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Has streamflow changed in the Nordic countries?

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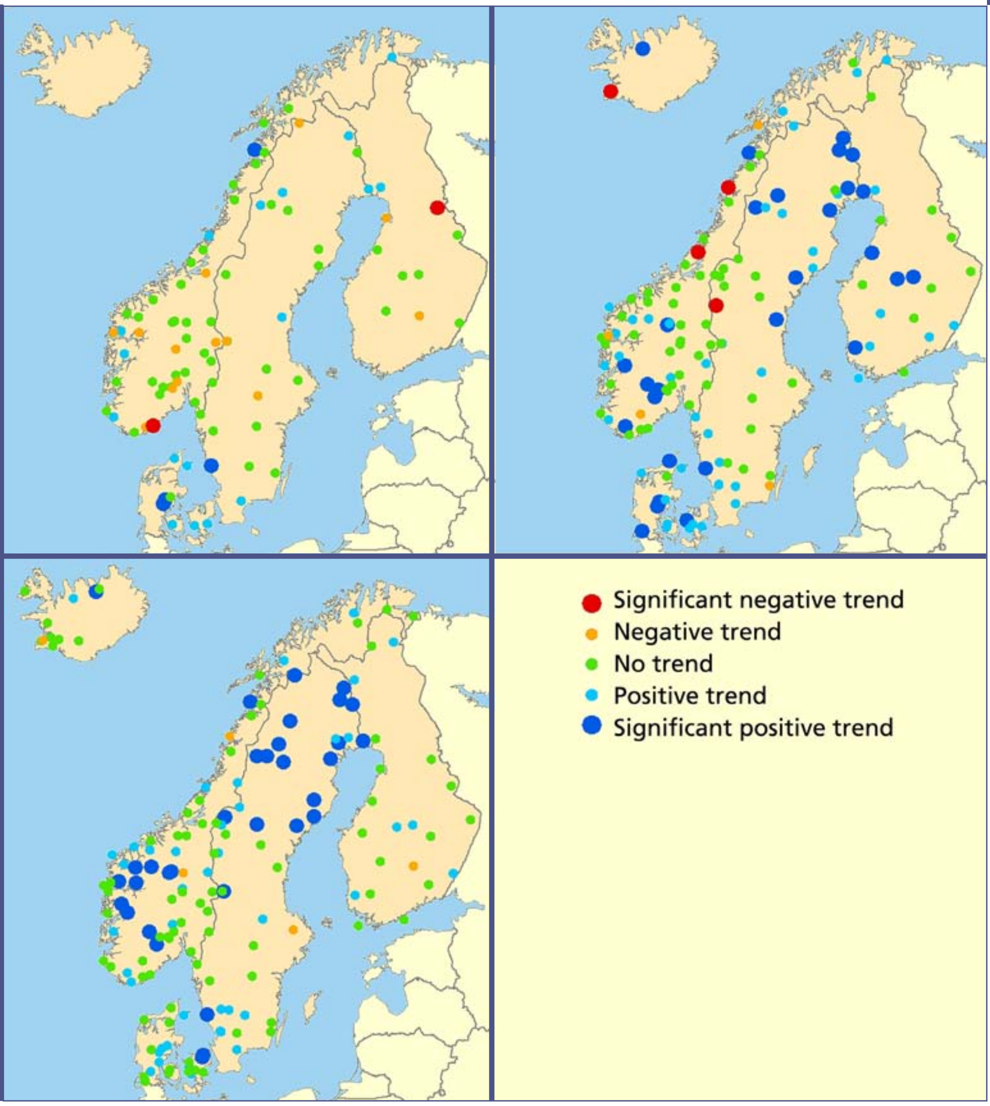
REPORT



Has streamflow changed in the Nordic countries?

Norwegian Water Resources and Energy Directorate (NVE)
2010

Report No 1

Has streamflow changed in the Nordic countries?

Published by: The Norwegian Water Resources and Energy Directorate

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Print: NVE
Number printed: 50
ISSN: 1502-3540
ISBN: 978-82-410-0705-7

Abstract: Climate change studies traditionally include elaboration of possible scenarios for the future and attempts to detect a climate change signal in historical data. This study focuses on the latter, but includes a qualitative comparison to streamflow scenarios. It can be concluded that the observed temperature increase has clearly affected the streamflow in the Nordic countries. These changes correspond well with the estimated consequences of a projected temperature increase. The effect of the observed and projected precipitation increase on streamflow is less clear.

Keywords: Streamflow trends, Nordic region, Climate change, Flood, Drought

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January 2010

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Preface

Climate change implying changes in annual average streamflow, in the seasonal distribution of flow or in the magnitude and frequency of floods and droughts may have extensive impacts on water management, agriculture and aquatic ecosystems. Countries such as Norway, Sweden, Iceland and Finland where much of the electricity production is based on hydropower are especially sensitive to long term variations in streamflow. Hydrological changes may require new investment and designs, operation and management practices related to hydropower plants. It is therefore of vital importance to society that these aspects are studied further.

The analyses described in this report were carried out by the "Statistical Analysis group" of the Nordic research project Climate and Energy (2003-2006). A summary of the results can be found in the final report of the project (Fenger, 2007). This project included a comprehensive assessment of the impacts of climate change on renewable energy sources in the Nordic and Baltic countries. The CE project was funded by Nordic Energy Research, the Nordic energy sector and the national hydrological and meteorological institutions of the participating countries.

