation function

which determines the relations between radiation, temperature on one side and discharge on the other. Fig 4 a shows the crosscorrelation functions of temperature and discharge in frequency during three selected periods in 1989, as defined in fig 2. Most obvious is the frenquency of about 28, corresponding with a daily peak. Fig 4 b shows the crosscorrelation functions between temperature and discharge. It is obvious that the relation between temperature and discharge varies with time,

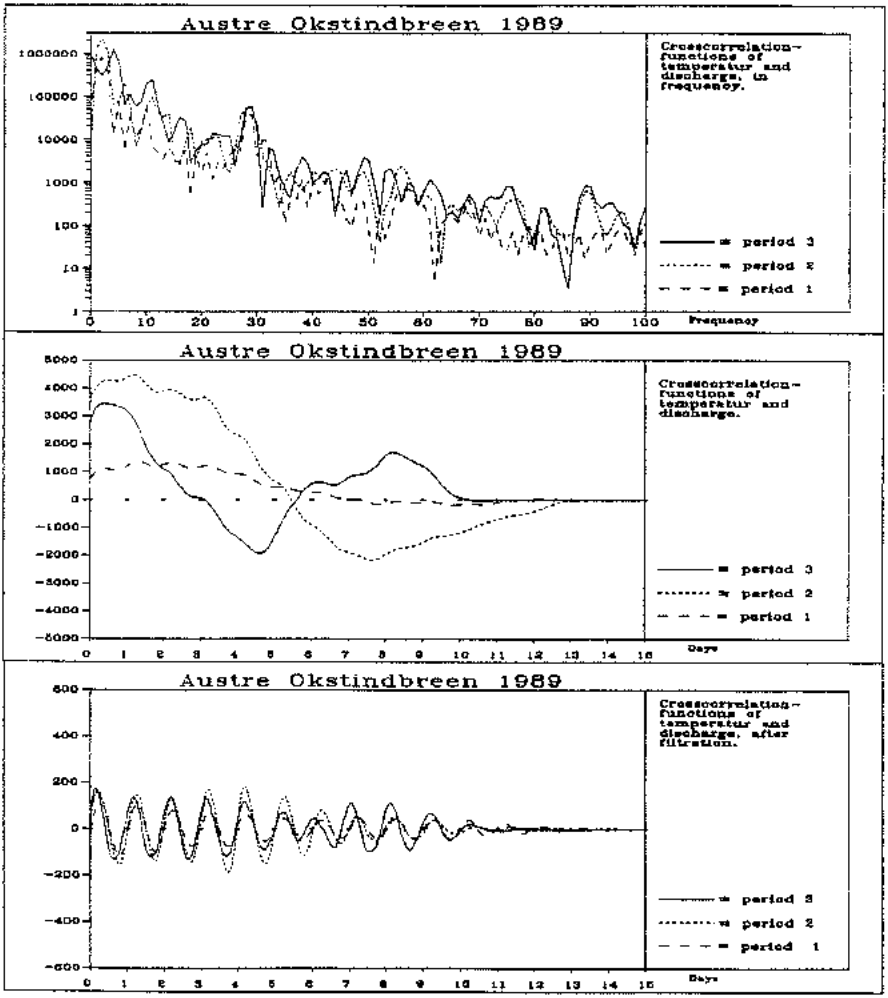

Fig.4 shows the crosscorrelation functions of temperature and discharge in frequency during three periods in 1989. Further is shown the crosscorrelation functions of temperature and discharge. Finally the crosscorrelation functions upon filtering are shown.

indicating that with time the response of the discharge to a given temperature change is quicker. Finally fig. 4 c shows the crosscorrelation functions upon filtration of frequencies with periods longer than 2 days. Again the daily peaks are obvious, but it is impossible to determine where the filtered functions correlate, which means the daily correlation is missing.

RESULTS AND DISCUSSION

From the net radiation measurements it is possible to calculate an equivalent amount of ablated snow or ice. In the present case, measurements were made above ice. The ratio between the ice and snow covered areas changes with time, and the albedo is different above snow and ice. The effects are not taken into account here. During short periods, variation is of minor importance, but the absolute amount of meltwater from radiation is probably inaccurate.

The relation between temperature and ablation was not established directly, but it is the frequency content that is compared. The amount of ablation was determined during longer periods through direct observations on the glacier.

The discharge was measured directly in the the stream below the outlet of the lake in front of the glacier. The lake moderates the discharge variations.

As the relation between radiation, temperature and discharge was determined using the results obtained from the auto- and crosscorrelations, considering the glacier as an impulse response function,it was possible to calculate a theoretic discharge, and compare it with the measured one. The results are shown in fig. 5.

Discharge 1988

Observations comprise the period 10 July to 3 August. The average discharge was 16 m^3 s^{-1}. The precipitation was close to normal with a mean value of 2.2 m^3 s^{-1}. The mean during the similar period in 1981-87 was 1.4 m^3 s^{-1}. The net radiation corresponds to a discharge of 5.1 m^3 s^{-1}. The mean temperature was about 7.4 °C on the glacier at about 800 m. The ablation during the period determined by measurements on the glacier corresponds to 10.0 m^3 sec^{-1} of which radiation accounted for 5.1 m^3 sec^{-1}. During the period, an additional amount of water released from reservoirs, as snow melt outside the glacier margins or from errors in the above mentioned calculations is not accounted for. This amount corresponds to 3.8 m^3 s^{-1}. During 1981-87, the reservoir amounted to about 36%, compared with 23% in 1988. This is probably explained by the fact that little snow remained outside the ice-covered area when observations started, as a result of little accumulation during the winter, and high

