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Climate, Water and Energy

Long time series

A review of Nordic studies

Report by the CWE Long Time Series group

NVE SMHI SYKE

Hydrological Service
National Energy Authority

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Abstract:

Awareness that emission of greenhouse gases will raise the global temperature and change the climate has led to studies trying to identify such changes in long-term climate and hydrologic time series. This report, written by the ”Long time series group” in the Nordic Council of Ministers supported project “Climate Water and Energy”, gives an overview of such studies carried out in the Nordic countries. Possible consequences for the hydropower sector are outlined. Regarding future research there is a need for a pan-Nordic study identifying large-scale regional differences in terms of non-stationarity and climate and streamflow variability. Studies of proxy series should be encouraged in order to study decadal to century-scale variability. Finally, focus on possible consequences of climate change regarding extremes and the energy sector is of vital importance.

CONTENTS

1 INTRODUCTION

Hege Hisdal, Norwegian Water Resources and Energy Directorate, Norway.

There is a strong interrelationship between climate and water resources systems. A change in one of the systems will induce a change in the other (Kundzewicz, 2002). This again will change both the supply of and demand for energy. Countries that base much of their electricity production system on hydropower are especially sensitive to long term variations in streamflow. Unpredictable hydrological changes will increase the risk associated with the development and use of water resources. As a result, new investment, design, operational and management practices might be needed.

Indirectly the hydrologic cycle might be altered by human induced changes as for example greenhouse gas emission through a changed climate. Human induced changes might also directly affect streamflow, soil moisture and groundwater through anthropogenic impacts in the basin itself. Examples are river regulation, building of dams and reservoirs, land use changes, deforestation, urbanisation, and groundwater overdraft. In addition, hydrologic behaviour changes over all time scales due to natural climate variability. The natural energy system is responsible for the major changes of climate and thereby hydrology (Collier, 1998). Other cycles such as the hydrologic cycle itself, the carbon cycle and other biochemical cycles, produce fluctuations within the major changes or accelerate or decelerate these changes. Changes of solar radiation due to changes in the orbit of the earth about the sun, cause climate changes with periodicities of several thousand years that amongst others can explain fluctuations in the global ice volume (US National Academy of Sciences, 1975). The effects of natural climate variability and human induced changes are often difficult to separate.

Awareness and concern that increased emission of greenhouse gases would raise the global temperature grew in the 1980s. In 1988 the World Meteorological Organisation (WMO) and the United Nations Environment Programme (UNEP) jointly established the Intergovernmental Panel on Climate Change (IPCC). Its terms of reference include an assessment of the available scientific information on climate change and its impacts amongst others on the hydrologic cycle. Climate change studies traditionally include elaboration of possible scenarios for the future and attempts to detect a climate change signal in historical data. This report focuses on the latter. Such studies look for trends and jumps and also establish knowledge about the natural climate and hydrologic variability. Changes might be detected in annual as well as seasonal and extreme values. It is important to be aware that even if annual averages remain unchanged, a change in seasonal or extreme values might be present.

Instrumental climatic or hydrologic records rarely extend to the length of 200 years. These records are long enough to document changes at inter-annual time scales. Our knowledge of the climate and hydrology for longer periods, such as decadal- to century-scale, depends largely on analyses of proxy-data such as isotope records from tree rings, fossils, corals and ice cores, spanning the last 500 to several thousand years. The Nordic countries are privileged to have a good spatial coverage of long time series that have undergone a quality control to avoid stations that are affected by human activity. This enables a regional study of changes in long time series.

Information about observed changes in the climate system is summarised in the Third Assessment Report of the IPCC (IPCC, 2001a). The global average surface temperature has increased since the late 19th century. The largest increases in temperature during the last 25 years have occurred over the middle and high latitudes of the Northern Hemisphere and except over Eastern Asia, precipitation has increased as well. In the Northern Hemisphere, decreasing snow cover and land- and sea-ice extent are positively correlated with the temperature increase. In IPCC (2001b) the observed changes regarding hydrology are summarised. It is stated that "*There are apparent trends in streamflow volumes -increases and decreases- in many regions. However, confidence that these trends are a result of climate change is low because of factors such as the variability of hydrological behaviour over time, the brevity of instrumental records, and the response of river flow to stimuli other than climate change.*" In general the changes in annual streamflow follow the changes in precipitation. However, it is seen as very likely that the widespread glacier retreat and shift in timing of high streamflow from spring to winter can be linked to the increases in temperature. The detected changes in climate and hydrology might vary considerably between regions.

This report is written by the "Long time series group" within the framework of the two-year project (2002-2003) "Climate Water and Energy" (CWE). The directors of the Nordic hydrological institutes (CHIN) initiated CWE with funding from the Nordic Energy Research of the Nordic Council of Ministers focusing on climatic impact assessment in the energy sector. The report contains an overview of recent and ongoing studies of long time series of precipitation, temperature, streamflow and other hydrologic variables in the Nordic countries. The time series studied are as far as possible not influenced by interference at the measurement site. Hence the detected changes are caused either by natural climate variability or human induced climate change. In the various studies presented, no attempt is made to distinguish between these two causes of change, but trends found in the hydrological variables are often linked to trends in climatological parameters or changes in circulation patterns.

Chapter 2 summarises the results of the Nordic CHIN-project "Time series analysis" initiated in 1992, followed by Chapter 3 describing studies from the individual countries. A separate chapter, Chapter 4, describes possible consequences of changes in climate and streamflow for the hydropower sector. Finally in Chapter 5, conclusions are given together with recommendations for future research. There are two appendices: one describing some tests that are applied to the studies described and one listing Nordic streamflow data available for analyses. The data are stored in a database at NVE.

2 NORDIC PROJECTS

Hege Hisdal, Norwegian Water Resources and Energy Directorate, Norway.

2.1 Background

Various national studies of long term variations in climatic and hydrological variables have been carried out in the Nordic countries. The aim has been twofold, to describe natural variability and to describe changes attributable to human activity. To study the regional distribution of changes, there is a need to study data from several countries and to include a common time period. The latter is important because the trend or changes found will be strongly influenced by the period studied (Hisdal *et al.*, 2001).

CHIN in 1992 initiated the project "Time series analysis". A common interest in a Nordic data set for time series analysis resulted in a Nordic project group with the following main objectives:

- to establish a Nordic data-set suitable for time series analysis;
- to carry out statistical time series analysis and interpret the results in terms of geophysical causes, e.g., possible climate change.

A working group including members from all the Nordic countries carried out the study that was later affiliated as a sub-project, "Historical runoff variations in the Nordic countries", with the Nordic research program "Climate Change and Energy Production" with funding from the Nordic Council of Ministers (Sælthun *et al.*, 1998). The following two sections summarise the final report from this project (Hisdal *et al.*, 1995) and the results from a continuation of the "Time series analysis" project (Hisdal *et al.*, 1996).

2.2 "Historical runoff variations in the Nordic countries"

2.2.1 Data and methods

A total of 160 streamflow records (40-152 years) of daily data from Denmark, Estonia, the Faroe Islands, Finland, Greenland, Iceland, Norway and Sweden were collected. The data were stored in a common database, a local, Nordic version of the European Water Archive (EWA) of the Flow Regimes from International Experimental and Network Data (FRIEND) Project (Roald *et al.*, 1993; Rees and Demuth, 2000).

The criteria for selecting series for the data set were:

- the basin should be unaffected by man-made changes in the river flow regime;
- the series should together give a nation-wide coverage;
- the series should be as long as possible.

These criteria are sometimes in conflict, as the longest series often will be affected by human activities in the basin, causing various forms of inhomogeneities in the series. The series were therefore classified into three categories:

- series suitable for analysis on a daily level, i.e. for seasonal variability and trends in extremes;
- series suitable for analysis of monthly values, i.e. seasonal trends;
- series only suitable for analysis of trends in annual values.

The records from the Faroe Islands and Greenland only had a maximum of 13 years of data and contained large gaps. These series were therefore excluded from the main analysis, but their temporal patterns were compared visually with the other series.

Based on the similarity in the annual flows between the series, 13 regions were found. These included two glacier regions, one in Iceland and one in Norway. Within each region a regional series was calculated. Also, one or two typical series were selected within each region. The selection was based on the length of the series, the number of missing values and the position of the basin within the region. Most of the typical series corresponded well in behaviour with the regional series, showing that the regions found were sufficiently homogeneous for the purpose of the study.

Annual and seasonal values were analysed both for regional and typical series. For the latter, floods and summer low flows were also analysed. To visualise the general behaviour of the streamflow by eliminating short-term fluctuations in the time series, a Gauss filter (WMO, 1966; Schönwiese, 1983) was applied to annual and seasonal series. These series were also analysed for trends by Spearman and Mann's trend test (WMO, 1966), and persistence by a simple run test (WMO, 1988). Changes might also appear as sudden jumps and the typical series were tested for jumps in the mean values (Schumann, 1994). The features of seasonal floods and summer low flow were examined by comparing both the mean values and the coefficients of variation. Changes in the decadal means were studied and linear regression trend analysis of the size and the date of the flood peaks and summer low flow were performed.

2.2.2 Results and conclusions

Wet and dry years tend to cluster. Hence, the period analysed will very much influence the direction of a trend. For example, all regions except Iceland had some high annual streamflow values in the late 1980s and beginning of the 1990s that gave increasing tendencies. This is important to bear in mind when discussing the results.

The results of applying a Gauss filter on the regional series of annual mean values are illustrated in Figure 1. The combination of the different tests gave a picture of the regional changes in streamflow that have occurred in the Nordic countries and Estonia. Looking at the common period 1930-80 that could be studied for most regions, it was possible to identify three zones for the annual values:
- a westerly zone consisting of Denmark and the western part of Norway with increasing streamflow;
- a central zone including eastern Norway, Sweden and the northwestern part of Finland with decreasing streamflow;

- and an eastern zone containing the main part of Finland and Estonia where the streamflow decreases in the beginning of the period before increasing from the middle of the period towards the end.

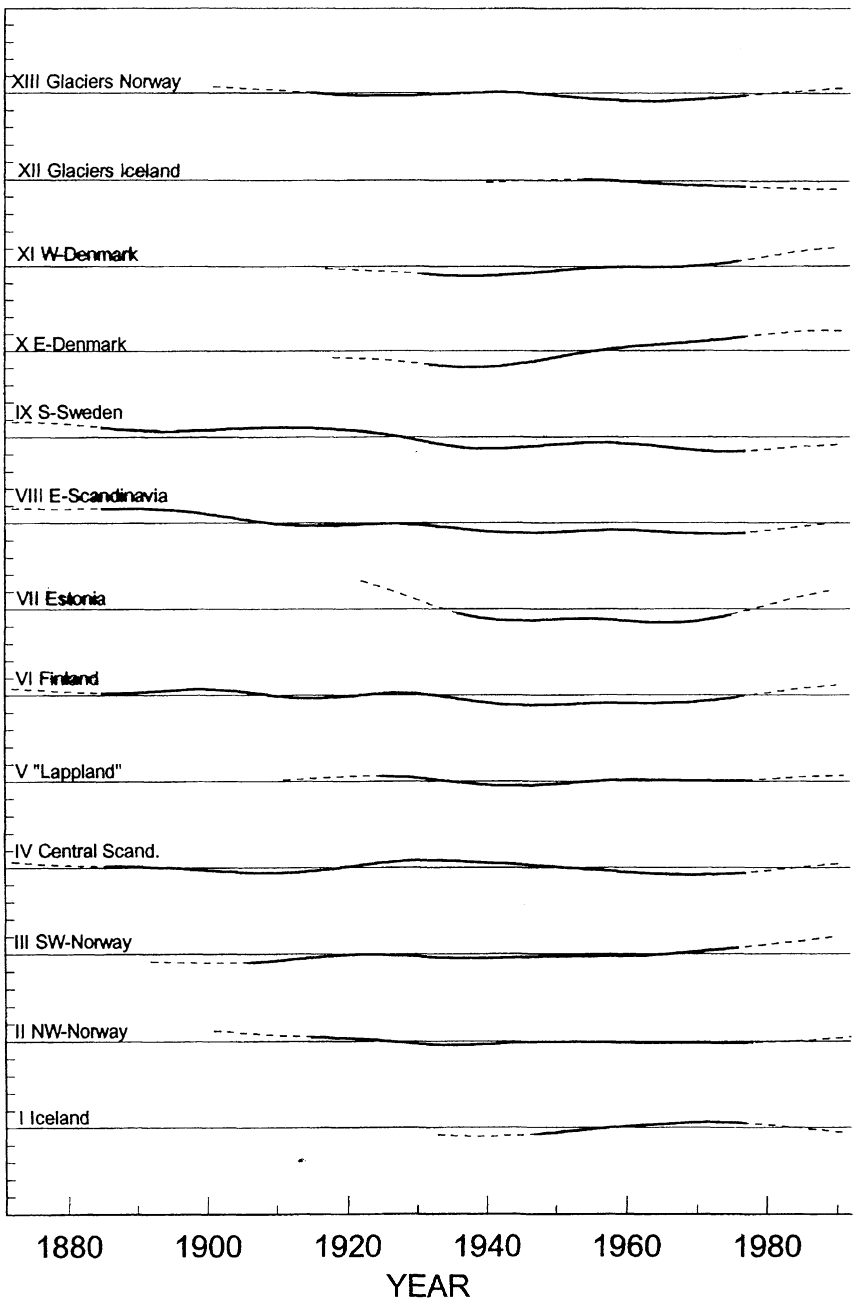

Figure 1. *Long term streamflow variations in the Nordic region (from Hisdal et al., 1995)*

Variations between different seasons within the same region were often found to be considerable and stronger trends could be found in seasonal series as compared to annual series.

Regional patterns in the flood trends were found for all seasons except the summer. For the period 1930-90 a decrease in the winter maximum over almost all of Sweden and in central Norway and an increase in western Denmark and eastern Finland was found. In northern Scandinavia an increasing trend in the spring flood was found due to a number of high values in the late 1980s. Reduced autumn floods in central Norway and increasing trends in the summer low flow in the southern part of the study area were also found. The results also showed a tendency toward an earlier start of the spring flood in southern Sweden, central Sweden and central Norway. Analysing the total period of record, for the series that start before 1930, it was found that the trends often disappeared due to high or low values in the beginning of the period. This confirms the high sensitivity of trend analyses to the period analysed and also indicates that what is seen as a trend in a short period, might be a part of a longer-term fluctuation.