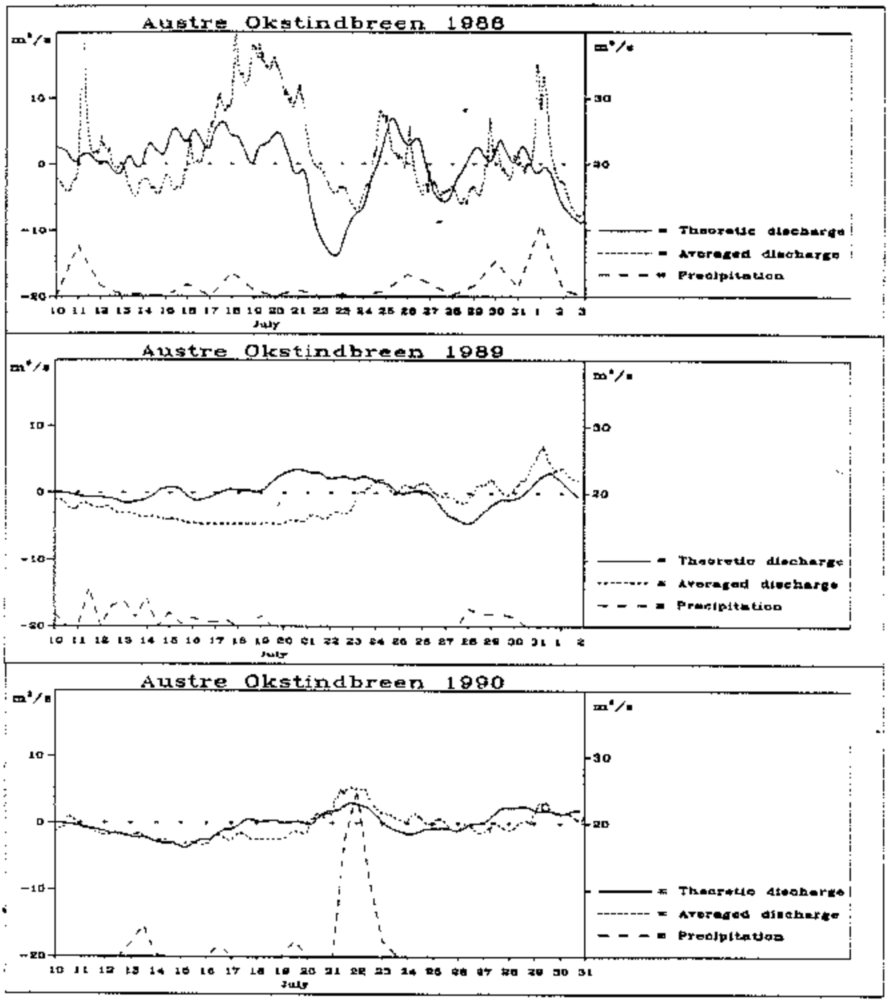

Fig.5 shows the measured averaged discharge and the calculated averaged discharge in 1988-90. It is noted that the precipitation is not used in calculations.

ablation during May and June.

Figure 5a shows that the averaged discharge and the theoretical averaged discharge coincide during the later part of the period, except during periods with precipitation. Throughout the period of observations, there is a delay of about 1.5-2 days between the climatically determined and the actual discharge. During the first week of observations, less than expected amounts of water discharged. During the following week, the discharge was higher than expected and, except for 2-3 days with less than expected amounts, the last part of the period of observation showed values of similar magnitude.

The summer was warm in Northern Norway in 1988. The ablation period started early, and temperatures remained high - in general 1-2 °C above normal until September. The ablation was unusally high, giving rise to a large meltwater discharge. It is apparent that the internal drainage system must have been well developed when observations started, and probably most of the early summer storage of water within the glacier and in the snow had disappeared when observations started. That little water remains in reservoirs and that the internal discharge system is well developed is emphasized by the large variations observed. Nevertheless, the variations show that the internal drainage system is capable of accommodating much water during some periods and releasing it through others.

Discharge 1989

Observations comprise the period 10 July to 3 August. The average discharge was 8 $m^3 s^{-1}$.The precipitation corresponds to 1.7 $m^3 s^{-1}$. The net radiation during the period amounts to about 3.7 $m^3 s^{-1}$. The mean temperature during the period of observations was 5.5 °C at about 800 m. The ablation during the period determined by measurements on the glacier corresponds to 5.5 $m^3 s^{-1}$. The reservoir term corresponds with about 0.8 $m^3 s^{-1}$. Compared with the previous years, the amount of water released from reservoirs is very low, constituting about 10% of the total discharge.

Figure 5 b shows that that the averaged discharge and the theoretical averaged discharge do not coincide through the period of observations. During the first 10-12 days, less water than expected is released whereas, during the last 10-12, days more than expected was released. Through the period, most rain fell in the first week, but rather little response was seen in the discharge. Throughout the period of observations there is a time lag of about 2-4 days between the climatically-determined discharge and that actually measured.

The summer was cold in Northern Norway in 1989. The ablation period started late, and the temperatures remained low until late July. The middle of July was very cold, and during 2-3 days snow fell over the entire glacier. As the winter accumulation was the highest measured on the glaciers in the area, much snow was present throughout the summer, and the development of the internal drainage system was slow. It is probable that storage of meltwater took place in snow and in the glacier well into July, and the opening of the storage reservoirs took place a few days before or after 24 July. After that date, water was released from storage. At the same time, the delay time changed to about 1-1.5 days.

Discharge 1990

Observations comprise the period 10 July to 30 July. The average discharge was 10.5 $m^3 s^{-1}$. The ablation during the period determined by measurements on the glacier corresponded to 6.5 $m^3 s^{-1}$. The precipitation corresponded to 1.2 $m^3 s^{-1}$. The reservoir term corresponded to 2.8 $m^3 s^{-1}$. The water released from reservoirs corresponded to about 26% of the total discharge.

Fig. 5 c shows the averaged discharge and the theoretical averaged discharge during the period of observations, but this year solely based on temperature measurements. Generally they coincide, except for a few days before the large precipitation event, during which the discharge increased markedly, before decreasing during the following days. Probably water was stored in the days before. On 20 July, one day before the precipitation event, the discharge increased about 3 $m^3 s^{-1}$ within a few hours late in the afternoon. Observations at the glacier terminus around 1900 hours showed that the water emerging from the glacier portal was highly discoloured. Probably a major conduit or reservoir had opened. Possibly it was closed or cut off from the drainage system for a few days. During the following night, the discharge remained high, without the decrease usually observed. The analyses do not show any significant delay time.

The summer was close to normal during 1990. The ablation period started rather early and the ablation during the summer was close to the mean value measured in the area. The accumulation was slightly higher than normal. When the ablation period ended, the glacier mass balance was close to equilibrium.

During the period of observations, the drainage system was rather unchanged and, during much of the period, water was released from reservoirs. Throughout the period there were marked daily variations in discharge, indicating that the daily variation in the ablation in the ice-covered areas influenced the discharge. Otherwise, variations were small. This period occupies an intermediate position between the two other summers.

Conclusions

The results show that the connection between the climatically determined discharge and the actually measured discharge varies between years. During years with little ablation a weakly-developed internal drainage system and a large storage capacity in snow, water is released slowly from the glacier, and discharge fluctuations are small. This is in contrast with years when ablation is high, the drainage system is well-developed, and the storage capacity in snow is low. Then, large fluctuations often occur. In addition the periods of storage or release of water in reservoirs vary from one year to the next and influence the amount of water released from the glacier at a given moment. Obviously the method described needs further development towards a quantification of input sources before coincidence between calculated and measured discharge is obtained.

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VOLUMETRIC CHANGES AT THE EAST SVARTISEN ICE CAP DURING 1945-85

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ABSTRACT

Changes which have taken place during the last 50 years at glaciers of the East Svartisen ice cap are well documented. Although the period has been characterized predominantly by retreat of the glacier margins, the rates of the retreat have varied, as have changes of ice thickness at different altitudes. Comparison of photogrammetric maps from several outlet glaciers indicates the variability of the frontal retreat.

Recently a map of the entire ice cap (about 150 km^2) was constructed using aerial photographs taken in 1985. Using digitizing of this map and comparing it with the map constructed from aerial photographs taken in 1968 by NGO, it was possible to evaluate the volumetric changes of the entire ice cap during a 17-year period. The analyses suggest that, although most glacier margins and glaciers situated below 500-700 m were retreating, there was a major difference between surface changes of the northernmost part of the ice cap compared with the steeper western part, which was almost unchanged, and in places actually glacier advance was observed. The southern part, with Austerdalsisen, experienced a major change at the calving front in Austerdalsvatnet, but otherwise changes were small. The eastern part with Lappebreen showed little sign of change, except a small retreat at the snouts. This may indicate that the general glacier retreat might cease before long.

INTRODUCTION

Climatic change results in changes at glaciers. In response to climatically-controlled variations of volume and distribution of annual accumulation and ablation, both the size and the topography of a glacier change. The redistribution of mass, driven in part by ice thickness and surface topography, depends on the glacier dynamics.

Variations of length (terminus position) are the clearest evidence of glacier change, but there is a time lag between climatic change and the response of a glacier terminus. The lag occurs because the climatic change affects the mass-balance over the entire length of the glacier. Accordingly, the arrival of the information is spread out in time and the relation between glacier fluctuations and climate is difficult to resolve.

Because time-series of mass-balance cover only a few decades and few glaciers, it is difficult to examine directly the long-time-scale relationship between mass-balance variations and changes of terminus positions of glaciers.

Mapping of glaciers by aerial and terrestrial photogrammetry provides a snapshot of the volume and aerial extent. The surveys permit the entire surface of a glacier (and its surroundings) to be described by three-dimensional co-ordinates. If repeated mappings have been accomplished, it is possible to determine changes with great accuracy, and to establish a further control on mass-balance observations.

The present paper presents the results of investigations of volumetric and aerial change at the East Svartisen ice cap and its outlet glaciers during the last 45-50 years. General Circulation Models suggest that future climatic warming, associated with changing atmospheric composition, may be most intense in zones around the Arctic Circle (Hansen and others, 1988). Therefore it is of interest to know the changes that have occurred recently or are occurring presently at glaciers in the area.

DATA AQUISITION AT SVARTISEN

The East Svartisen ice cap, with its outlet glaciers, covers an area of about 150 km^2 between 66°32'N and 66°40'N (Østrem et al.,1973) between the deep valleys Glomdalen to the west and Blakkådalen to the east. Most glaciers supplied by the ice cap terminate at 800-900 m above sea level, but the three principal outlets, Austerdalsisen, Fingerbreen and Lappebreen descend to much lower altitudes.

Maps based on aerial photographs of Fingerbreen, Lappebreen and Austerdalsisen taken in 1945 and 1968 have been produced (Knudsen and Theakstone 1984). Additional maps based on terrestrial photogrammetric surveys in 1970, 1975, 1979 and 1981 have provided data about glacier changes at Svartisen (Knudsen and Theakstone 1981, Knudsen and Theakstone 1984, Theakstone and Knudsen 1986, Theakstone 1989). Mean errors of point positions are within ± 1.5 m (Theakstone and Knudsen 1980). Glacier changes at Svartisen were summarised in a Glacier Atlas (Theakstone 1987/88).

The whole of Svartisen was covered by a further set of aerial photographs taken in 1985. A 1:25000 scale map of East Svartisen, based on the photographs, was completed in 1991. Regrettably a flat central area between about 1200-1300 m was impossible to survey because of snow conditions and virtually no contrast in the photographs. In July 1990 a visit was made to Fingerbreen and a terrestrial photogrammetric survey was made of the frontal area. The east Svartisen ice cap is shown as fig. 1.

The mass balance was not determined at any outlet glaciers from the ice cap, but from mass balance measurements at Engabreen, precipitation measurements in the area, and discharge measurements from basins in the area, it is possible to estimate the mass balance.

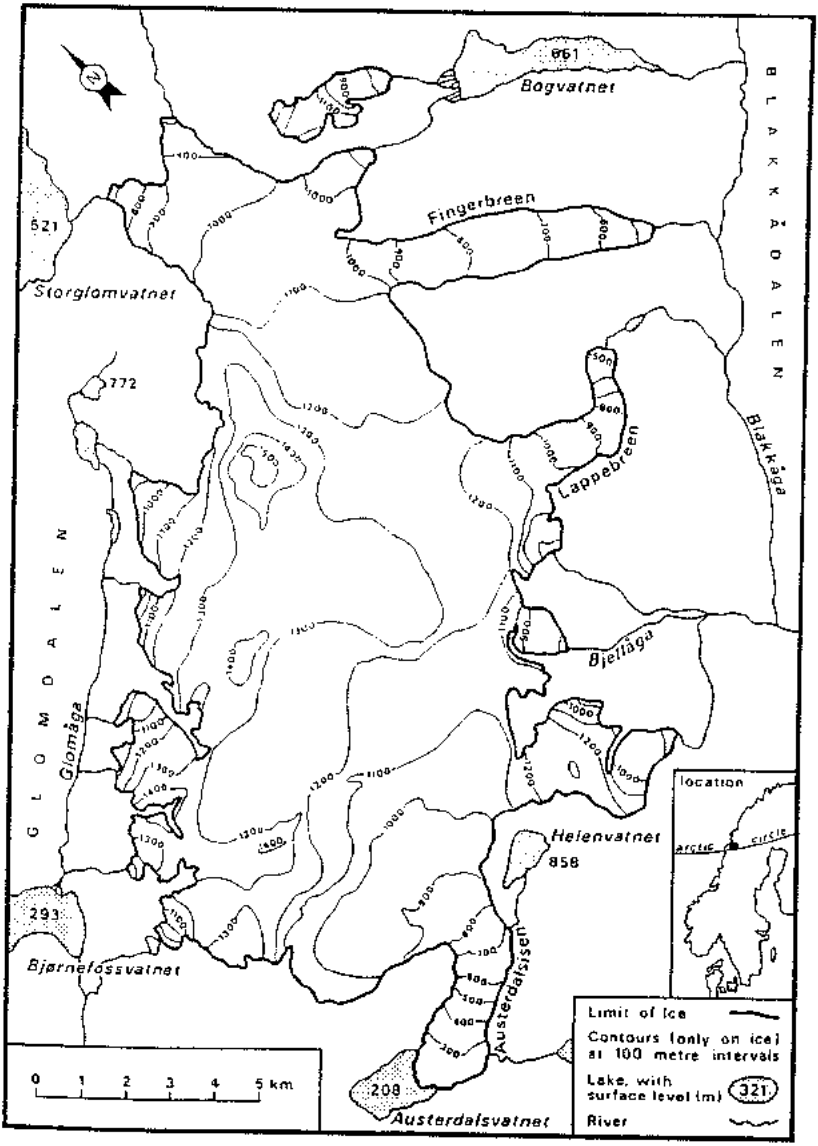

Fig.1 The east Svartisen ice cap and its outlet glaciers.

Haakensen et al. (1981) found that winter balance at East Svartisen glaciers was about 85 % of the balance at Engabreen, and the summer balance about 120 % of the balance at Engabreen. Prior to observations at Engabreen, the mass balance there was assessed using precipitation and temperature measurements at Glomfjord (Theakstone and Knudsen 1992). The result of the mass balance considerations is shown in Table I.