The results corresponded well with studies carried out by the individual Nordic countries. A comparison with changes in precipitation gave coinciding patterns for annual values as well as the summer and autumn seasons. Because of snow accumulation and snowmelt, the precipitation and streamflow patterns differed for the winter and spring seasons. The results found in the project did support a theory of a changing circulation pattern resulting in increased westerlies and a northerly displacement of the prevailing westerlies.

The study concludes by stating that time series analyses of streamflow alone cannot help distinguishing between natural and human-induced climate change. It was also stated that an extrapolation of a trend into the future is not possible and that future research is needed to explain streamflow trends by changes in climate parameters and circulation patterns.

2.3 Further results from the "Time series analysis" project

In a continuation of the CHIN-project "Time series analysis", the correspondence between long term changes in streamflow and precipitation was studied (Hisdal *et al.*, 1996). Representative precipitation stations were found for the typical streamflow series analysed in Hisdal *et al.* (1995), except Estonia where no precipitation data were available. Annual mean values for the periods 1961-90, 1921-90 and the total period of record were analysed. The jump test in Schumann (1994) and a linear regression trend test were performed.

It was found that the combined use of a jump and trend test gave valuable information about the structure of variation in the time series. For about 50% of the streamflow records, a coinciding jump or trend was found for the corresponding precipitation station. The discrepancies in the results were interpreted to be caused by:

- the influence on streamflow by climatic factors other than precipitation, e.g. temperature (evapotranspiration);
- the influence on streamflow by human impacts in the basin;
- the precipitation stations not being representative for the basins.

3 NATIONAL STUDIES

3.1 Denmark

Søren E. Larsen and Niels B. Ovesen, National Environmental Research Institute, Denmark.

3.1.1 Introduction

There is a long and well-established tradition in Denmark for publishing reports that include analyses of runoff in Danish streams. The Danish company Hedeselskabet has published a total of 10 reports on runoff, the latest one in 1978. In 1994, the National Environmental Research Institute (NERI) took over the responsibility for hydrometric monitoring in Denmark, and for reporting the results. These results were first published in a report by NERI in 2000. This report (Ovesen *et al.*, 2000) provides a characterisation and analysis of runoff in Danish rivers. The report is based on the archive of hydrometric data collected over the last century. The runoff is described by means of characteristic parameters, duration curves, extreme value analyses, trend analyses and mapping of runoff and water balance. The report presents an overview of the national hydrometric data archive and provides maps, tables and key data.

3.1.2 Runoff characteristics

In Denmark, runoff has been registered systematically since 1917. It was Hedeselskabet that started the registration in a number of selected Danish rivers. Runoff is currently measured continuously at almost 400 monitoring stations distributed in Denmark's approximately 64 000 km small and large streams. The total basin of the monitoring stations constitutes approximately 55% of the total area of the country. Denmark's largest stream is river Gudenå (149 km), which drains an area of more than 2 600 km^2. The river with the most water, however, is river Skjern Å with an average streamflow of approximately 37 m^3s^{-1}.

For many years the water stage has been registered by means of manual readings of a water level gauge placed at many of the stations, but also automatic chart recorders have been in operation since the beginning of the 20^{th} century. Nowadays, registrations are normally performed by dataloggers and occasionally with a telemetry link to the stations. At most stations, however, the actual registration is still performed by the use of float and pulley in a stilling well. Flow measurements are performed by the use of a propeller instrument.

Fall gradients of Danish streams fall almost exclusively within the interval of 0.1-10 per thousand. The gradient tends to decrease downstream in the river system (the closer it gets to the coast), but there are marked deviations between the various parts of the country. The streams on Bornholm, for instance, have relatively large gradients.

The flow velocity in streams varies between approximately 0.2 and 0.5 ms^{-1} and the velocity is often higher in large streams. The average velocity is approximately 0.3 ms^{-1}. The flow regime is generally unstable on the Danish islands, and more moderate in streams in northern and western Jutland.

The average annual mean runoff for Denmark as a whole is 318 mm (10.1 $ls^{-1}km^{-2}$). In the eastern part of the country it is approximately 200 mm, and in the western part 400 mm per year. In the central and southern parts of Jutland the annual mean runoff exceeds 600 mm. The considerable differences in runoff are related to precipitation pattern, evaporation, regional groundwater migration and abstraction. In years with sparse precipitation, such as e.g. 1976 and 1996, the runoff is less than 200 mm, and in years rich in precipitation, such as e.g. 1981 and 1994, it is more than 450 mm. For the country as a whole the average annual precipitation for the period 1971-1998 is 854 mm. The potential evaporation is 520 mm and the runoff is 322 mm.

3.1.3 Analyses

The latest report on runoff characteristics in Denmark (Ovesen *et al.*, 2000) included analyses of trends in time series of annual mean precipitation and annual mean temperature for Denmark during the 125-year period 1874-1998. 1874 is the earliest year with reliable meteorological measurements in Denmark. Also the periods 1917-1998 and 1971-1998 were analysed for trends.

The report also included tests of trends in time series of daily runoff values from 39 different hydrometric stations. The time series start in different years, the longest beginning in 1917. All time series have a complete record of data in the period 1971-1998. The following runoff variables have been analysed for trends:

- annual mean runoff;
- annual maximum runoff, and annual minimum runoff.

The trend analysis was done by applying both a parametric and a non-parametric statistical method. The methods are described briefly in Appendix 1 and in further detail in Ovesen *et al.* (2000).

The time series of annual maximum and minimum runoff values were analysed with respect to return periods and duration curves. The generalised extreme value distribution was used to characterise the distribution of annual extreme values (see Ovesen *et al.*, 2000, for details).

3.1.4 Results

The annual mean precipitation in Denmark for the period 1874-1998 is shown in Figure 2. There has been a general increase in the precipitation during the period, but with considerable year-to-year variations. The result from the trend analysis confirms a significant increase during the periods 1874-1998 and 1917-1998 (P=0.02% and P=1.2%). The parametric and non-parametric analysis gave very similar results. During the period 1874-1998, the annual mean precipitation has increased by 0.76 mm per year, and in total the precipitation has increased by 95 mm during the 125 years. The precipitation has increased 78 mm in total during the period 1917-1998. The increase in precipitation can give an increase in runoff.

The parametric analysis also showed that the time series of annual mean precipitation is without memory, i.e. the autocorrelation is zero.

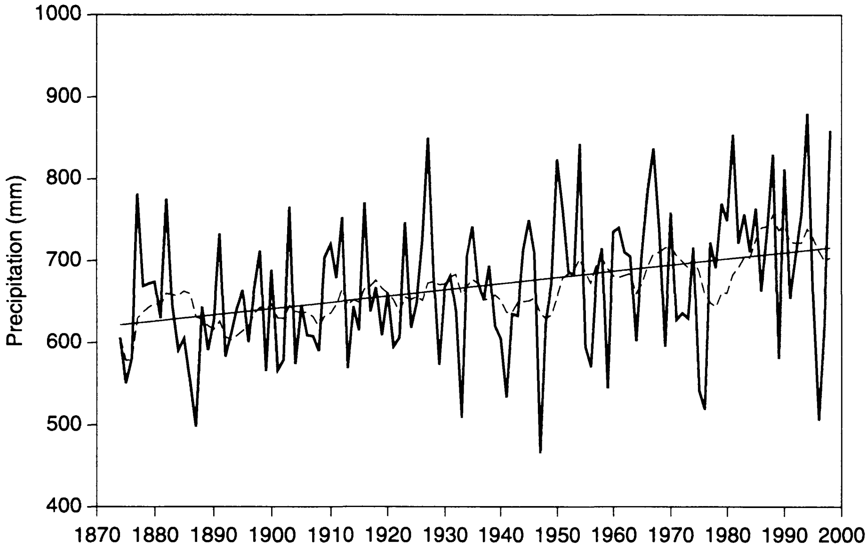

Figure 2. *Annual mean precipitation in Denmark for the period 1874-1998. The plot shows the best linear fit through data (y=621+0.76x) as well as the 10-year moving average.*

The time series of annual mean temperature is shown in Figure 3. Again large year-to-year variations can be seen with a general increase in temperature during the period 1874-1950. Between 1950 and 1990 there is a slight decrease in temperature and the last 9 years (1990-1998) have been quite warm

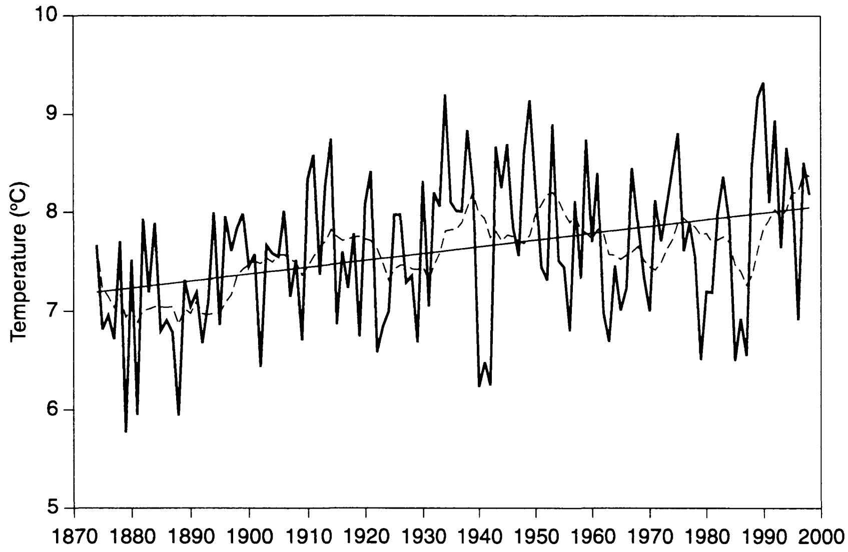

Figure 3. *Annual mean temperature in Denmark for the period 1874-1998. The plot shows the best linear fit through data (y=7.19+0.0069x) as well as the 10-year moving average.*

The trend analysis showed a significant increase in temperature (P=0.03%), 0.0069 °C per year between 1874 and 1998 and in total 0.8625 °C during the 125 years. Since 1860, the global temperature has increased by 0.3-0.6 °C (ICPP, 1995). Denmark has experienced a higher increase in temperature. The increase was especially significant during the period 1874-1950 with an estimated increase of 0.0146 °C per year. The parametric analysis shows a significant autocorrelation of order 3, i.e. the memory is three years in the time series of annual mean temperature. The significant increase in temperature can lead to increased evaporation and therefore less runoff in Danish streams.

The trend analysis of the 39 time series of annual mean runoff showed an increase at 32 stations. For 6 of the 32 stations the increase was significant at a 5% significance level. A total of 7 stations showed a decrease in annual mean runoff, but none of these were significant. In general, the runoff has therefore increased since 1917 and this increase can be related to the significant increase in precipitation.

The trend analyses of the time series of annual minimum values showed decreasing trends at 16 stations and 3 of these were significant at a 5% significance level. The number of stations with a positive trend was 22, and 6 of these had a significant increase. The annual minima have increased as much as the annual mean runoff during the period 1917-1998.

The annual maximum time series also showed a generally increasing trend with 22 out of 39 time series having an upward trend. However, only 3 of these stations have significant increasing trends. Decreasing trends were found at 13 stations with 5 stations having a significant decrease.

Examples of the time series of annual mean, maximum and minimum are given in Figure 4. The plots on the left are from Lindholm stream in the northwestern part of Denmark draining sandy soils. On the right are time series from river Odense draining a basin with more clayey soils and situated on the island of Funen. The best linear fits are also included in the plots. For Lindholm stream, the annual maximum is significantly decreasing and for river Odense, the annual minimum is significantly increasing.

Time series analysis of the various runoff variables was also carried out for data from the period 1971-1998 in order to infer regional patterns in the changes in runoff. Only very few of the time series had significant trends, but the overall tendency was that decreasing tendencies mainly occurred in the eastern part of Denmark.

3.1.5 Conclusions

The trend analyses of annual mean precipitation and annual mean temperature for Denmark during the 125-year period 1874-1998 showed significant upward trends for both time series. The precipitation increases gradually throughout the whole period, but the highest temperature increases occur during the first 75 years of the time series and finally during the 1990s.

The annual average runoff shows an increasing trend for the past 80 years in most of the Danish streams. This relates primarily to the corresponding increase in the quantity of precipitation. Some streams, however, show a decreasing trend caused by, for example, water abstraction from the stream or from groundwater within the basin. Also the annual maximum and minimum runoff show a predominantly increasing trend, but the results are not unambiguous. The indicated trends are only significant in a small proportion of the analysed time series.