MASS BALANCE AT ENGABREEN

	bw m	bs m	bn m	Acc. m	Years
1945/68	3.03	-2.59	0.44	10.12	23
1968/85	2.91	2.32	0.59	10.15	17
1985/90	3.25	2.33	0.92	4.60	5
MASS BALANCE AT EAST SVARTISEN GLACIERS (estimated)					
1945/68	2.57	3.10	-0.53	-12.19	23
1968/85	2.47	2.78	-0.31	- 5.27	17
1985/90	2.76	2.80	-0.04	- 0.20	5

Table 1. Calculations and measurements of mass balance at Engabreen and East Svartisen glaciers based on Haakensen et al. (1981) and Theakstone and Knudsen (1992). Obviously the net mass balance in both regions has increased.

RESULTS

The East Svartisen ice cap

The quality of the aerial photographs taken in 1945 made it impossible to survey the entire ice cap. The changes between 1968 and 1985 were determined using the maps from 1968 and 1985. They show that the changes in areal extent appear close at the glaciers terminus and in connection with most nunataks of the ice cap. In total an area of about 2 km^2 melted free of ice. The changes in ice thickness is also concentrated at the glacier margins. At higher levels the changes are small, but it is possible to observe a slight decrease of the surface.

Except for changes at the three major outlets commented on seperately below, the major changes observed were as follows: The outlets north of Fingerbreen have retreated about 300 m. The thickness change varies between 35 and 45 m close to the terminus, and up to 1100 m it is above 20 m.

The southwest part of the ice cap was varying, with parts of the margins advancing, and others retreating. Ice loss was little, and in several areas the surface level increased, showing values of about 10 - 20 m.

An evaluation of the mass balance of the ice cap determined from surface change at 410 evenly distributed points gave a value of about -8 m water.

loss, from about 80 metres to 40 metres, occurred between 500 m and 700 m.

Between 1968 and 1985 maps of Lappebreen show continued retreat, although at a reduced rate. Right at the 1985 margin the ice loss was 40 m. Some areas above 800 m were unchanged during the period.

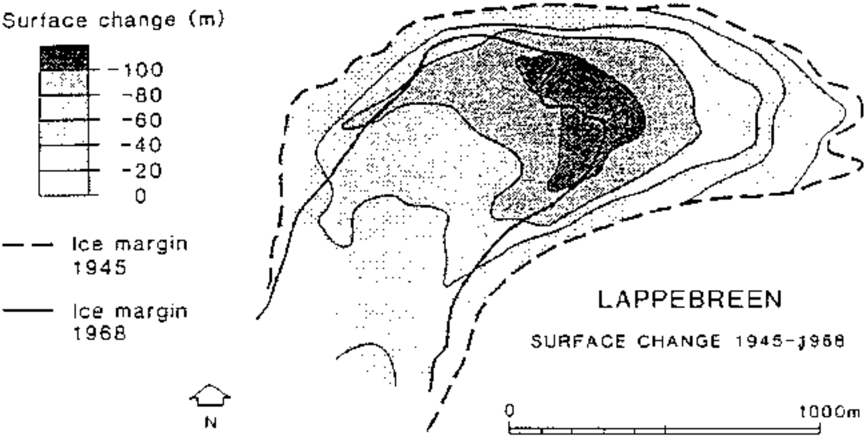

Fig. 3. Changes of surface elevation of Lappebreen between 1945 and 1968.

Austerdalsisen

Mass loss has been great at the glacier, which descends southwestwards from the southern limit of East Svartisen into a lake at about 210 m. The lake developed rapidly from the turn of the last century. In 1945, the lake surface area was 1.9 km^2, and in 1954, when the glacier margin was more than 2.5 km from its 1897 position, it was 3.6 km^2.

Between 1954 and 1970 the glacier margin continued to retreat rapidly through the lake. Along the margins resting on bed rock at higher levels, retreat was slower and at about 400 m above sea level it was less than 100 metres on each side of the glacier. On the surface considerable wasting of ice took place, with a maximum value of about 100 metres at the glacier margins at lake level and about 70 metres close to the centre line. At about 700 meters the surface change was less than 10 metres.

Between 1968 and 1985 the retreat continued at about the same rate through the lake, although the surface ice loss decreased. In 1983 the thickness of the grounded section of the glacier in the lake was 140 m less than in 1945.

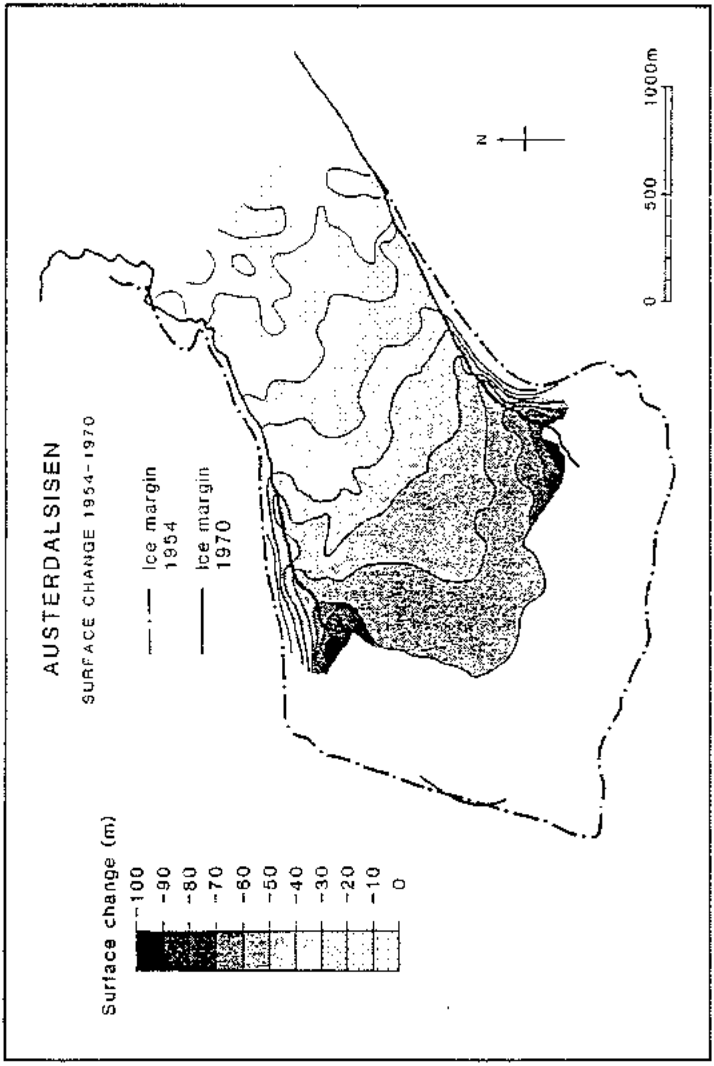

Fig. 4. Changes of position of the margins and the thickness of the glacier Austerdalsisen, 1954 -70.

CONCLUSIONS

Glacier change may occur as a result of climatic change. At the East Svartisen glaciers, the change since 1945 has been evident, resulting in a thinning and retreat of glaciers. During recent years the retreat has decreased, and actually some high lying glaciers facing towards Glomdalen have either reached a stable position or are slightly advancing. Except for Austerdalsisen, which is terminating in a lake, glaciers terminating at low levels have retreated little recently, probably reflecting a less negative mass balance during recent years. The retreat at Austerdalsisen is mainly the result of calving of the glacier into a lake. This is in contrast with the glaciers terminating on land, which to a larger degree react directly to changes in mass balance.

A comparison of mass balance during 1968-85 determined from mapping and calculations based on observations at Engabreen, showed similar values. The difference is probably explained by uncertainties with both methods.

ACKNOWLEDGEMENTS

The authors wish to thank Professor J. T. Møller for his substantial contribution to the photogrammetric work at Svartisen, and to Cartographer J. Dalsgård, who constructed the map of the entire East Svartisen ice cap. The studies at Svartisen have been supported by research grants from the Natural Environmental Research Council, British Council and Statens Naturvidenskabelige Forskningsråd.

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PLUVIALISMENS GENOMBROTT I NORDEN

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ABSTRACT

Most Nordic treatises on the hydrological cycle in the 17th century presupposed that water was transferred from oceans to springs by subterranean veins. There were, however, different versions of this theory, and a temporal development can be seen. The establishment, the modern view according to which rain water is sufficient to explane the springs, was established by the measurements of Perrault, Mariotte and Halley in the last three decades of the 17th century. The diffusion of pluvialism into the Nordic countries began already in 1690's, but it took almost a century before it was generally accepted. Some regional differences, due to political conditions and different scientific traditions, can be seen in the contributions of the four universities.

INLEDNING

Vi torde alla dela samma grundsyn på det hydrologiska kretsloppet. De konkurrerande teorierna förekommer inte mera i diskussionen, vilket kanske är förklaringen till, att både vår egen teori och dess forna konkurrenter har saknat namn i det hydrologiska språket. Om vi däremot betraktar hydrologins historia så måste vi operera med begrepp vars innehåll består av de olika teorierna om källornas usprung. Det är ganska opraktiskt att hänvisa till ett begrepp genom att gång på gång återge dess innehåll i stället för att använda en term, men det tycks faktiskt inte finnas några termer för de grundläggande teorierna om källornas ursprung och därmed hela den hydrologiska världsbildens struktur. Därmed kan det vara berättigat att försöka lansera sådana termer.

Den process, som här kallas för pluvialismens genombrott, har naturligtvis tidigare behandlats i litteraturen. En översikt av den allmänna utvecklingen finns t.ex. hos Biswas (1970). Flera bidrag om utvecklingen i Norden har publicerats, men de flesta begränsar sig till ett land eller några enskilda forskare. Ett försök att tillämpa paradigmteorin har publicerats tidigare (Kajander 1986) och upprepas här i en något förbättrad och utvidgad version. Den källmaterial som används här består för det mesta av dissertationer på latin, vilka annars är praktiskt taget oläsbara för de flesta av dagens hydrologer. Skrifterna på nordiska språk torde vara mera läsbara och har behandlats utförligare, t.ex. av Frängsmyr (1969) och Gottschalk (1988).

TEORIER OM KÄLLORNAS URSPUNG

Det som vi uppfattar som teorier om *det hydrologiska kretsloppet,* behandlades under 1600- och 1700-talet vanligtvis under begreppet *källornas (och/eller åarnas) ursprung.* Av de följande teprierna är de flesta cykliska, men åtminstone transmutationismen är strängt taget en icke-cyklisk teori, där man inte kan tala om *vattnets* kretslopp.

Enligt pluvialismen har källvattnet sitt ursprung enbart eller så gott som enbart i regnvattnet. Nästan alla författare under 1600-talet påstod, att det finns somliga som håller sig till denna uppfattning, men låter bli att nämna dem. Alla torde nog ha varit eniga om, att regnvattnet bidrar till avrinningen, men de flesta var eniga om, att den kontinuerliga avrinningen måste ha ett annat ursprung. Både nederbördsmängden och jordmånens genomtränglighet uppfattades som alldeles otillräckliga. De flesta sökte alltså olika semipluvialistiska lösningar.

Enligt transmutationismen uppstår källvattnet till största delen i underjordiska grottor därigenom att luft förvandlas till vatten. Denna teori lanserades av Aristoteles, som också stod bakom läran om transmutationerna, dvs att ett element förvandlas till ett annat element om en för dess natur främmande kvalitet blir rådande. Luften är ett varmt och fuktigt element, medan vattnet är kallt och fuktigt. I kalla förhållanden förvandlas alltså luft till vatten. Det är kallt i luftens mellersta region, där molnen uppstår, men mycket kallare är det inom jorden, vilket betyder att mycket större mängder av luft förvandlas till vatten därstädes. Denna teori blev aldrig dominerande trots att Aristoteles i övrigt var en obestridlig auktoritet. Tvärtom började den tyna av samtidigt med den dogmatiska neoaristotelismens framfart i början av 1600-talet. En orsak till detta är, att transmutationsläran ifrågasattes mer och mer även i neoaristoteliska kretsar. Om det inte finns transmutationer så måste också transmutationismen förkastas - eller modifieras så, att det är vattenångan som förvandlas till vatten. Då är det emellertid bättre att tala om pseudotransmutationism. Men transmutationismen var problematisk även för dem som godkände läran om transmutationerna. Man hade inga bevis för att det skulle finnas väldiga grottor inom bergen. Teorin hade dock anhängare, bland annat vid Wittenbergs universitet under 1500-talets senare del, vilket är anmärkningsvärt med tanke på att många nordbor studerade vid detta stora lutherska lärosäte.

De flesta semipluvialistiska teorierna förutsatte ett underjordiskt hydrologiskt kretslopp. Enligt arterialismen strömmar vattnet från havet genom underjordiska ådror till källorna. Denna teori hade flera anhängare bland antikens ledande tänkare: Plinius bland stoikerna, Lucretius Carus bland epikureerna osv. Oftast åberopades dock Bibelns auktoritet, i synnerhet den så kallade (Renqvist 1938) "Salomos jämviktslag" (Pred. 1:7). Det heter (enligt Vulgata-baserade översättningar), att "alla floder löpa i hafvet, dock varder icke hafvet dess fullare; till det rum, der de utflyta, dit flyta de igen". Dessutom fick teorin stöd av den under renässanstiden mycket utspridda analogin mellan makrokosmos och mikrokosmos, där blodådrorna är en förebild till vattenådrorna Problemet var förstås att förklara, hur vattnet kan strömma uppåt inom jorden och bli av med salten. Sifonismen förklarar uppåtströmmandet genom att betona rörelsens kontinuitet, utan vilken det skulle uppstå ett vakuum. Attraktionismen föreslår stjärnornas eller själva jordens dragkraft, medan de övriga förklaringarna talar om uppåtdrivande exhalationer, jordens svampaktighet och sugkraft eller kapillärkraften. Några menade, att vattnets rörelse bestäms av dess egen natur, vilket torde hänvisa till läran om elementens tyngd: Jorden är tyngre än vattnet, av vilken orsak vattnets naturliga rörelse inom jorden är uppåt. De flesta resonerade dock så, att vattnet är ett tungt element som rör sig nedåt alltid när det är möjligt. Även då kan vattnets naturliga rörelse vara från havet till källorna, ifall havets mellersta delar ligger högre än jorden, vilket en del påstod. - Athanasius Kirchers teori kan också anses vara en variant av arterialismen, även om hans *hydrophylacier* är alltför vattendragsaktiga för att analogin med blodådrorna skulle kännas naturlig.