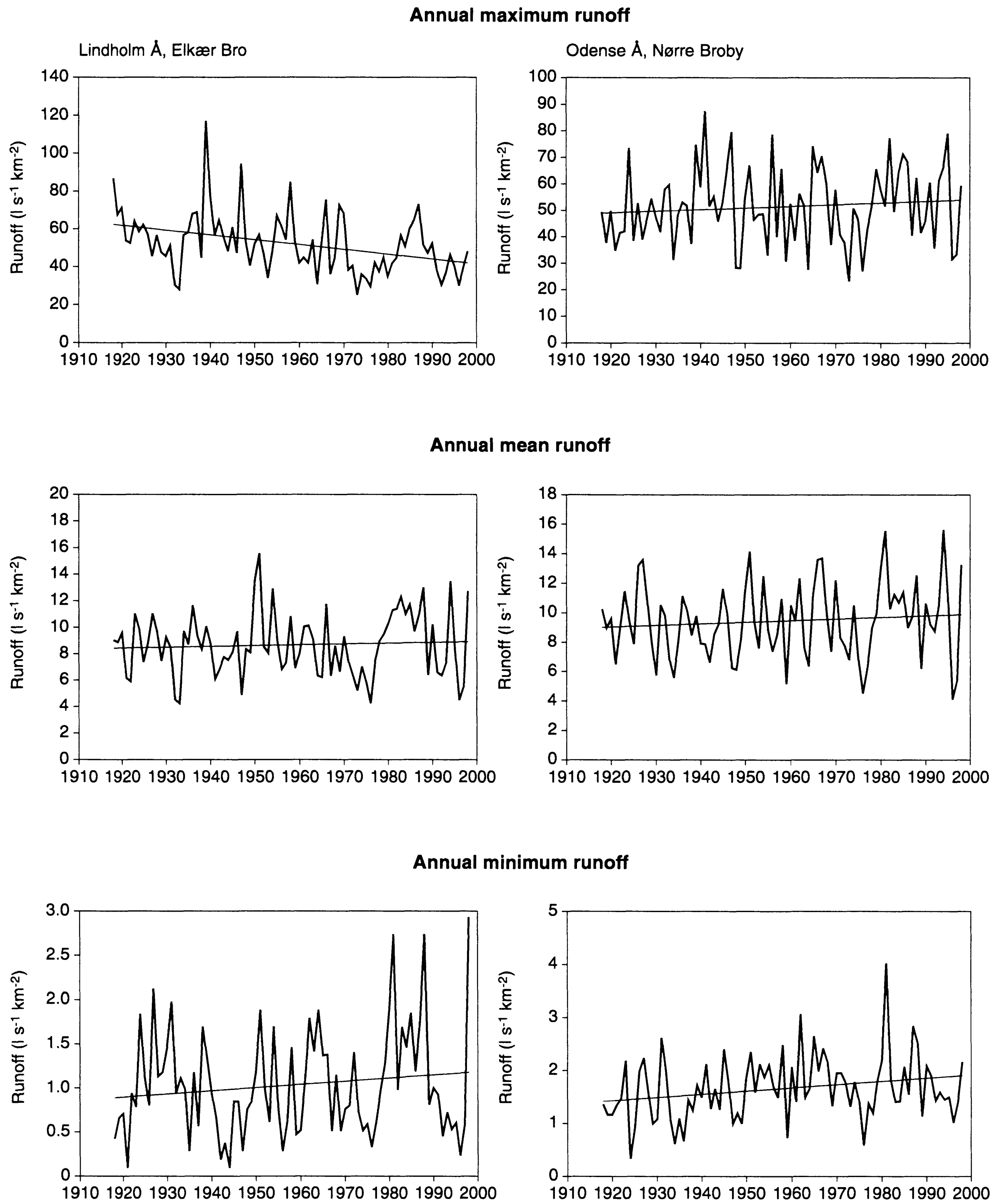

Figure 4. *Plot of time series of annual maximum, mean and minimum runoff for two selected hydrometric stations.*

3.1.6 Ongoing projects and recommendations for further research

A new Danish research project, "Consequences of weather and climate changes for marine and freshwater ecosystems – Conceptual and operational forecasting of the aquatic environment (CONWOY, URL: www.conwoy.ku.dk)", started in 2002. One of the scientific work packages of this project includes a detailed analysis of national data on climate variables and streamflow for modelling the variability in the time series and testing and modelling trends and extreme values. The models should then facilitate the hind- and forecast of weather-induced changes in hydrology.

The latest trend analyses of runoff in Danish streams included data for the period 1917-1998. We suggest an analysis of the extended time series with data from the period 1917-2002. The analysis should include trend testing for both annual variables and seasonal variables (monthly variables). Furthermore, the analysis should include a more thorough treatment of extremes, such as annual extreme values, threshold analysis and analysis of seasonal extremes. We also suggest making a re-analysis of the time series with a common period (e.g. 1960-2002) in order to investigate regional differences in the trends and extremes of runoff. This is of great interest in Denmark, because of the clear gradient in precipitation from the western to the eastern part of Denmark.

3.1.7 Other variables

Available variables not included in the study described could be snow cover, radiation and sea ice.

3.2 Finland

Veli Hyvärinen and Esko Kuusisto, Finnish Environment Institute, Expert Services/Hydrology Division, Finland.

3.2.1 Introduction

This chapter describes the trends and fluctuations in the Finnish climatic and hydrological time series observed up to 2002. The series have been selected so that climate change or variations – whatever their backgrounds may be – are the main reason for the hydrological variations. Thus, for example, streamflow observation series strongly or moderately affected by forest drainage or regulation have been excluded.

Most of the analyses are based on the Finnish national hydrological data base HYDRO, which belongs to the major database HERTTA of the Finnish Environment Institute (SYKE, 2001). This data base includes rather long data series of lake water level, streamflow, areal precipitation, areal water equivalent of snow, lake and river ice, water temperature, groundwater level, ground frost etc. The longest hydrological observation series in Finland, that of ice break-up in Tornio River, begins in 1693. The earliest lake level series and streamflow series begin in 1847, and there are some ten other series longer than 100 years. From most main rivers there are observations from 1911.

Streamflow from small basins with no lakes has been observed mainly from the late 1950s; these series are not included in this approach. Pan evaporation, groundwater level and soil moisture series are only 25 to 42 years long.

3.2.2 Summary of research

Streamflow

Streamflow observation series from lake outlets are rather precise, even during winter, because the lake outlets are ice-free. At river stations ice cover, ice dams and frazil ice jams often disturb the stage-streamflow relationship. These stations have been excluded from the studies summarised - except the stations of southernmost Finland from where undisturbed long-term observations from lake outlets are lacking and where ice reduction in river stations is rather limited.

The first comprehensive time series analyses of streamflow were made by Hyvärinen and Vehviläinen (1980). A rather clear increase in winter flow in southern Finland was detected. Later observations and analyses have confirmed the strong increase in winter flow in south and west - as well as a clear increase in central parts of Finland (Hyvärinen and Leppäjärvi, 1989; Hiltunen, 1994a and 1994b; Hyvärinen, 1998). Increasing winter air temperatures and increasing winter precipitation have been the obvious reason for the increasing winter flows in these areas. Winter temperatures have increased in Finland during the 20th century in average by 1 °C; the largest increase rate was recorded in the 1990s. In northernmost Lapland, where winters have continued to be cold enough to maintain wintry conditions, no marked trends in the winter flows have been observed. Mean annual temperature decreased in Lapland during the period 1961-1990; in 1991-2000 some increase was observed also there. Three examples of the changes in runoff regimes are presented in Figure 5. In the north, no trend in winter flow is observed. In southern and central Finland especially winter flow has increased during the period, in southwest Finland mean annual flow has also increased, and the spring flood peak has shifted towards an earlier date.

Autumn flows have also been increasing in southern and central Finland during the 20th century, although there are no noticeable trends in summer flow or in spring maximum flow. In most of Finland the annual runoff has increased, on average 0.5 mm a^{-1}, but in parts of southwest Finland the average increase of annual runoff has been up to 1 mm a^{-1} during the 20th century (Hyvärinen *et al.*, 1995; Hyvärinen, 1998).

There is, however, no marked trend in the longest streamflow series in Finland, that of Lake Saimaa to River Vuoksi, situated in southeast Finland. This series starts in 1847. The reason to the absence of trend, at least partly, is the heavy burn-beating in large areas in the southern parts of the drainage basin (totally 61 060 km^2) in the middle of the 19th century (Hyvärinen *et al.*, 1995). The deforestation considerably decreased evapotranspiration in these areas for more than half a century. As a result, runoff in the middle of the 19th century was higher than in the surrounding areas where burn-beating was of less importance. After the burn-beating was forbidden, the areas became forested again.

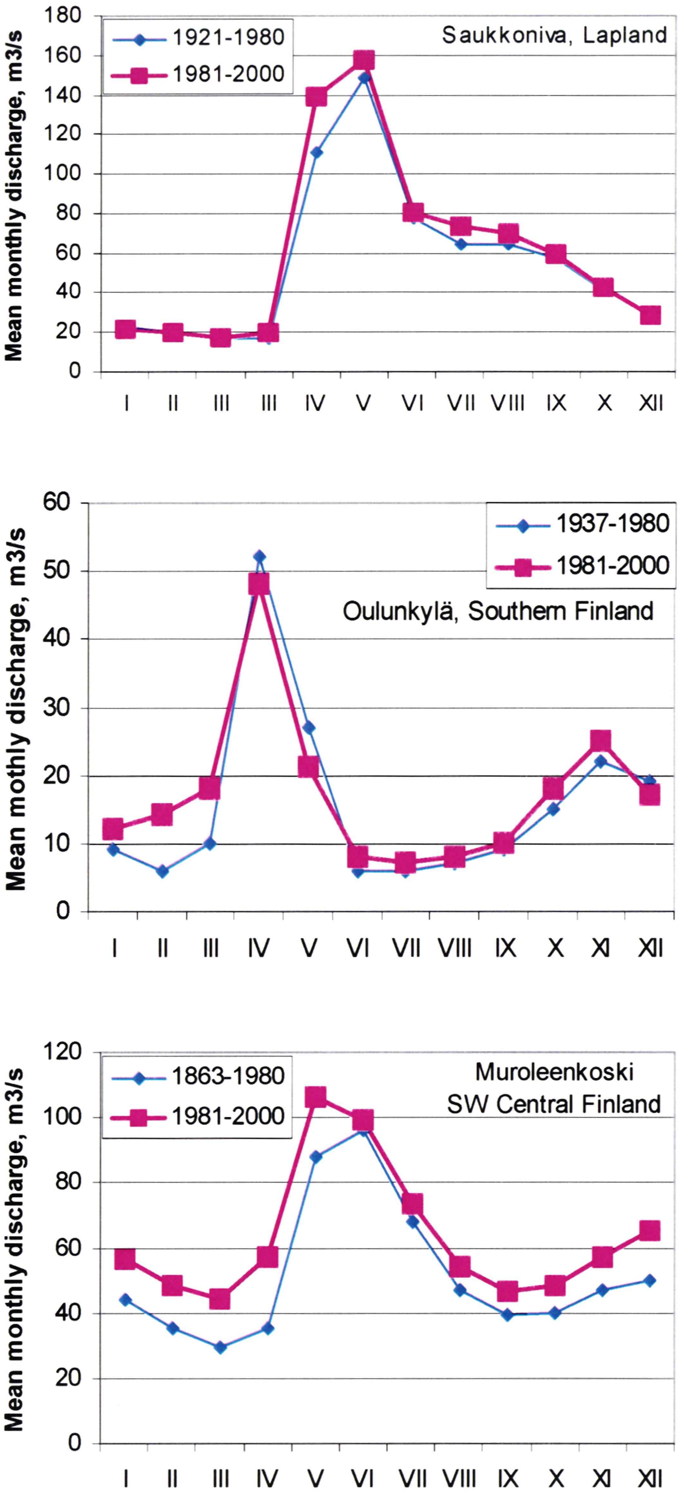

Figure 5. *Mean monthly streamflow in Saukkoniva (location: 68°55'N, 26°55'E, basin area: 5160 km^2, lake percentage: 4.7 %), in Muroleenkoski (location: 61°51'N, 23°54'E, basin area: 6102 km^2, lake percentage: 12.2 %) and in Oulunkylä (location: 60°14'N, 24°59'E, basin area: 1680 km^2, lake percentage 2.5 %).*

Precipitation and evaporation

As was indicated above, annual river flows have been increasing in many parts of Finland during the 20th century, possibly already during the second half of the 19th century. Has this been due to a simultaneous increase in precipitation and/or decrease in evaporation - if the minor influence of artificial reservoirs is neglected?

Although simple to ask, this is a rather difficult question to answer. Class A pan observation series for 1961-1990 show no clear trend (Järvinen and Kuusisto 1995). The 1980s were rather wet in Finland, which might have affected evaporation. Cloudiness has been increasing, which might have decreased evaporation slightly, although the annual mean air temperatures have simultaneously been increasing, by 0.5 to 1°C during the period 1901-1995 (Tuomenvirta and Heino 1996). During the 1990s, there were several very hot summers with rather high evaporation.

In any case, the changes in evaporation can hardly have been sufficient to explain the runoff increases. This suggests that precipitation must have been increasing. Heino (1994) corrected and analysed 36 long-term precipitation series from the rain gauge records of the Finnish Meteorological Institute. The longest precipitation series, Kuopio, began in 1884, although most series started at the beginning of the 20th century. In many series there is no visible trend, but a few stations in western Finland show an increase of up to 1 mm a^{-1}. The increase in annual precipitation at several stations is 0.5 mm a^{-1} during the 20th century. This seems to agree with the increase in runoff in some areas.

Trend analyses of areal precipitation series of the Hydrological Office (recently of SYKE) show slightly higher precipitation increases than the point series of Heino in many drainage basins, especially in southern and western Finland with an increase of up to 1 mm a^{-1} during the period 1911-1993 (Reuna, 1994).

The number of rain gauges increased during the observation period until about 1990. Especially the number of gauges in orographically higher sites increased during the observation period. This implies that the areal precipitation series of SYKE must be inhomogeneous to a certain extent. The rain gauge type was also changed in 1981. Precise analyses of the homogeneity of areal precipitation are not available. Therefore no examples of areal precipitation time series are presented in this section.

Snow cover

Increasing winter temperatures have intensified snowmelt in the middle of the winter in western and southern Finland towards the end of the observation period 1946-2001. This and the increasing rainfall in the middle of winter have decreased the snow cover in these areas (Table 1). In central Finland no trend is observed in the snow storage. In eastern and northern Finland, the maximum water equivalent of snow has been growing quite clearly.

The increase in the number of snow survey sites during the observation period causes some inhomogeneity in the existing snow cover time series – a matter that requires more detailed analyses. The snow survey method itself has remained unchanged throughout the whole observation period, and the changes in the calculation method of areal water equivalent of snow during the observation period do not have a marked effect.

Table 1. *Mean maximum water equivalents of snow (L_{max}) for some drainage basins in Finland in the periods 1961-1990 and 1991-2002.*

Drainage basin	L_{max} (mm) 1961-1990	L_{max} (mm) 1991-2002	Difference (%)
Vantaanjoki	109	76	-30
Kyrönjoki	92	69	-24
Vuoksi	146	155	+6
Oulujoki	162	188	+17
Kemijoki	175	205	+18
Paatsjoki	149	192	+29

Ice cover

Records of freezing and ice break-up dates started on Lakes Kallavesi and Näsijärvi in the 1830s, and on Lake Oulujärvi in the 1850s (Kuusisto, 1987). A shortening of the ice cover duration by 2-3 weeks has occurred on all these lakes, mainly between 1880 and 1940. No change has been observed in the last decades.

Kajander (1995) analysed the longest hydrological observation series in Finland, the date of ice break-up of the Tornio River, starting in 1693. It shows that in recent decades the break-up has occurred about two weeks earlier, on average, than during the first decades of the series. The air temperature in April and May has increased in this area during the period from which temperature records are available from Haparanda (1860 onwards).