Enligt destillationismen strömmar havsvattnet nedåt in i jorden, in i grottor, där det förvandlas till ånga av den underjordiska elden. Ångan stiger sedan uppåt, tills den förvandlas till vatten nära jordytan. Denna teori, som alltså förutsätter en underjordisk eld samt stora grottor nere i jorden, blev populär under 1600-talets senare hälft. Dess främsta representant var Rene Descartes, vars auktoritetställning kan ha bidragit till teorins framgång. Destillationen uppfattades oftast som en variant av arterialismen - antagligen för att det fortfarande skulle vara möjligt att åberopa Salomos auktoritet . Man kan dock konstatera, att analogin med blodådrarna inte fungerar inom destillationismen: det är ångan och inte vattnet som stiger uppåt.

Enligt tartarismen sjunker vattnet ända ned till jordens centralhåla, som av Platon kallades för Tartaros. Platon gav ingen fysikalisk förklaring till vattnets uppåtströmmande, medan J. J. Becher, som utvecklade teorin, förklarade saken med jordens centraleld. Ett lämpligt namn för Bechers teori är tartarodestillationismen.

PARADIGMSKIFTE ELLER PARADIGMETABLERING?

Pluvialismens genombrott innebar inte bara en förändring av den hydrologiska världsbilden, utan därmed introducerades också den kvantitativt empiriska metoden. Liknande genomgripande omvälvningar kallas ofta för vetenskapliga revolutioner, t. ex. den kopernikanska eller den kvantmekaniska revolutionen. Därmed kunde det vara befogat att tala om *den pluvialistiska revolutionen*. En vetenskaplig revolution är dock inte vilken paradigmetablering som helst utan ett paradigmskifte, vilket alltså förutsätter, att det före revolutionen fanns ett etablerat paradigm. Om det i stället för ett paradigm fanns flera rivaliserande paradigmkandidater eller skolor, av vilka en åsidosatte de övriga, bör man kanske undvika ordet *revolution* . Paradigmteorins fader Kuhn (1970, s 10-22) talade i detta sammanhang bara om *the route to normal science* , dvs en utveckling mot en situation där det råder ett paradigm. Brante (1981) däremot talar om en utveckling från ett förparadigmatisk stadium över ett flerparadigmatiskt till ett enparadigmatiskt stadium.

Man kan påstå, att arterialismen (inklusive de olika destillationismerna) var ett paradigm på 1600-talet, ända fram till pluvialismens genombrott. De rivaliserande teorierna diskuterades visserligen i så gott som alla skrifter som handlade om källornas ursprung, men nästan lika vanligt var det att författaren bekände sig till just arterialismen. Transmutationismen som hade en hel del anhängare på 1500-talet, var nu utslagen, och pluvialismen hade ytterst få anhängare före Perraults tid. Å andra sidan lyckades man aldrig lösa arterialismens två stora anomalier, dvs ge en övertygade förklaring för vattnets uppåtströmmande och avsaltning. Därmed kan man säga, att arterialismen var i kris under hela den tid den dominerade fältet. Lika gärna kan man betrakta situationen som flerparadigmatisk.

Pierre Perrault publicerade sin avhandling om källornas ursprung anonymt år 1674, medan Edme Mariottes mera omfattande verk publicerades postumt år 1686. Ingendera hade alltså kunnat delta i diskussionen med ytterligare bidrag. Edmund Halley däremot publicerade sina avdunstningsstudier i flera artiklar. Dessa bidrag räckte för de flesta, det var sällan man citerade några andra empiriska pluvialister. Ännu mera sällsynta var egna empiriska studier, som dock kunde ha bidragit till att belysa frågan om generaliseringen av de ovannämnda forskarnas resultat. Detta är inte typiskt för en paradigmatisk situation.

UTVECKLINGEN I NORDEN

I brist på dokument kan man inte säga mycket om den hydrologiska världsbilden i Norden under medeltiden och reformationstiden. Det fanns visserligen framstående naturvetare såsom Tycho Brahe och Petrus Severinus, men deras huvudintressen låg utanför hydrologin. De båda nordiska rikena hade sedan 1470-talet också var sitt universitet, som dock blev illa försummade och återupprättades först i slutet av 1500-talet. Man brukade i stället skicka unga män till tyska universitet, i synnerhet till Wittenberg. Transmutationismen var stark i Wittenberg, men arterialismen hade också sina anhängare. Man kan anta, att de lärda i Norden som hade en uppfattning om saken var anhängare av någondera av dessa skolor. Från 1600-talet finns det bl.a. gott om dissertationer, också från de nya universiteten i Åbo och Lund. Norge och Island hade inga universitet och följaktligen få inhemska litterära dokument, men det finns flera normänner bland de nedannämnda författarna. Utväxlingen mellan Sverige och Finland (samt Sverige och Skåne) var också rätt omfattande.

Hydrologins historia i Norden börjar egentligen med finländaren Sigfrid Aronus Forsius. Hans svenskspråkiga lärobok *Physica* (ca.1611) blev inte tryckt på grund av meningsskiljaktigheter bland myndigheterna. Den var alltså kontroversiell och är alltså inte nödvändigtvis representativ för sin tid. Forsius , som citerar Cardanus och Scaliger, är arterialist. Han ger flera alternativa orsaker till vattnets uppstigning: vattnets egen natur, stjärnornas dragkraft och jordens sugkraft. Av de övriga teorierna avfärdar han pluvialismen i en sats, medan transmutationismen får betydligt mera uppmärksamhet (1951 s 139-141). Ungefär på samma linje är Benedict Leuchovius (1619), vars respondent Eskil Petræus blev senare den dominerande gestalten vid det nygrundade universitetet i Åbo

Caspar Bartholin den äldre (1621) hänvisar till mikrokosmos-analogin, men betonar å andra sidan att vattnet inte stiger upp genom raka ådrar utan genom mycket krokiga vägar. Han vill inte heller godkänna tanken om en attraktiv kraft i vattenådrorna som skulle likna den kraft som enligt en allmän uppfattning uppehåller rörelsen i djurens blodådror. Bartholin ställer sig bakom sifonismen och förkastar pluvialismen och transmutationismen, hänvisande till vanliga argument, men medger, att regn- och smältvattnet bidrar till källorna. Han godkänner tanken om en vattenfylld Tartarus i jordens mitten när han talar om jord-vatten-klotets struktur, men betraktar den med skepsis i samband med frågan om källornas ursprung. Motsägelser av detta slag är typiska för tidens eklektiker. Ställningstagandet för Tartarus-kosmografin stöder tanken om en gemensam elementsfär för vattnet och jorden, medan ifrågasättandet av samma kosmografi gör det lättare att avfärda tartarismen, som för sin del strider mot läran om källornas oceaniska ursprung. Gestrin (1632) är också anhängare av sifonismen.