No trend can be seen in the mean maximum thickness of lake ice in the Finnish Lake District for the period 1912-1992 (Kuusisto, 1994). Even in southern Finland, where air temperatures have been increasing during winter, the annual maximum of ice thickness has generally remained unchanged.

This is mainly due to the complex dynamics of the growth of the ice cover. In cold winters, especially if the snow cover on a lake is thin, the ice formed is mostly or totally blue ice, while in mild winters, often with heavy snowfall, the ice grows upwards as snow-ice.

Water temperature

In most Finnish observation sites, the temperature of surface water in lakes has not changed remarkably during the observation periods. In the southern part of the Lake Saimaa system, in Lauritsala, the temperature has slightly increased since 1924 (Korhonen, 2002). This may have led to increasing lake evaporation; however, no analyses are available of the trends of lake evaporation in Finland. Besides increased air temperature, one reason to rising water temperatures may have been the increased turbidity of water at the measuring site.

Groundwater level

The Finnish groundwater observation sites are mainly situated so that direct human impact in the water level is as low as possible. Soveri *et al.* (2001) analysed – together with several water quality variables – the groundwater level observation series from 53 stations in Finland, in most cases for the period 1975-1999. In some observation sites a seemingly regular fluctuation of groundwater level, with a period of five to seven years, was discovered. In most cases no clear trend was observed; furthermore the Finnish groundwater observation series are generally too short for reliable trend analyses.

3.2.3 Conclusions and further research

The hydrological changes and trends hitherto observed in Finland are mostly in line with the expected climate change effects on the hydrological conditions, for instance increasing winter flow in the south and increasing snow cover in the north. There are also some exceptions. For example the no-trend status in winter flow in Lapland agrees well with the observed air temperature in this area (Tuomenvirta *et al.,* 2001) but not so well with some global climate scenarios which predict strongly increasing temperatures especially in the north. In fact, air temperature decreased in Lapland during 1961-1990 but started to increase after this period.

It can also be concluded that a considerable amount of work is required in Finland for estimating the representativity of the existing areal precipitation series, areal snow water equivalent, possible changes in evapotranspiration and in groundfrost observation series etc. Even streamflow series need more investigation.

3.3 Iceland

Páll Jónsson, Hydrological Service, National Energy Authority, Iceland.

3.3.1 Introduction

The Hydrological Service (HS) of the National Energy Authority in Iceland was established in 1947 and that is the start of systematic measurements of water level and streamflow. Prior to the year 1947 there were some observations of water level and streamflow measurements made at different locations, but most of these were not systematic and can be difficult to take into account in the analysis of long time series. In the first four years of operation all the gauges were staff gauges with readings at the most once a day, but more frequently the readings were taken only once or twice a week, although an attempt was made to take further readings during flood events. In 1951 the first stilling well was established and that is the start of continuous recording of water level and runoff. Today the hydrometric network in Iceland operated by the HS consists of 194 gauging stations with continuous recording and more than half of the stations have been modernised with pressure transducers and electronic data recording. As a result of this rather short history of systematic hydrological measurements in Iceland, the study of long time series has not been systematic.

3.3.2 Data

As systematic measurements of water level and streamflow started in Iceland as late as 1947, there are only a few time series that are more than 50 years long with the longest "continuous" record being 70 years. Figure 6 gives an overview of the length of the times series of streamflow in Iceland. The total number of time series is 214, but this is not the complete picture since some of the time series may have gaps and some of the time series from the operation of hydropower stations are missing. The number of time series that can be analysed is therefore probably greater than shown in Figure 6, but the quality of the missing series is likely to be lower than for the time series shown.

Almost all the time series of streamflow have been "corrected" for ice problems and many are also "corrected" for missing data or other problems occurring at the gauging stations interfering with the measurements. In recent years many of the time series have been digitised and re-evaluated with modern techniques and in this process they have been quality checked. This project was initiated in 1993 in co-operation between the HS and the National Power Company (NPC) in Iceland. The program for re-evaluating old data with modern techniques has continued with the NPC and the National Energy Authority (NEA) in co-operation with a committee on evaluation of the hydropower potential in Iceland. The procedure for this re-evaluation and quality checking is now rather well established and consists of the following steps:

- all streamflow measurements are entered into the electronic database and recalculated using modern techniques;
- all water level data are digitised and entered into the database;
- the rating curves are re-evaluated and a report on the making of the rating curve is written;
- the water level data are re-evaluated and corrected for ice and other problems occurring during the data collection;
- all corrections to the data are documented and a report on the new data is written.

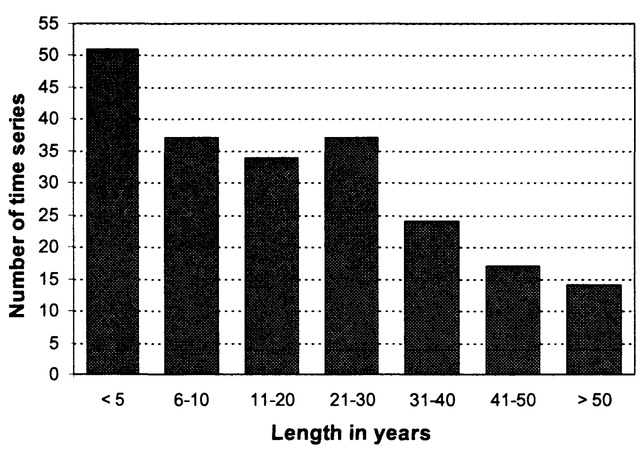

Figure 6. *The length of time series of streamflow in Iceland*

It is very important that the data are marked when they have been corrected, because the data are often used to calibrate a hydrological model of the river basin. In turn the model can be used to replace missing or corrected data to give a better evaluation of the streamflow. This feedback between measurements and models is very important in increasing the quality of both.

In 1984 a committee on the quality and use of streamflow series was established. The objectives were to quality control streamflow data and make as long time series as possible at different geographical positions in the country. The resulting series can be very mixed in the sense that they may be partly calculated from hydrological models based on meteorological data. This can be very useful since meteorological series tend to be longer than their hydrological counterparts and therefore can be used to make the streamflow series longer. Some of the time series are created applying regional analysis where data from one location are transferred to another using hydrological models. The main interest of the committee is to establish long series to be used by the hydropower industry in Iceland, but the series can of course also be used for other purposes. The committee thus serves as an important forum for the discussion on the homogeneity and quality of runoff data.

3.3.3 Summary of research

Some studies of the hydrological variability and its relation to different climatological factors have been undertaken on the long time series in Iceland. One example is a study on the relation of hydrological variables to meteorological variables derived from the height of the 500 mb pressure level above Iceland (Snorrasson, 1990).

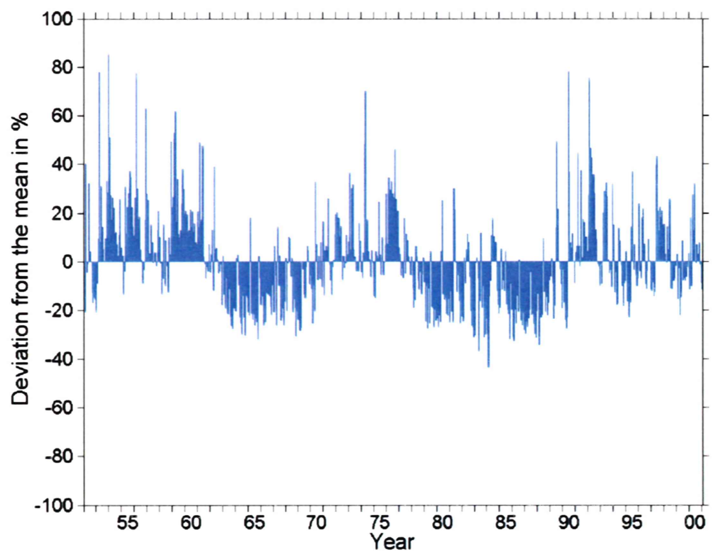

Figure 7. *Deviation of the monthly streamflow from the mean for the gauging station in Hvítá at Kljáfoss, 1952-2000*

Three 40 year long time series of runoff were studied. These time series are included in the database described in Section 2.2.1. In the study the deviation from the smoothed mean streamflow at each station was calculated and plotted as a function of time. Figure 7 shows as an updated example, the deviation of the monthly streamflow from the mean for the gauging station in Hvítá at Kljáfoss for the period 1952-2000. The series show periodical variations with approximately 20 year long periods (as can also be seen from the example in Figure 7). Similarly the strength of the westerly or southerly component of the average wind vector in the 500 mb pressure level was measured and the deviation from the smoothed mean was calculated. A comparison between the two variables was made and a very clear correlation was found. Periods of strong southerly component of the wind are related to periods of high runoff, whereas periods of weak southerly wind or rather strong northerly wind coincide with periods of rather low runoff.

3.3.4 Conclusions and further research

The Hydrological Service has undertaken systematic water level and streamflow measurements for 55 years. Therefore most of the available long time series in Iceland are shorter than 50 years. Some studies have been done on long time series in the past, in particular flood frequency analysis and correlation analysis with climate variables. Many of the time series have been quality checked and re-evaluated using modern techniques in recent years. There exist in Iceland, many long time series for other variables than runoff, some of them going back centuries. Many of these series, in particular the meteorological time series, are of good quality and also longer than the runoff series. However, some of the time series can only be characterised as proxy-data, but can still be very useful in research on climate change.

The Hydrological Service considers the project on Climate, Water and Energy as a great opportunity to systematically analyse and quality control long time series in Iceland and furthermore to develop methodology for time series analysis including flood frequency and regional analysis. In Iceland many types of floods occur e.g.:

- spring floods due to snowmelt;
- floods due to heavy precipitation;
- autumn and winter floods due to heavy rainfall and temperature increase during snow-cover conditions on frozen ground;
- glacial melting during summer;
- joekulhlaups (glacial outbursts) from dammed lagoons in the glacier or from volcanic eruptions under the glacier.

Therefore, a systematic study of flood types and of the seasonal occurrence of floods at each measuring site would be valuable.

3.3.5 Other variables

Although the Hydrological Service is mostly concerned with runoff and water level time series, there are other areas where one can find long time series that are useful for research on long term climatic variability. For Iceland these series can be put into different categories. Below is a list of some time series of alternative variables from Iceland that could be analysed in a long-term climate variability context.

Meteorological series
The Icelandic Meteorological Office (MO) was established in 1920 and thus has longer records of systematic measurements of meteorological parameters than the HS has of hydrological variables. There are still longer records of temperature measurements at some locations in Iceland, the longest continuous recording being the record from Stykkisholmur from around 1820. This series is used e.g. to calculate the North Atlantic Oscillation (NAO) Index.

Also other meteorological parameters have been measured for over 100 years but the quality of these measurements is not very good for the first years. Relevant time series are:

- precipitation from around 1850;
- cloud cover from around 1875;
- air pressure from around 1820;
- snow depth at Reykjavík from around 1920;

- ozone concentration in the atmosphere from around 1960.

Glaciological series

Terminus positions have been systematically measured from around 1940 and give very valuable information about the melting of glaciers in Iceland. Mass balance measurements have taken place for Hofsjökull since 1985 and for Vatnajökull and Langjökull from around 1990. Ice core drilling has been conducted in Bárðarbunga in Vatnajökull giving dating of ice layers back to around 1650, and in Hofsjökull giving precise dating back to 1970. These ice cores give valuable information on the total annual precipitation in the past.

Other series

Other time series can be considered for analysis of climate change. Some of them are partly continuous records whereas others can only be considered as proxy-data. Possible time series are:

- suspended sediment (measured systematically since around 1950);
- bedload measurements (conducted systematically at three locations for the last three years, otherwise spread);
- ice break up in three large lakes in Iceland (not systematic, but can give valuable information);
- sea ice distribution around Iceland (date very far back in time, but are not systematic);
- chemistry of Icelandic rivers (monitored and analysed since around 1970, but systematically only from around 1995).

3.4 Norway

Lars A. Roald, Norwegian Water Resources and Energy Directorate, Norway.

3.4.1 Introduction

Long-term time series are available for air temperature, precipitation, water levels in lakes and rivers and streamflow in Norway from the end of the 19th century or early 20th century at a number of sites. The meteorological time series are available as daily series on digital form since 1957, and back to the start of the observations as monthly and annual values. The water level and streamflow series are available as daily values since the start of the observations. Shorter series are available for other variables such as snow depth or water equivalent, water temperature, ice condition, groundwater levels, depth of frozen soil, sediment transport etc.

It is necessary to examine the homogeneity prior to a study of possible changes in a time series or a group of series. Nordli (1997) has examined the homogeneity of long-term temperature series, and Astrup (2000) has examined the homogeneity of most of the long-term Norwegian streamflow series. Based on the findings of such studies, it may be necessary to homogenise the time series prior to the analysis. Hanssen-Bauer and Førland (1994a) describe homogenisation of monthly Norwegian precipitation series.

3.4.2 Summary of research

Most of the Norwegian studies are based on regional methods. Hanssen-Bauer and Nordli (1998) divided Norway into 6 temperature regions based on 46 series as shown in Figure 8 (left). Regional index series were developed based on monthly mean temperatures for the period 1876-1997, and possible trends were examined. Hanssen-Bauer *et al.* (1995) and Hanssen-Bauer and Førland (1994b) divided Norway into 13 precipitation regions based on 78 series as also shown in Figure 8 (right). Regional index series were developed based on monthly precipitation sums for the period 1876-1997, and possible trends were examined. Roald *et al.* (2001) divided Norway into 13 runoff regions based on 84 daily streamflow records for the period 1924-1990, as shown in Figure 9. Regional index series were developed for each region. These studies have been summarised in Førland *et al.* (2000). The index series will be extended to include year 2001, and the runoff series will be extended back in time as long as there are some reliable data in each region. The revised index series will be reported in Roald (2003). Figure 10 shows long-term variability in the longest data series in eastern and western Norway.

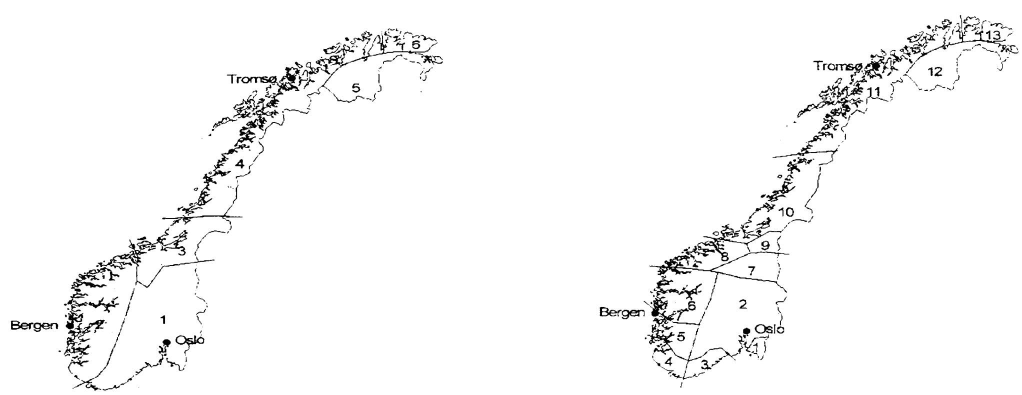

Figure 8. *The temperature regions (left) and the precipitation regions (right)*

Roald (1999) studied the long-term variability of annual floods based on daily streamflow values at 50 gauging stations as a part of the HYDRA research program. The analysis was based on single series, and examined the variability of the flood flow and the seasonal occurrence of each flood, expressed as the Julian date of the peak flood each year. The 1995-flood in Norway and the HYDRA program triggered also a systematic compilation of information of floods and other climate driven natural disasters from the databases as well as from historical sources. Roald (2002) has developed a chronology of such events, which will be utilised in further research.

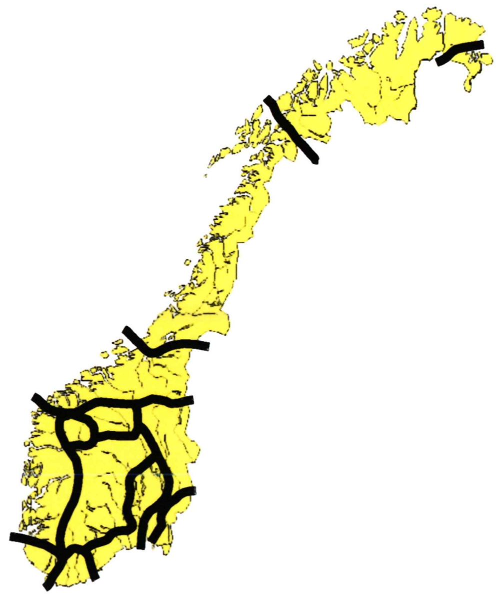

Figure 9. *The Norwegian runoff regions (Førland et al., 2000).*

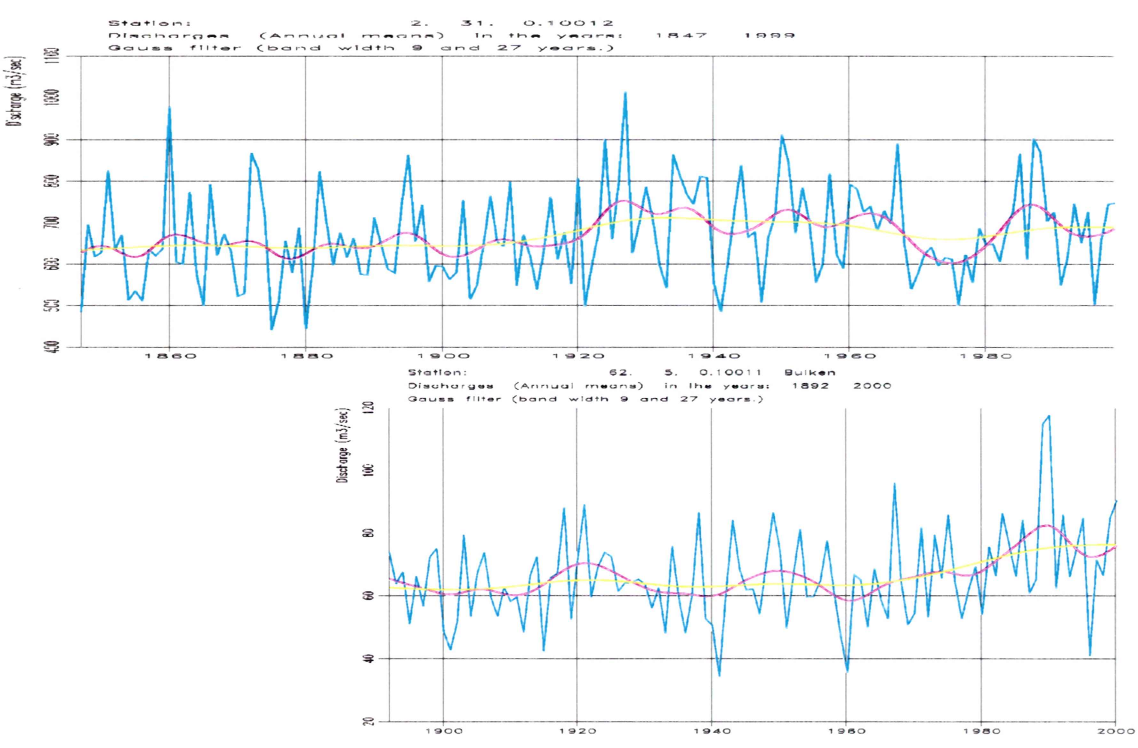

Figure 10. *Long-term variability of the annual mean streamflow in River Glomma in eastern Norway (upper) and River Vosso in western Norway (lower).*

3.4.3 Conclusions and further research

Annual temperatures have increased in all regions in Norway since 1876. The linear increase in annual temperature is between 0.04-0.08 °C per decade. The temperature has increased by 0.07-0.14 °C per decade in the spring. The summers have become significantly warmer in northern Norway, while the autumn has become warmer in southern and western Norway. The mean value 1980-99 has been higher than the 1961-90 normal in all parts of Norway in the winter as well as on annual basis. The summers and autumns have also had positive anomalies in most regions since 1980. The largest winter anomaly (>1 °C) has occurred in southeastern Norway and in Troms and Finnmark.

Annual precipitation has increased in all regions except "Sørlandet" since 1896. The linear increase is between 0.5 and 1.8% per decade, and is statistically significant in 6 of the 13 regions, and most pronounced in Nordland, Troms and parts of Trøndelag and Finnmark. The spring precipitation has increased more than 2.5% in region 10 and 11, and in region 13 in the summer. The precipitation has decreased at "Sørlandet" in the winter, spring and summer. The mean annual precipitation in 1980-1999 exceeded the 1961-1990 normal in all parts of Norway west and north of the mountain divide. The annual precipitation was 5 to 7% above the normal in western Norway, the winter precipitation has an excess of more than 25%.

The annual runoff has decreased from 1924 to 1975 and has increased to 1990 in southeastern Norway. The annual runoff was stable or slightly decreasing in western and central Norway until 1965, and has increased since. The annual runoff has increased in region 11 Troms and Finnmark from 1924 to 1970, and has been stable since then.

The spring runoff has increased in all regions, most markedly in the mountainous regions. The summer runoff has declined markedly in southeastern and central Norway (regions 1-4 and 7). Other regions have stable summer runoff, except the glacier region, which peaked in the warm 1930s. The autumn runoff has increased markedly in western Norway (regions 5 and 6), especially since 1960. Central Norway and Nordland (regions 7-10) have had a small increase, while southeastern Norway (regions 1-4) has had a small decrease. The winter runoff is stable or slightly decreasing in most regions.

No clear trends can be found in the annual flood series, except in basins which have been regulated during the observation period. Reservoirs will generally reduce the annual range, and appears in the records as systematic trends towards lower floods. Floods tend to cluster in periods over some years. The period 1927-1940 was rich in extremes, and another period started in 1987. Other periods have been identified in the 18th and 19th century from historical information and from direct observations in the second part of the 19th century (Roald, 2002). The date of the annual flood maximum varies considerable in coastal rivers, but is quite stable in alpine rivers and in the inland. Spring floods dominate some periods, while others are dominated by autumn floods, especially from Trøndelag to Lofoten.

Roald (2003) has found that coastal basins on the extreme western coast do not have any increase in the streamflow in the 1990s, as found inland in the coastal maximum rainfall zone. This is contrary to the climate scenarios, which indicate the largest increase on the extreme coast. This will be examined in the further studies. The year to year variability in streamflow and especially in the extremes is closely linked to dominating circulation patterns, and should be examined in future studies. An important data source for this work is the monthly circulation maps, which are available back to the late 18th century.

3.4.4 Other variables

Proxy series such as sediment cores have been used to study the occurrence of floods the last 4500 years (Nesje *et al.,* 2001). The summer temperature in eastern Norway has been reconstructed back to 1749 based on the harvesting date of crops (Nordli, 2001). The spring/summer temperature has been reconstructed back to 1734 for West Norway. This reconstruction has been used to evaluate changes in some glaciers, using the position of moraines as additional information (Norli *et al.*, 2002). Ice break-up data are available from Lake Randsfjord for the years 1769 to 1879. The maximum water equivalent of the snow is available each year at a number of sites back to at least the 1930s, and can serve as data for validating results of model simulations. Data can be added back to the start of the 20th century from a number of stations held at the Norwegian meteorological institute.

3.5 Sweden

Göran Lindström, Swedish Meteorological and Hydrological Institute, Sweden

3.5.1 Introduction

Recent years have been remarkable in Sweden. The year 2000 was the year with highest annual precipitation ever recorded, and two spectacular flood events took place. The prolonged summer storms in the central parts of the country caused flooding in the basins of Ljungan, Ljusnan and Dalälven among others. Continued rain in the autumn led to flood problems in Arvika in the southwestern part of the country. The water stage in Lake Vänern, the largest lake in Sweden, rose to an all time high level in January 2001. It was estimated that the water level would have been the highest ever recorded, with recordings dating back to 1807, if the lake would have remained unregulated. 1998 was the second rainiest year.

Systematic and comprehensive recordings of temperature and precipitation in Sweden started in 1860. There are a few temperature records that go even further back, most notably the ones from Uppsala (starting 1722), Stockholm (1756) and Göteborg (1807). The long series from Stockholm and Uppsala have been analysed in detail by Moberg (1996). Very few streamflow stations existed in the 19th century, but thereafter, and especially from around 1910, a better coverage is available. There are, however, three runoff series that extend well into the 19th century: the outlets of Lake Vänern (from 1807) and Lake Vättern (1858) and in river Dalälven at Fäggeby (1852).

3.5.2 Summary of research and main conclusions

Alexandersson and Eriksson (1989) studied climate fluctuations in Sweden since 1860, with data up to and including the year 1987. The three last years in the study were comparatively cold. The situation after that has been quite different. Alexandersson (2002) gave the most recent study of precipitation and temperature in Sweden. The study covers the period 1860-2001, and the country was subdivided into four regions. All together 29 temperature stations and 87 precipitation stations were included. The temperature was found to be 0.5-0.9 °C higher during 1926-2001 than during 1860-1925, with the largest increase in the northern part of the country. Annual precipitation increases were estimated to range from 7% in the south to 23 % in the north, when comparing the period 1921-2001 with 1860-1920. Spring temperature and winter precipitation showed particularly large increases.

The analysis of extreme precipitation amounts over 24 hours by Vedin and Eriksson (1988) was one of the corner stones in the Swedish national guidelines for determination of spillway design floods. This study has been updated continuously, and the most recent compilation was presented by Alexandersson and Vedin (2001a). They suggested that the frequency of extreme rainfall events has been fairly constant during the past 100 years, but that rather few events occurred in the 1960s and 1970s.

Air pressure observations are available from about 1870 at 15 stations. Based on this information, Alexandersson *et al.* (2000) and Alexandersson and Vedin (2001b) studied storm frequency. They concluded that storms did not occur more frequently now than before. Analysis of ice freeze and break-up dates indicate a slight shortening of the period with ice cover on Swedish lakes (Eklund, 1999).

Jutman (1991) and Lindström (1999 and 2002) have made recent studies of variations in water resources and flood frequency. Figure 11 summarises variations in runoff and floods in Sweden during the 20^{th} century. The conclusions from the most recent study (Lindström, 2002) were that runoff increased by some 4 % seen as an average over the whole country, but that the change was not statistically significant. The results from trend analyses depended very much on the chosen time period. The 1970s were dry, with an anomaly of -9 % compared to the whole century, and the 1920s, 1980s and 1990s were wet, with an anomaly of +8%. The three longest runoff series indicate that runoff was even higher during the 19^{th} century, but at lower temperatures (Figure 12). A remarkable feature of recent years is the combination of relatively high temperatures and high runoff in northern Sweden.