Joachim Burser (1639) skrev en relativt omfattande avhandling om källornas ursprung, men märkligt nog tiger han om pluvialismen och dessutom regnvattnet över huvud taget. I övrigt är denne Soro-professor redan en representant för något nyare ideer. I början ställer han mot varandra två teorier, pseudotransmutationismen - alltså inte mera transmutationismen - och arterialismen, av vilka han föredrar den senare. Efter att ha grundligt diskuterat de olika teorierna om vattnets uppstigande, visar han sig vara destillationist. Också Lodberg (1657 s 14-17) och Tausen (1685) utgår ifrån Salomos jämviktslag och visar sig föredra den destillationistiska tolkningen. Lodberg diskuterar också sifonismen och förkastar den, men tiger om både pluvialismen och transmutationismen. Tausen däremot behandlar både pseudotransmutationismen och pluvialismen. De auktoriteter han åberopar till stöd för arterialismen är något ovanliga: Homeros och Lucretius Carus.

Både Anders Arrebo (1661, s 88, 91, 104-106) och Haqvin Spegel (1685, s 104) står för en arterialistisk syn i sina skapelsedikter, men ingendera försöker förklara processen fysikaliskt. Spegels beskrivning av det atmosfäriska kretsloppet låter visserligen pluvialistiskt: enligt honom kan "altjd Soolen bljda / Förskaffa Watn nog i heela Werlden wjda" (s 106). Arrebo nöjer sig med att godkänna regnvattnet som ett tillskott till avrinningen (1656 s 106).

Daniel Achrelius (1680, s 217-221) avfärdar utan diskussion både pluvialismen och transmutationismen, eftersom den vise Salomon tydligt konstaterar, att orsaken till källorna är havet. Här är det ju fråga om källor (fontibus) och älvar (fluminibus), medan bäckarna (torrentes), som fylls av regn- och smältvattnet, är en annan sak. Av de olika teorierna för vattnets uppåtstigande gillar Achrelius den kircherska, men han avfärdar inte heller tanken om att oceanens mellersta delar ligger högre än jordytan. Den kircherska förklaringen kommer fram också i hans egen gradualdissertation (Miltopæus 1672) samt i en senare dissertation (Achrelius 1686). Petrus Hahn (1688) följer Achrelius och citerar honom. Hahn avfärdar transmutationismen som "en ofantlig hallucination och stor absurditet", medan Achrelius

(1686) anser pluvialismen vara en absurd teori när det gäller den torrida zonen.

Döbeln (1685) avfärdar pluvialismen och transmutationismen med vanliga argument, medan Kircher anklagas av honom för att i onödan ha ökat tingens antal med hydrophylacier, aërophylacier etc. Döbeln själv gör sig till anhängare av tartarodestillationismen, vars spatiella enkelhet tydligen tilltalar honom jämfört med destillationismen och den kircherska arterialismen.

Det fanns också en representant för den pluvialistiska minoriteten bland tidens dissertationslitteratur. Petrus Aurivillius, professorn i grekiska vid Uppsala universitet, var præses för en avhandling (1675), som visserligen argumenterade på det gamla sättet, utan hänvisning till några kvantitativt empiriska undersökningar. Hans respondent Petrus Lagerlöf var senare præses för en dissertation (1691), som var mera kortfattad men på ungefär samma linje.

Caspar Bartholin (1689) är cartesian, men ingalunda destillationist. Han utgår ifrån Salomos jämviktslag, men drar inte några arterialistiska slutsatser. I stället avfärdar han de icke-pluvialistiska teorierna som absurda: Destillationismen fungerar inte, eftersom de uppåtstigande ångorna skulle bli stoppade av ogenomträngliga jordskikt, som brukar förekomma där det finns källor. Det är också oriktigt att anta, att ångorna skulle stanna i de översta jordskikten i stället för att rymma ut ur jorden. Arterialismen har inte kunnat förklara vattnets uppåtströmmande och avsaltning. Pseudotransmutationismen förkastas av Bartholin utan vidare diskussion: processen är riktig, men dennsker inte i grottorna, utan "i det höga". Källorna uppstår alltså av regnvattnet, som sjunker ner i jorden, samlas i håligheter och strömmar ut i källorna. Detta gäller även de permanenta källorna, där vattnets utlopp är mycket trångt. Senecas anmärkning om jordmånens ogenomtränglighet gäller för åkern, inte för skogsjorden. Det påstås också, att regnvattnet inte skulle räcka till, men den berömde franske matematikern Mariotte har bevisat det motsatta. - Caspar Bartholin den yngre argumenterar huvudsakligen med jordmånens struktur. Han går inte närmare in på Mariottes mätningar, utan nöjer sig med att i korthet återge resultaten. Synvinkeln är alltså geohydrologisk och inte hydrometrisk såsom hos Perrault och Mariotte. Bartholin är dock veterligen den första som citerar Mariotte i Norden.

David Fog (1693) konstaterar bara, att "vår berömde Bartholin" har bevisat de icke-pluvialistiska teorierna vara absurda. Christian Kölichen (1704) behandlar Platons Tartaros-lära men kommer aldrig till frågan om källornas ursprung eller hydrologin över huvud taget. Uppsatsen handlar i stället om den underjordiska elden. Diskussionen om källornas ursprung tycks därmed ha upphört i Danmark i det här skedet. Peder Horrebow (1748, s 186-187) behandlar frågan bara i förbigående och konstaterar, att det inte finns belägg för de konkurrerande teorierna. Tre år senare kommer dock Georgius Nicolaus Holm med en neoarterialistisk avhandling.

Holm (1751) känner till Perraults och Mariottes resultat och citerar dem flera gånger. Han menar dock, att dessa inte kan generaliseras, eftersom det finns så få nederbörds- och vattenföringsmätningar från världens olika vattendrag. Han anser också, att avdunstningen har grovt överskattats, i synnerhet när det gäller avdunstningen från havet. Det har enligt honom bevisats, att vattenångan består av bubblor, vilket begränsar avdunstningen när luftrummet börjar bli fylld av dessa bubblor. Havsvattnet avdunstar dessutom svårare än sötvattnet, enligt kemisterna. Pluvialismens otillräcklighet åskådliggörs bäst om man betraktar Kaspiska havet. Holm uppskattar dess genom att använda Mariottes resultat från Frankrike och visar att både nederbörden och avdunstningen är alldeles otillräckliga. Därför måste det finnas *euripi*, dvs. underjordiska kanaler, genom vilka vattnet strömmar från havet till källorna. Ett bevis för deras existens är de stora virvelströmmarna, där vattnet dras in i jorden. Holm åberopar här bl.a. Arrebo och Kircher. Ett annat bevis är havsfiskarna som förekommer i högt belägna insjöar. Holm försöker inte ge någon fysikalisk förklaring till vattnets uppåtstigande eller dess avsaltning.