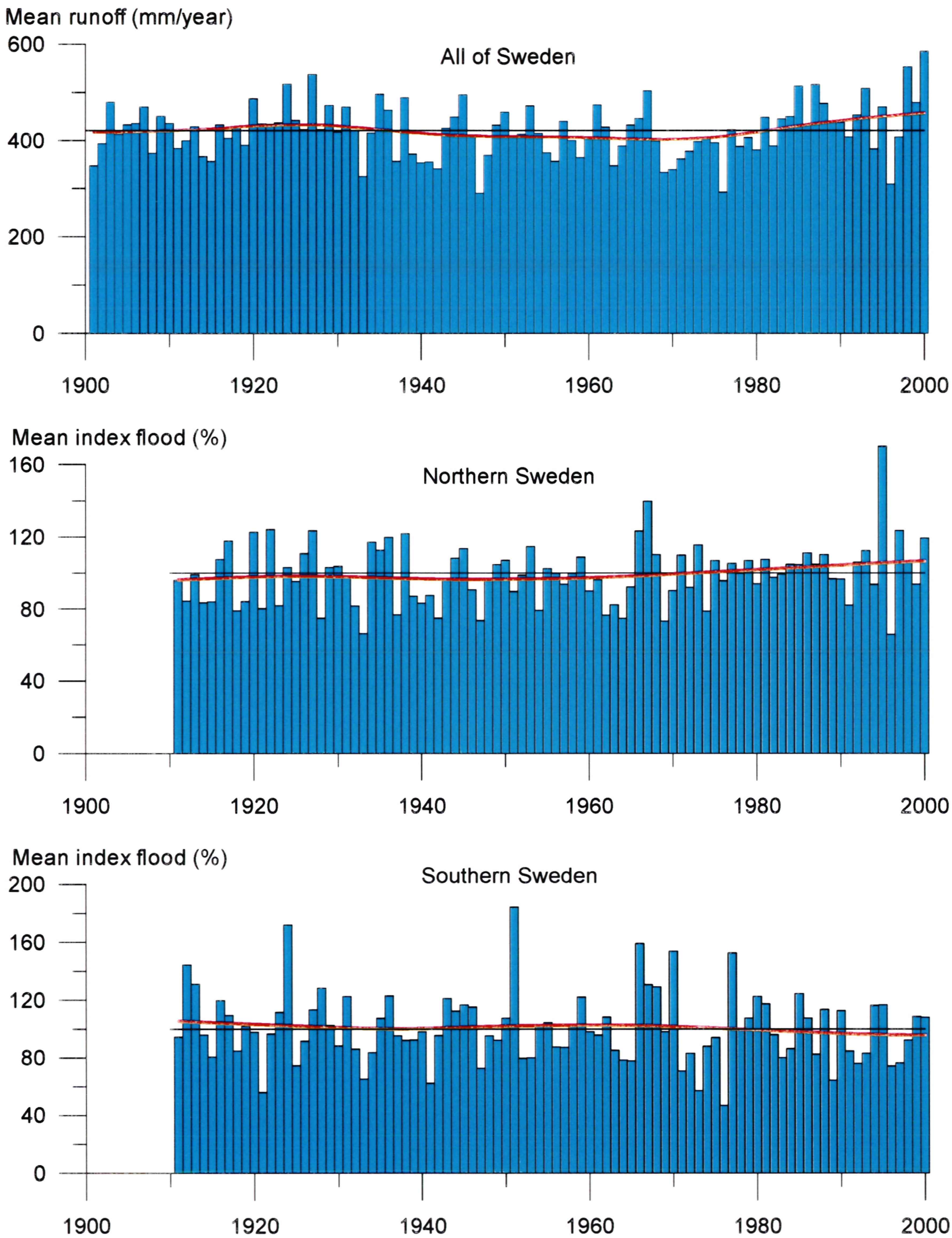

Figure 11. *Mean annual runoff from Sweden, 1901-2000, based on data from 15 large basins (top), and mean index floods for northern Sweden (middle), based on 28 series, and southern Sweden (bottom), based on 15 series. The period 1941-2000 was used as reference period for the index floods. The thick curves are Gauss-weighted averages over 30 years.*

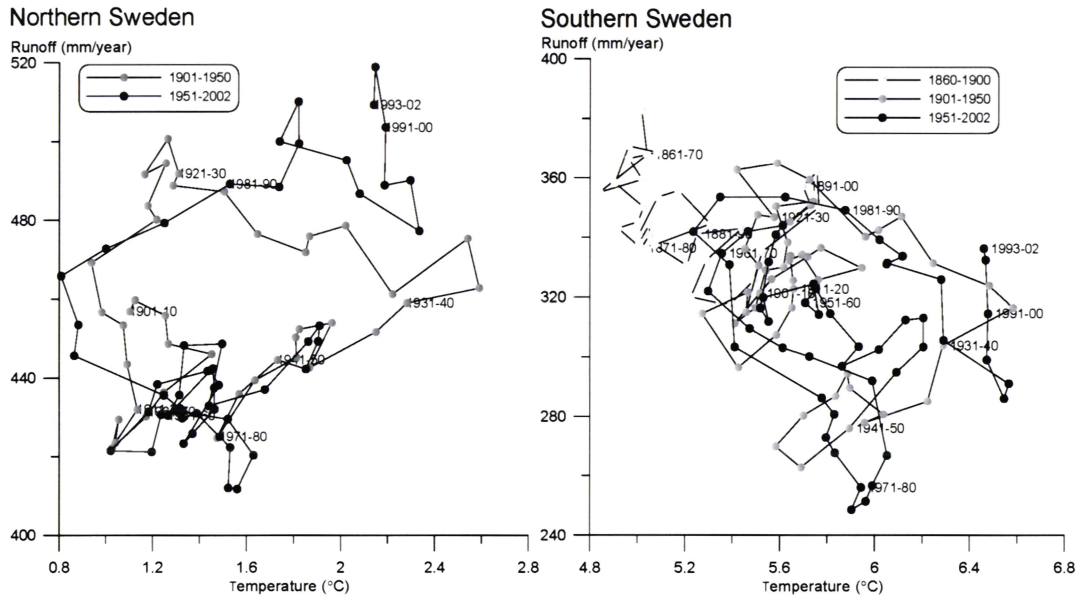

Figure 12. *Joint analysis of air temperature and runoff. Dots show moving averages over the last 10 years. The temperature is based on work by Alexandersson (2001).*

The recent surplus in runoff in northern Sweden primarily occurred during the spring flood (Figure 13), as an effect of increased snow accumulation associated with westerly winds. In the south, winter runoff was higher than earlier, in accordance with mild and wet winters, whereas summer runoff was lower than earlier in recent years (Figure 13).

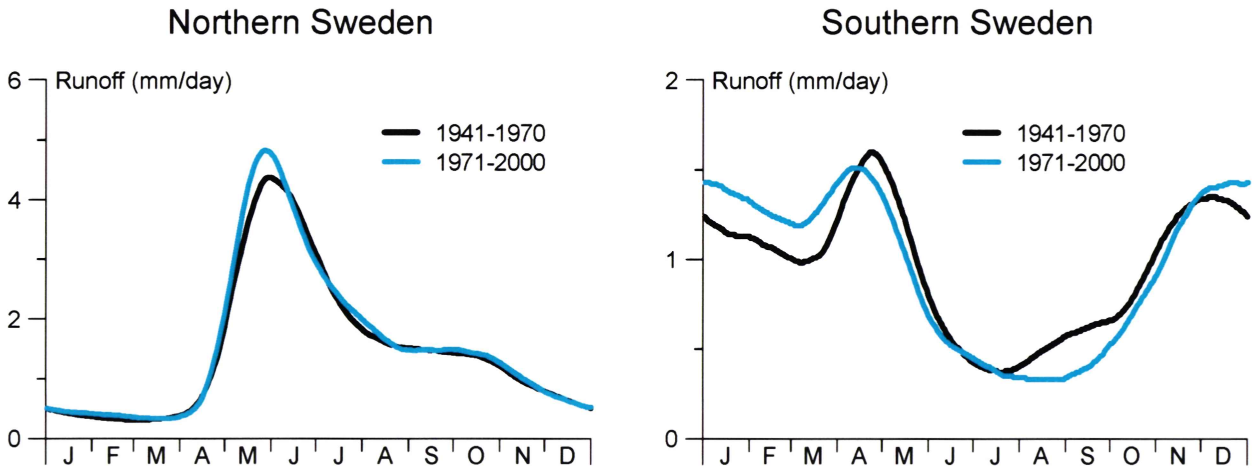

Figure 13. *Seasonal distribution of runoff in northern and southern Sweden, during 1941-1970 and 1971-2000.*

The increase in average flood level in northern Sweden was larger than the increase in annual runoff. Annual maximum floods increased with about 10 % over the 20th century. The analysis of flood peaks, however, suffers from uncertainties in the data. Flood peaks in old data were probably underestimated. The clearest increase was, thus, found in basins with the less reliable observations. Seen in a shorter perspective, autumn floods in northern Sweden increased considerably during the period 1970-2000. Similar autumn floods, were, however, experienced in the 1920s. Flood levels in the southern part of the country decreased slightly.

3.5.3 Ongoing projects and recommendations for further research

As a final contribution to the Swedish regional climate modelling programme, SWECLIM, the subproject DETECT has been initiated. The aim of this project is to compare recent mild and wet years with the changes suggested by climate scenarios. In addition, further attention should be paid to joint analysis of precipitation, temperature and runoff, since the observed increase in precipitation records from the 20th century is much stronger than that in runoff. A particular problem here is homogeneity and changes in observation methodology, for instance the introduction of wind shields for rain gauges, and the increased observation frequency in runoff.

3.5.4 Other variables

There are other long records that can be used as indicators of climatic variation, such as ice freeze and break-up dates, snow cover days, tree rings and historical flood marks. Ice break-up has been recorded in Lake Mälaren since 1712, and similar information is available from nine lakes in northern Sweden, starting at about 1870. Snow cover observations exist from 1900. Tree rings have been analysed for Torne Träsk, dating back to 500 BC, and Blaikfjället.

4 POSSIBLE CONSEQUENCES FOR THE HYDROPOWER SYSTEM

Erik Holmqvist, Norwegian water Resources and energy Directorate, Norway

4.1 Introduction

The total hydropower production will of course be affected by changes in total runoff, and in addition by changes in the seasonal distribution of runoff. A temperature rise will to some extent influence the energy demand according to the season and the region. This will cause changes in the operation of the reservoirs, which may have consequences for ecology and recreational use of the reservoirs and the river downstream.

In addition flood risks and dam safety will be affected by climate change. However, the present procedures for calculation of design floods for the Nordic hydroelectric system are based on the assumption that the climate is stable.

4.2 Power production

In addition to the volume changes in inflow, the production will be affected by changes in the seasonal distribution of the inflow. Increased winter inflow will allow more reservoir capacity to be used for flood attenuation, thus reducing spillage and increasing both winter and total production.

Weighted by the regional hydropower production, according to Sælthun *et al.* (1998) the overall change of inflow in Finland, Sweden and Norway will be + 2 % over 30 years and + 6 % over 100 years. This is based on an assumption of a temperature increase of about 0.4 °C/ 10 years and an increased precipitation of 1.5 – 2 %/ 10 years (Table 1). The 30 years scenario used will cause a total increase in hydropower production of 2.5 %. The expected change in seasonal distribution accounts for one fifth due to reduced spillage. The largest uncertainty in this simulation is connected to the estimates for northern Sweden. This region represents nearly one third of the total production, and the climate gradients are large in this area. Moreover, the representation of the Scandinavian energy system is unbalanced in the simulation, as 570 hydropower plant modules represent Norway, while Sweden is represented by two modules and Finland only by one.

A climate change might increase the variability in runoff, however this topic is less studied. An increased variability might increase the risk of dry spells in spite of the expected increase of the annual average runoff. For a power system highly influenced by hydropower, as in the Scandinavian countries, this might cause great challenges.

Table 2. *Inflow statistics and estimated inflow changes (Sælthun et al., 1998).*

Module	Inflow TWh/year	Estimated change %	
	Total	+ 30 yrs	+ 100 yrs
Glomma	10.6	+1	+4
Norway East (except Glomma)	26.6	+2	+5
Norway South	16.4	+2	+5
Norway South West	15.5	+5	+15
Norway Central	11.4	+5	+15
Helgeland	12.3	+3	+8
Troms	7.4	+4	+10
Finnmark	2.0	0	-1
Sweden North	51.6	+1	+4
Sweden South	13.4	-2	-5
Finland	12.6	0	0
Total	198.1	2	6

4.3 Electricity consumption

For the Nordic countries empirical models are used to study the impacts of climate change on the electricity demand (Sælthun *et al.*, 1998). These models mainly concentrate on temperature, although other factors such as sunshine, humidity, wind and precipitation also have an effect. A temperature rise of 1 – 1.5 °C within 30 years is expected to reduce the energy consumption from 1 to 3 % in the Nordic countries. Compared with other changes in the electricity demand over time, these effects are marginal.

The capacity savings, however, will be more significant, since the peak demand as well as the greatest temperature rise occur in the heating season during the wintertime.

4.4 Reservoirs

A reservoir operation strategy will aim at maximising the value of the energy produced. Generally, this is accomplished by maximising the energy production in the high demand season, and by minimising the spillage.

At present, the pattern of operation of many reservoirs is as follows; empty in late winter, rapid filling during the spring flood, high in the summer and nearly full in the autumn. As a general rule, summer and autumn levels may become lower and winter levels higher. This may have consequences for the recreational use of the reservoirs and for ecological aspects as fish production in the reservoirs.

Changes in operation of the reservoirs and the seasonal change of production of energy will have an influence on the rivers downstream. Increased inflow to reservoirs and higher energy production during winter will of course increase streamflow in rivers downstream. This might have an influence on the ice conditions in the river, as increased streamflow will favour frazil and bottom ice production. On the other hand, an increased winter temperature will decrease the ice cover season, and most coastal rivers and lakes will normally lack a stable ice cover. In inland areas more unstable ice conditions and higher frequencies of winter ice jams can be expected (Sælthun *et al.,* 1990).

4.5 Flood risk and dam safety

Skaugen *et al.* (2002) studied changes of extreme precipitation in Norway caused by climate change. Totally 16 different stations, representing different climatic regions, were analysed. Based on downscaled precipitation values from the global model of the Max Planck Institute in Hamburg, time series of twenty years were generated to describe the current climate of 1980-99 and the future climate of 2030 – 2049. These time series serve as training data for a precipitation simulation model, the Randomised Bartlett-Lewis Rectangular Pulse Model, and time series of thousand years were generated to assess possible changes in the extreme precipitation due to climate change. The general results showed that the extreme values and the seasonal variability would increase. For a major part of the stations the mean annual maximum precipitation increases with 10 – 30 %. For the 1000-year one-day event, most of the annual values increase with 10 – 100 %. However, there are some stations with more or less unchanged or reduced extreme values as well.

Flood characteristics are not only influenced by precipitation. The soil moisture content, which is strongly affected by evapotranspiration, is another factor. Further, in high latitude and mountain areas the snow regime is of great importance. All these components are influenced by climate change. The influence of snow is twofold. Snowmelt floods are a combined effect of winter precipitation accumulation and meteorological conditions during the melting season. The overall effect of a climate change is expected to be reduced spring floods. Reductions in the length of the period with snowfall and snow covered ground, increase the length of the rain flood season. This will give an increase in the combined rain and melt floods during the autumn and the winter.

In order to obtain a description of the hydrological changes, flood statistics simulations for 25 Nordic basins were carried out (Sælthun *et al.,* 1998). The base line was the period 1961 to 1990, and simulations were carried out for the base line + 30 years and the base line + 100 years. It is important to stress that the number of precipitation days and the seasonal variation were kept unchanged. All precipitation amounts were adjusted with the same factor; thus the precipitation extremes were changed with the same ratio as the average precipitation. The results showed that the annual mean flood generally will increase in areas with dominating autumn floods and reduce in areas dominated by spring floods. One exception to this pattern was Jökulsa in Iceland, where the large glaciated areas gave increased spring floods. For some basins at the western and northern coast of Norway the annual mean floods increased with 40 – 50 % within 100 years. For example at Bulken, Vosso at the west coast of Norway, the estimated mean flood within 100 years was approximately of the same size as the present 20-year flood.

When it comes to dam safety, the following questions are important:
- How will the flood risk change?
- Will procedures for design flood estimation reflect the actual flood risk changes?
- How is the total dam safety situation affected? (Both a product of the design flood, the operation of the reservoir and timing of critical reservoir stage conditions with critical flooding season.)

The main challenge for flood risk and dam safety is that all estimates are based on historical series. In a changing climate a traditional statistical flood frequency analysis breaks down, as one of the central assumptions, that of stationary statistical properties, is invalid.

5 CONCLUSIONS AND FURTHER RESEARCH

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This report summarises recent studies of changes in climatological and hydrological time series in the Nordic region and for the individual Nordic countries. Such studies are important to improve understanding of natural variability and to detect climate change signals. The Nordic study described in Chapter 2 revealed regional differences in streamflow trends for the time period 1930-80. Focus was on annual and seasonal data. A qualitative comparison with studies carried out in the individual Nordic countries gave a good correspondence, as did a comparison with changes in precipitation. Further studies of the link between changes in streamflow and precipitation and temperature made clear the importance of selecting representative precipitation stations.

The national studies vary both regarding the period and variables analysed. Most studies focus on annual and seasonal values, less attention is given to extremes, especially droughts. The link to the energy sector is generally missing. To make a qualitative estimate of regional differences in the changes found, comparison between the national studies is possible. However, the results would be uncertain due to the various time periods analysed. Hence, 'pan-Nordic' studies identifying larger scale regional differences in streamflow in terms of non-stationarity and climate variability are lacking, especially with a focus on extremes and possible consequences for the energy sector.

Possible consequences of a climate change for the hydropower system are described in Chapter 4. A change in hydrological conditions might affect e.g. the power production potential itself, how the reservoirs can and should be operated as well as flood risk and dam safety. It is of vital importance for the society that these aspects are further studied.

The results of a study of non-stationarity, as trends, will depend on the period of the available time series and the region under study. To study regional differences in changes in streamflow it is a key issue to maintain a hydrological database of high quality data from all over the Nordic countries. To get a good spatial resolution a reasonable and common time period should be selected. However, as long time series as possible are important to study long term variability. It is especially important to link changes in hydrological parameters to changes in temperature, precipitation and other climate variables. Therefore, if possible, climate variables should also be included in the database.

Climate and streamflow records are long enough to document changes at inter-annual time-scales, such as variability caused by e.g. NAO fluctuations. Our knowledge of changes for longer periods, as decadal- to century-scale, depends largely on analyses of proxy-data. Very few such studies exist for Nordic locations and should therefore be encouraged. The use of proxy data is uncertain, but the results when different proxy data are compared and analysed regionally are often trustworthy.

Stationarity of a time series implies no trends, shifts or periodicity. This means that the moments of a distribution remain constant through time and hence, is a prerequisite for frequency analysis of extremes as floods and droughts. Non-stationarity may occur as a result of global climate change. Under non-stationary conditions the uncertainty related to dimensioning of different types of reservoirs will increase. If trends or sudden jumps are revealed, it is important to study how to incorporate this in the extreme value analysis. One method would be to keep the traditional frequency distribution, but to incorporate time-dependent parameters. Another option is to assume that climate change eventually will lead to a new climate regime under stationary conditions. Hence, based on time series of streamflow scenarios return levels of floods and droughts could be estimated under a changed climate.

To summarise, further Nordic research is needed and should focus on:
- establishing a database of long time series including climate, hydrological and proxy data. The importance of including data covering the whole Nordic region with a common time period should be stressed;
- carrying out trend studies especially focussing on trends in floods and droughts;
- studying changes in streamflow variability;
- linking the changes in streamflow to changes in precipitation and temperature;
- studying proxy series;
- studying changes in flood and drought frequencies by a) application and development of methods that take non-stationarity in streamflow into account and b) application of established methods on streamflow scenarios;
- studying implications of changes on the hydropower sector.

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APPENDIX 1 Applied Statistical Methods

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Data quality control

The purpose of the described studies was primarily to identify climate driven changes in long-term time series. There are, however, many other reasons for changes in the homogeneity. For example, changes in the monitoring practices, by introducing new instruments or changes in the frequency of the observations, can introduce systematic shifts in the observed series.

- Temperature series can be affected by changes in the shielding of the instrument, use of unreliably max. -min. thermometers in the early years of the series and of the heat-island effect generated by urbanisation around the gauging station.
- Precipitation series can be affected by changes in the exposure of the station i.e. by growing trees or new buildings, by introduction of a shield to reduce the wind losses or by introduction of alternative types of instruments.
- Streamflow series are crucially dependent on the quality of the rating curve. The use of the rating curve is based on the assumption of a stable relationship between water level and streamflow. This relationship will be distorted by shifts in the controlling section of a gauging station that will cause heterogeneity. The streamflow series can also be affected by hydropower regulations, diversion of water for other purposes, or changes in the land use of the upstream basin.

Changes may appear as gradual trends or as sudden jumps regardless of the cause, and requires careful examination to identify the causes of the change. The change may affect the annual values, the seasonality of the time series or the extreme values.

It is often necessary to homogenise time series prior to tests for trends to remove changes caused by other factors than climate variability. Information of the station history plays a crucial role in this work together with other time series within the adjacent region. Hansen-Bauer and Førland (1994) and Alexandersson (2001) describe homogenisation of climate data.

It is also necessary to calculate natural streamflow in series, which are fully or partially affected by hydropower regulation or storage or abstraction of water for other purposes. A reservoir will change the seasonal pattern of the streamflow, but will normally not change the annual values. Series with reservoirs, but without diversions in or out of the basin can be analysed without any correction for annual values, unless one or more of the reservoirs is operated multi-annually. It is absolutely necessary to correct the series in case of diversions. These corrections are usually done with daily data, and are based on the equation of continuity. Floods, and even more low-flows calculated this way tend to be unreliable, and must be used with care. The corrected series will normally represent seasonal means quite well.

Methods of analyses

Analysis of changes in the behaviour of long term time series are done by analysing individual time series (at-site analysis) or by analysing the average behaviour of a group of time series with similar temporal patterns (regional analysis). In the latter case many studies are based on the development of index series with a long-term variability typical for a region. The individual series within a region may vary in magnitude, and it is necessary to apply some scaling on each series to obtain comparable series, which can be pooled together. The scaling of each individual series is based on some moments of the series calculated for a standard period.

The standardised mean streamflow, $SQ_{m,i}$, or precipitation sum, $SP_{m,i}$, at the i^{th} station in region m is often defined by dividing each year of observed streamflow ($Q_{m,i}$) or precipitation ($P_{m,i}$) by the mean of the series ($QM_{m,i}$ or $PM_{m,i}$) for the standard period as follows:

$$SQ_{m,i} = \frac{Q_{m,i}}{QM_{m,i}},$$

$$SP_{m,i} = \frac{P_{m,i}}{PM_{m,i}}$$

For temperature it is common that each year of the i^{th} station in region m ($T_{m,i}$) is standardised by the standard deviation ($STDT_{m,i}$) and the mean ($TM_{m,i}$) for the standard period. The standardised temperature is then:

$$ST_{m,i} = \frac{\left(T_{m,i} - TM_{m,i}\right)}{STDT_{m,i}}$$

The pooled series can then be calculated as the average of the standardised series for each year in the current group or region. The homogeneity of an index series can be examined using the same methods as for single series.

Methods for identifying groups or regions

Homogenous groups or regions can be identified by statistical methods such as cluster analysis or principal component analysis (Hansen-Bauer *et al.*, 1996). The classification can be based on runoff statistics, climatic statistics or physiographic basin characteristics. A set of stations can alternatively be divided into geographical regions without use of statistical methods. These groups tend however to be less homogeneous than groups determined by statistical methods. Methods for testing the homogeneity of each group, as well as testing whether two groups differ significantly, has been developed by Wiltshire (1986), and has been developed further by Hosking and Wallis (1997).

Tests for trends or jumps

The same type of trend and jump tests can be applied for both at-site and regional series. Various methods for detection of changes in hydrological data are described in Kundzewicz and Robson (2000). In several of the studies described in this report both parametric and non-parametric trend tests were applied. For example in the Nordic study described in Chapter 2 and the streamflow trend analysis from Sweden described in Section 3.5, the series were tested for trends by fitting a linear trend equation and examining the significance of the trend by the Student–t test (parametric), and by the Mann-Kendall test (non-parametric) both described in Salas (1993).

In the Danish study described in Section 3.1, trends in precipitation, temperature and streamflow variables such as annual average, annual maximum and annual minimum streamflow were tested and estimated again using both parametric and non-parametric statistical methods. The parametric method is based on the paper by Bloomfield and Nychka (1992). This paper describes a statistical method in which the trend is assumed to be linear and estimated by the use of the least square method. The standard error of the trend estimate is estimated by applying spectral analysis to the residual process, which is assumed to be an autoregressive process of order p. The order of the autoregressive process was estimated using Akaike's information criterion (Akaike, 1974) and the parameters of the process were estimated by using the method in Burg (1967). A statistical test of the significance of the trend is calculated by the ratio of the trend estimate and the standard error of the estimate. Finally, a confidence interval for the trend estimate is calculated using Student's t-distribution. The non-parametric method is based on calculations of Kendall's tau (Kendall, 1975; Hirsch *et al.*, 1982). This method test for monotone trends, and this is a more general hypothesis and includes the hypothesis of a linear trend. Non-parametric estimates of the trends were calculated by applying the Theil-Sen slope estimator (Theil, 1950; Sen, 1968). Confidence intervals for the non-parametric trend estimates were calculated using the method described in Gilbert (1987).

The tests for jumps in series are based on split sample techniques. Schumann (1994) has developed a program for testing long-term time series for possible jumps based on a stepwise procedure:

1. The Mann-Whitney-Wilcoxon (rank) test
2. A ζ^2-test on the distribution of each series (to verify that the series is normally- or log normally distributed)
3. A Fisher F-test (to examine if the variance differs in each subset of the series)
4. A two-way Student T-test (to examine if the means of each subset differs significantly)

Test 2-4 are only applied if the Mann-Wilcoxon test indicates a jump in one or more years. Test 3 and 4 applies only to normally or log-normally distributed data. A summary of the tests can be found in Markovitch (1975). This test was applied for the study described in Cahpter 2.

Hubert et al. (1989) has developed an alternative segmentation test, which also has been applied to Nordic data series as has the Pettitt- test (Pettitt, 1979).

An alternative way of identifying jumps in data series is to analyse jointly two or more series. This is a common procedure in most operational homogeneity testing. Doublemass analysis is a very popular technique. Alexandersson (1986) has developed a test on the significance of jumps identified by this method.

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APPENDIX 2 Long term streamflow records

Classification:

D: Data suitable for analysis of daily values, also extremes, as well as monthly and annual averages.

M: Data suitable for analysis of monthly and annual values.

A: Data suitable for analysis of annual values, only.

Stations in Denmark.

FRIEND-number	Name	River	Natl. number	Basin area (km^2)	From	To	Classi-fication
0401010	Alstedbro	Uggerby å	03.01	153.0	1917	2002	D
0401011	Elkær bro	Lindeborg å	07.01	104.0	1918	2002	D
0401012	Arup	Arup å	11.02	108.0	1936	2002	D
0401002	Lindenborg bro	Lindenborg å	14.01	214.0	1925	2002	D
0401014	Tvilum bro	Gudenå	21.01	1282.0	1917	2002	D
0401006	Asted bro	Gudenå	21.02	185.0	1917	2002	D
0402008	Alergård	Skjern å	25.05	1061.0	1920	2002	D
0401004	Skibby	Århus å	26.01	119.0	1919	2002	D
NEW	Fulden	Giber å	27.04	47.0	1960	2002	D
NEW	Bredstrup	Spang å	33.02	65.0	1954	2002	D
0402013	Stavnanger	Ribe å	38.01	675.0	1933	2002	D
0402006	Bredebro	Brede å	40.01	292.0	1921	2002	D
NEW	Rørkær	Grønå	42.34	563.0	1959	2002	D
0402004	Nr Broby	Odense å	45.01	302.0	1917	2002	D
0402014	Årup	Brende å	46.01	71.0	1918	2002	D
NEW	Lindebjerg	Græse å	52.07	25.0	1946	2002	D
NEW	Strø	Havelse å	52.08	102.0	1947	2002	D
0403006	Bromølle	Åmose å	55.01	291.0	1920	2002	D
0403005	Kramsvad	Harrested å	56.02	16.0	1921	2002	D

Table cont.