På andra sidan av Öresund låter pluvialismens genombrott vänta sig. Riddermarck (1694) tycks inte ha hört något om Mariotte. Han avfärdar både transmutationismen och pluvialismen med gamla argument, och presenterar flera arterialistiska teorier, utan att diskutera dem närmare. Hans egen syn är attraktionistisk: vattnets uppåtströmmande är dess naturliga rörelse inom jorden och förorsakas av jordens magnetiska kraft. Som författare till dissertationen uppges uttryckligen respondenten Johan Fonthelius, men Riddermarck hade en liknande syn i en tidigare dissertation (1688), där han i korthet avfärdade transmutationismen, pluvialismen och destillationismen samt stödde en diffust formulerad kirchersk arterialism. I Uppsala bygger Harald Vallerius (1704) en syntes av arterialism och destillationism. Vattnets uppåtströmmande förklarar han med det atmosfäriska trycket. Pluvialismen, som enligt honom har många framstående anhängare, avfärdar han med vanliga argument. Inte heller Vallerius hänvisar till Mariotte eller Perrault eller deras kvantitativa rön.

Det är Urban Hjärne (1702, s 42-50) som först diskuterar Mariottes (och Bartholins) skrifter i Sverige. Han kritiserar pluvialismen genom att hänvisa till mätningar, som har gett lägre årsnederbörd än de som Mariotte publicerade, eller stora värden för transpiration, men medger, att största delen av avrinningen i Sverige består av regnvattnet. Arterialismen motiverar han främst med bibliska argument, men söker också en fysikalisk förklaring, som grundar sig på både atmosfärens tryck och jordens sugkraft. Hjärne var något av en auktoritet, och hans ställningstagande tillsammans med cartesianismens starka ställning i Uppsala torde kan antas ha fördröjt pluvialismens genombrott i Sverige.

I Åbo höll man länge fast vid aristotelismen, så att cartesianismen och övriga i Uppsala gällande nya ideer aldrig hann slå igenom innan hela universitetslivet lamslogs av den ryska ockupationen under åren 1713-21. Avbrottet innebar ett generationsskifte, vilket eventuellt kan förklara, att det första kvantitativt inriktade pluvialistiska dokumentet i kungariket Sverige kommer från Åbo - 40 år efter det motsvarande danska dokumentet. Præses till denna dissertation, matematikprofessorn Nils Hasselbom, kom från Sverige och hade studerat vid Uppsala universitet.

Hasselbom (1632) behandlar först transmutationismen, destillationismen och den kircherska arterialismen, av vilka de två senare är vackrare och mera trovärdiga men dock inte tillfredsställande. Destillationismens största problem är de ogenomträngliga jordskiktena, som förekommer just i de källrika områdena. Om ångan kunde tränga sig genom dessa, skulle också vattnet kunna göra det och falla tillbaka. Den kircherska arterialismens svaghet är, att vattnet enligt teorin måste göra flera avbrott, varmed också den föreslagna orsaken till uppåtströmmandet, luftens spänning och strömningar inom jorden, slutar att verka. Dessutom borde vattenådrorna vara mycket starkare än de rör som används i vattenledningarna, och påståendet, att sådana skulle finnas i jordens inre, hör mera till sagorna än till filosofin. Inte heller kapilläreffekten kan ge någon förklaring, för vattnet brukar inte stiga särskilt högt av denna orsak. Vidare är de förklaringar, som föreslagits till avsaltningen, ogiltiga. Saltvattnet kan förvandlas till sötvatten endast genom destillering, och även om det skulle lyckas genom perkolation, skulle vattenådrorna ganska snart fyllas ut och själva havet avsaltas. Den pluvialistiska teorin är däremot förenlig med alla naturlagar. Till påståendet, att regnvattnet skulle vara otillräckligt, svarar Hasselbom genom att citera Mariotte, Halley och Vallisnieri.

Hasselboms kollega i Uppsala, Samuel Klingenstierna (1740) börjar med att förklara destillationismen men kan dock inte godkänna den. Det finns inga bevis för existensen av de ådror genom vilka vattnet skulle strömma ner till grottorna. De underjordiska floderna brukar bestå av sötvatten och strömma mot havet, inte ifrån havet. Dessutom skulle det kondenserade vattnet återvända samma väg till djupet. Klingenstierna avfärdar också arterialismen genom att med en enkel kvantitativ betraktelse bevisa, att processen skulle ha för länge sen lett till avsaltning av själva havet, varmed också ådrorna skulle ha fyllts med salt. Han gillar inte heller pluvialismen, även om han berömmer Perrault och Mariotte samt citerar deras kvantitativa resultat. Av dessa bör man nämligen inte dra generaliserande slutsatser, i synnerhet när motsatta exempel har rapporterats. Klingenstierna menar också, dock utan att ge någon kvantitativ bedömning, att växterna konsumerar så mycket vatten till transpirationen, att det inte kan bli mycket kvar. Däremot har han inga invändningar mot roralismen, som han alltså betraktar som självständig teori.

I brist på dokument kan man inte säga något om pluvialismens utbredning i Norden under 1700-talets första hälft. På 1740-talet har den i alla fall kommit till både Lund och Uppsala, kanske i denna ordning. Enligt Gustav Harmens (1745) är dropparnas storlek den enda skillnaden mellan regn och dagg - pluvialismen och roralismen är alltså en och samma teori enligt hans mening. Huvudsaken i avhandlingen tycks vara att förklara jordmånens struktur och dess konsekvenser för grundvattnets rörelser, men Harmens citerar också Mariotte för att bevisa regnvattnets tillräcklighet. Av de semipluvialistiska teorierna kommenterar han sifonismen, den kircherska arterialismen samt tartarodestillationismen. Allt annat avfärdas som "Philosophorum antiquorum turba" - detta uttryck torde åsyfta främst transmutationismen - varom man kan läsa hos Perrault. Snart tog också sådana inflytelserika personer som Kungliga Vetenskapsakademins sekreterare Pehr Elvius (1748) och självaste Carl von Linne (1750) ställning för pluvialismen.

Den ledande neoarterialisten i Sverige var Johan Gottschalk Wallerius. I boken *Hydrologia, eller Wattu-riket* (1748) polemicerar han inte mot pluvialismen, men godkänner också två andra mekanismer för vattnets uppåtströmmande: den destillationistiska och den arterialistiska. Bland dem som följer honom är Åbo-professorn Pehr Kalm (1763). Till semipluvialisterna hör också kemiprofessorn och geologen Torbern Bergman (1773). Andra dokument (Nordenskiöld 1758; Wargentin 1763, Gadd 1772; Gadd 1786) tyder dock på, att pluvialismen började småningom dominera i Sverige och Finland.

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