FRIEND-number	Name	River	Natl. number	Basin (km2)	From	To	Classifi-cation
0403011	Ørslev	Tude å	56.06	148.0	1932	2002	D
0403004	Grønbro	Saltø å	57.01	63.8	1918	2002	D
0403012	Holløse mølle	Suså	57.02	756.0	1934	2002	D
NEW	LL Svenstrup	Ringsted å	57.08	195.0	1957	2002	D
NEW	Kimmerslev	Kimmerslev Møllebæk	58.06	19.0	1961	2002	D
0403003	LL Linde	Tryggevælde	59.01	130.0	1917	2002	D
0403014	Hasle Klinker	Baggeå	66.01	42.0	1922	2002	D

Stations in Iceland

FRIEND-number	Name	River	Natl. number	Basin area (km^2)	From	To	Classi-fication
	Elliðaárstöð	Elliðaár	1	272	1929	2001	M
	Reykjafoss	Svartá í Skagafirði	10	392.9	1933	2001	D
	Dynjandi	Dynjandisá	19	42.8	1957	2001	D
	Smjörhóll	Smjörhólsá	22	102.7	1945	2001	D
	Birningsstaðasog	Laxá í Aðaldal	32	1547.1	1948	2001	D
	Dynjandi	Brúará	43	596.3	1949	2001	D
	Forsæludalur	Vatnsdalsá	45	487.3	1949	2001	D
	Goðafoss	Skjálfandafljót	50	3306	1950	2001	D
	brú, Viðvíkursveit	Hjaltadalsá	51	303.2	1957	2001	D
	Árbæjarfoss	Ytri-Rangá	59	572.1	1960	2001	D
	Selfoss	Ölfusá	64	5678	1951	2001	D
	Kljáfoss	Hvítá í Borgarfirði	66	1669	1952	2001	D
	Faxi	Tungufljót	68	197.9	1952	2001	D
	Keldnaholt	Korpa	81	44.1	1957	2001	D

Stations in Finland

FRIEND-number	Name	River	Natl. number	Basin area (km^2)	From	To	Classi-fication
	Lylykoski	Vuoksi	0402420	4183	1936		D
	Konnus+Karvio	Vuoksi	0408087	16270	1931		A
	Tainionkoski	Vuoksi	0411450	61061	1847		A
	Huopanankoski	Kymijoki	1400900	2186	1910		A
	Äyskoski	Kymijoki	1402900	2157	1896		D
	Tainionvirta	Kymijoki	1405700	1421	1910		D
	Ripatinkoski	Kymijoki	1407830	3510	1939		D
	Anjala	Kymijoki	1410050	36275	1938		A
	Oulunkylä	Vantaa	2101700	1680	1937		D
	Halinen	Aurajoki	2800700	730	1938		D
	Kituskoski	Kokemäenjoki	3504800	546	1911		D
	Muroleenkoski	Kokemäenjoki	3506200	6102	1863		D
	Maurialankoski	Kokemäenjoki	3509410	2652	1931		D
	Harjavalta	Kokemäenjoki	3510450	26117	1931		A
	Lansorsund	Kyrönjoki	4201000	4833	1911		A
	Keppo	Lapuanjoki	4400610	3949	1931		A
	Niskakoski	Kalajoki	5300740	3065	1911		A
	Tolpankoski	Pyhäjoki	5400410	3408	1912		A
	Lammasjärvi	Oulujoki	5901900	3444	1901		D

Table cont.

FRIEND-number	Name	River	Natl. number	Basin area (km^2)	From	To	Classi-fication
	Jylhämä	Oulujoki	5903450	19839	1896		A
	Haukipudas	Kiiminginjoki	6000410	3814	1911		D
	Raasakka	Iijoki	6101950	14191	1911		A
	Simo	Simojoki	6400410	3109	1911		D
	Kummaniva	Kemijoki	6501700	8538	1921		D
	Marraskoski	Kemijoki	6503600	12303	1919		D
	Isohaara	Kemijoki	6504450	50683	1911		A
	Muonio	Tornionjoki	6700800	9259	1938		D
	Karunki	Tornionjoki	6702200	bif.	1911		D
	Onnelansuvanto	Teno	6801000	10864	1962		D
	Saukkoniva	Paatsjoki	7100800	5160	1921		D
	Kaitakoski	Paatsjoki	7101950	14575	1947		A

Stations in Sweden

FRIEND-number	Name	River	Natl. number	Basin area (km^2)	From	To	Classi-fication
	Kukkolankoski Övre	1	16722	33930	1911	2000	D
	Junosuando Tornegr.	1	50002	4351	1939	2000	M
	Torneträsk	1	50145	3346	1918	2000	M
	Kallio	1	50148	14477	1911	2000	M
	Räktfors	4	17	23103	1937	2000	D
	Niemisel	7	20	3781	1938	2000	D
	Ytterholmen	7	1123	1012	1924	2000	M
	Niavve	9	591	1718	1936	2000	M
	Sikfors krv [R)]	13	1788	10816	1928	2000	M
	Vindeln	28	50023	11851	1911	2000	M
	Sorsele	28	50131	6056	1910	2000	D
	Laisan	28	50149	1774	1911	2000	M
	Överstjuktan	28	50130	418	1911	2000	M
	Solberg	28	436	1081	1911	2000	D
	Torrböle	30	50107	2860	1915	2000	M
	Anundsjön	36	50027	1465	1923	2000	D
	Solbergsvattnet	40	50068	2428	1924	2000	M
	Rengen	40	1341	1110	1937	2000	D
	Fångåmon	40	50062	164	1941	2000	M

Table cont.

FRIEND-number	Name	River	Natl. number	Basin (km^2)	From	To	Classification
	Öster-Noren	40	50058	2384	1901	2000	M
	Medstugusjön	40	50059	224	1921	2000	M
	Äcklingen	40	1309	156	1939	2000	D
	Gimdalsby	42	97	2164	1932	2000	M
	Hasselasjön	44	50109	651	1919	2000	M
	Ljusnedal Övre	48	1169	340	1925	2000	D
	Tänndalen	48	1223	227	1929	2000	M
	Ersbo	53	654	1104	1912	2000	D
	Fulunäs	53	655	883	1913	2000	M
	Fäggeby	53	50079	25058	1852	2000	A
	Vattholma	61	50110	294	1917	2000	M
	Hammarby [R)]	61	50115	891	1910	2000	M
	Övre Hyndevad	61	138	4044	1889	2000	A
	Vättern	67	50085	6383	1858	2000	A
	Nömmen	74	50090	157	1910	2000	M
	Getebro	75	855	1333	1920	2000	D
	Källstorp	77	50091	342	1922	2000	M
	Hålabäck	86/87	736	5	1928	2000	M

Table cont.

FRIEND-number	Name	River	Natl. number	Basin area (km^2)	From	To	Classification
	Torsebro R)	88	2191	3665	1908	2000	D
	Möckeln	88	1069	1026	1922	2000	M
	Rörvik	98	200	159	1907	2000	M
	Simlången	100	50097	260	1928	2000	D
	Gårdsilt	100	1207	55	1928	2000	M
	Vikaresjön	101	50098	826	1933	2000	D
	Assmebro R)	103	1166	653	1934	2000	M
	Ås R)	105	50102	2160	1909	2000	M
	Vänern	108	50105	46886	1807	2000	A
	Vassbotten	112	751	624	1914	2000	M

R) Somewhat affected by regulations

Stations in Norway

FRIEND-number	Name	River	Natl. number	Basin area (km^2)	From	To	Classi-fication
	Sarpsfoss	Glomma	2.31	42000	1846	1999	A
	Solbergfoss	Glomma	2.605	40221	1901	90/01	M/A
1702028	Elverum	Glomma	2.119	15426	1872	90/02	M/A
	Stai	Glomma	2.117	8901	1908	90/02	M
1702026	Knappom	Glomma/Flisa	2.142	1625	1916	2002	D
1702023	Narsjø	Glomma/Nøra	2.11	1187	1930	2002	D
1702027	Atnasjø	Glomma/Atna	2.32	465	1916	2002	D
	Losna	Glomma/Lågen	2.145	11087	1896	2002	A
1702025	Skjenna/Lårgård/Rosten	Glomma/Lågen	2.614	1755	1880	2001	D
	Aulestad	Glomma/Mjøsa/Gausa	2.28	866	1929	2002	D/M
	Vinstern	Glomma/Lågen/Vinstra	2.167	467	1915	1990	A
1702029	Lalm	Glomma/Otta	2.25	3942	1914	2001	M
	Fredriksvatn	Glomma/Otta	2.223	935	1942	90/01	M/A
	Breiddalsvatn ndf	Glomma/Otta	2.147	131	1917	2001	A
	Døvikfoss	Dramselv	12.68	16020	1912	90/02	A
1712010	Kistefoss	Dramselv/Randselva	12.228	3666	1916	2001	M
1712009	Etna	Dramselv/Randsfjord/Etna	12.70	557	1916	2002	D
	Fløafjord	Dramselv/Begna	12.82	1844	1921	2001	A
	Vindevatn	Dramselv/Begna/Vindedøla	12.92	262	1919	2001	D

Table cont.

FRIEND-number	Name	River	Natl. number	Basin (km^2)	From	To	Classi-fication
	Krøderen	Dramselv/Snarumselv	12.98	5094	1889	2001	A
	Kongsberg	Numedalslågen	15.15	4219	1913	2001	A
1716015	Jondal	Numedalslågen/Jondalselv	15.21	150	1920	2002	D
	Hjartsjø	Skienselv/Hjartdøla	16.32	215	1919	1990	A
171601?	Kirkevoll bru	Skienselv/Tinne	16.23	3837	1905	2001	A
1716016	Møsvatn	Skienselv/Tinne/Måna	16.19	1506	1909	2001	A
	Strengen-Hogga	Skienselv/Eidselv	16.203	3250	1911	1997	A
	Hagadrag	Skienselv/Bøelv	16.51	732	1912	2002	M
	Dalsfoss ndf.	Toke	17.10	1198	1917	1988	M
	Rygene total	Nidelva	19.127	3947	1900	92/02	A
	Evenstad	Nidelva	19.36	3514	1915	1992	A
	Nisser dam	Nidelva/Nisserelv	19.8	240	1914	1990	M
1720005	Flaksvatn	Tovdalselv	20.3	1794	1899	2001	A
1720001	Austenå	Tovdalselv	20.2	225	1924	2002	D
1722004	Kjølemo	Mandalselv	22.4	1740	1896	1999	M
1724001	Tingvatn	Lygna	24.9	266	1922	2002	D
	Fidjelandsvatn	Kvina	26.4	627	1919	1990	M

Table cont.

FRIEND-number	Name	River	Natl. number	Basin (km^2)	From	To	Classi-fication
1727004	Hetland	Hellelandselv	27.26	70	1915	2002	D
1728001	Haugland	Håelv	28.7	134	1918	2002	D
	Suldalsoset	Suldalslågen	36.1	1308	1904	90/02	M
1741001	Stordalsvatn	Etneelv	41.1	127	1912	2002	D
	Sandvenvatn	Opo	48.1	464	1908	2002	D
1750001	Hølen	Kinso	50.1	229	1923	2002	D
	Viveli	Eio/Veig	50.4	386	1915	2002	M
1755001	Røykenes	Oselv	55.4	50	1934	2002	D
1762001	Bulken	Vosso	62.5	1102	1892	2002	D
	Nese	Eksingedalselv	63.1	342	1909	2001	A
	Brakestad	Eksingedalselv	63.2	220	1930	2000	A
	Steinslandsvatn	Steinslandselv	64.2	243	1930	2000	A
	Fossevatn	Matreelv/Brydalselv	67.1	64	1917	2001	A
1768001	Kløvtveitvatn	Kløvtveitelv	68.1	4.3	1930	2002	D/M
	Brekke bru	Flåmselv	72.5	265	1941	2001	D
	Tya	Årdalselv	74.2	292	1911	2001	A
	Ytri bru	Fortunelv	75.2	367	1918	2000	A

Table cont.

FRIEND-number	Name	River	Natl. number	Basin (km^2)	From	To	Classi-fication
	Veitestrandvatn	Årøyelv	77.2	384	1901	2001	A
1781001	Hersvikvatn	Hageelv	81.1	7.0	1934	2001	D
1782001	Nautsundvatn	Guddalselv	82.1	220	1908	2002	D
1783001	Viksvatn	Gaular	83.2	505	1902	2002	D
	Jølstervatn	Jølstra	84.1	384	1902	1990	A
	Breimsvatn	Breimselv	87.1	585	1900	1990	A
1788001	Lovatn	Loelv	88.4	234	1901	2001	D
1789001	Hornindalsvatn	Eidselv	89.1	378	1900	2002	M
	Dalsbøvatn	Mørkedalen vassdrag	91.2	26	1935	2001	D
1801001	Engesetvatn ndf	Tenfjordelv/Engesetelv	101.2	42	1923	2001	D
1803001	Horgheim	Rauma	103.4	1142	1912	2001	D
1805001	Øren	Gusjåelv	105.1	94	1923	2001	D
	Elverhøy bru	Driva	109.3	2443	1907	97/01	A
	Festa	Driva	109.7	171	1919	2001	M
	Risefoss	Driva	109.9	738	1936	2001	D
	Bjørset dam	Orkla	121.10	2286	1902	2002	A
1822002	Haga bru	Gaula	122.2	3062	1908	2000	D

Table cont.

FRIEND-number	Name	River	Natl. number	Basin (km^2)	From	To	Classi-fication
	Merrafoss	Gaula/Lundesokna	122.3	239	1919	1990	M
	Rathe	Nidelv	123.20	3061	1881	2001	A
1824001	Høggås bru	Stjørdalselv	124.2	491	1912	2002	D
1833001	Krinsvatn	Stjørna	133.7	205	1916	2002	D
1838001	Øyungen	Årgårdselv	138.1	238	1916	2002	D
	Fiskumfoss øvre	Namsen	139.34	3256	1908	1997	A
1840001	Salsvatn	Moelv	140.2	422	1916	2002	D
	Åbjørvatn	Åbjøra	144.1	384	1908	2001	M
1852001	Fustvatn	Fusta	152.4	520	1908	2002	D
1857001	Vassvatn	Kjerringå	157.3	16	1916	2002	D
1862001	Skarsvatn	Lakselv	162.3	144	1916	2002	D
1865001	Strandå	Strandvasså	165.6	23	1916	2002	D
1866001	Lakshola	Laksåga	166.1	230	1916	2002	D/M
	Kobbvatn	Kobbelv	167.3	386	1916	2001	A
1868001	Storvatn	Lommerelv	168.1	71	1916	1991	D
1877001	Sneisvatn	Sneiselv	177.4	29	1916	2002	D
1891001	Øvrevatn	Salangselva	191.2	524	1916	2002	D

Table cont.

FRIEND-number	Name	River	Natl. number	Basin (km^2)	From	To	Classi-fication
	Stabburselv	Stabburselv	223.1	1103	1923	2001	M
	Skoganvarre	Lakselv	224.1	941	1921	2001	A
1934003	Polmak	Tana	234.1	14169	1911	90/02	D
1944001	Neset	Neiden	244.1	2911	1911	2002	D
	Karpelv	Karpelv	247.1	124	1927	2000	D
	Murusjøen	Muruelv	307.5	349	1926	1990	M
1954001	Landbru limn.	Linvasselv	307.7	60	1944	2002	D
1956002	Nybergsund	Klara	311.6	4410	1909	2002	D
1956001	Femundsenden	Klara	311.4	1769	1908	2002	D
1956003	Engeren	Klara/Engerå	311.460	400	1911	2002	D
	Magnor	Vrangselv	313.10	357	1911	2002	D