Nordic Energy Research is now funding a follow-up project to the CE-project, the project Climate and Energy Systems: Risks Potential and Adaptation. In this new project, the trend analyses are updated to 2005. Temporal and spatial correlation is taken into account, but any reference to significance is avoided as long term persistence cannot be accounted for. The conclusions, however, are the same as in this report.

Oslo, January 2010

Morten Johnsrud

Director, Hydrology Department

Summary

Climate change studies traditionally include elaboration of possible scenarios for the future and attempts to detect a climate change signal in historical data. This study focuses on the latter. A pan-Nordic dataset of more than 160 streamflow records was analysed to detect spatial and temporal changes in streamflow. The Mann-Kendall trend test was applied to study changes in annual and seasonal streamflow as well as floods and droughts for three periods: 1961-2000, 1941-2002 and 1920-2002. The period analysed and the selection of stations influenced the regional patterns found, but the overall picture was that trends towards increased streamflow were dominating for annual values and the winter and spring seasons. Trends in summer flow highly depended on the period analysed whereas no trend was found for the autumn season. A signal towards earlier snowmelt floods was clear and a tendency towards more severe summer droughts was found in southern Norway. A qualitative comparison of the findings to available streamflow scenarios for the region showed that the strongest trends found are coherent with changes expected in the scenario period, for example increased winter discharge and earlier snowmelt floods. However, there are also expected changes that are not reflected in the trends, such as the expected increase in autumn discharge in Norway. It can be concluded that the observed temperature increase has clearly affected the streamflow in the Nordic countries. These changes correspond well with the estimated consequences of a projected temperature increase. The effect of the observed and projected precipitation increase on streamflow is less clear.

1 Introduction

Climate change implying changes in annual average streamflow, in the seasonal distribution of flow or in the magnitude and frequency of floods and droughts will have extensive impacts on water management, agriculture and aquatic ecosystems. Countries such as Norway, Sweden, Iceland and Finland where much of the electricity production system is based on hydropower are especially sensitive to long term variations in streamflow. Hydrological changes may require new investments and design, operational and management practices related to hydropower plants. It is therefore of vital importance to society that these aspects are studied further.

Studies of climate change traditionally include elaboration of possible scenarios for the future and attempt to detect a climate change signal in historical data. The latter type of studies looks for trends and jumps and also establishes knowledge about the natural climate and hydrological 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. This paper focuses on detecting climate change signals in historical streamflow records. The question of whether human induced climate change is already influencing hydrology is frequently asked. To see if observed trends in streamflow fit with projected scenarios, a qualitative comparison between the observed trends and available streamflow scenarios is made.

Information about observed changes in the climate system is summarised in the Third Assessment Report of the IPCC (IPCC, 2001a). The largest increases in temperature during the last 25 years have occurred over the middle and high latitudes of the Northern Hemisphere and precipitation has increased as well, except over Eastern Asia. 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, and it is seen that the detected changes in climate and hydrology might vary considerably in space.

Individual national studies for the Nordic countries (for example Lindström and Bergström, 2004; Førland *et al.*, 2000; Ovesen *et al.*, 2000; Hyvärinen, 1998; Hanna *et al.*, 2004) also show that trends in climatic and hydrological variables, either natural or human induced, vary considerably between regions. An overview of recent and ongoing studies of long time series of precipitation, temperature, streamflow and other hydroclimatological variables in the Nordic countries can be found in Hisdal *et al.* (2003). The national studies vary both regarding the period and variables analysed. 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. 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 time period studied. A previous Nordic study on regional differences in trends focused on annual and seasonal streamflow, and on the time period 1930-80 (Hisdal *et al.*, 1995).

Meanwhile, streamflow records have been updated, and a similar study is possible for a longer period. Enhanced climate change may result in stronger and longer lasting changes in streamflow, so that the likelihood of change detection might grow (Kundzewicz, 2004). This is an argument for continuous examination of updated streamflow records, including an updated 'pan-Nordic' study to identify larger scale regional differences in streamflow in terms of non-stationarity and climate variability, and possible consequences for the energy sector.

Most studies look at annual and seasonal values. Less attention is given to extremes, especially droughts. Amongst the reasons are that extremes are especially prone to man-made environmental changes and also more vulnerable to measurement errors. Detected trends are therefore more difficult to relate to changes in climate.

In the latter half of the 20th century a two to four percent increase in the frequency of heavy precipitation has been observed over mid- and high latitudes of the Northern Hemisphere (IPCC, 2001a). This tendency is also observed for the western part of Norway and Grønås *et al.* (2005) state that this agrees with expected human induced climate change. Even if changes in annual streamflow usually follow the changes in annual precipitation, the change in floods does not relate that well to the increase in heavy precipitation. Recent studies of trends in annual maximum floods (Kundzewicz *et al.*, 2005) and peak over threshold floods (Svensson *et al*., 2005) worldwide, and annual maximum floods in Europe (Kundzewicz, 2005) conclude that although more intense precipitation has been documented, a coherent and general increase in high river flows could not be detected. Also, streamflow records from Norway, Finland and Sweden covering different periods were included in the studies. In the present study annual maximum autumn floods and annual maximum spring floods are studied separately to distinguish between rain and snowmelt floods. A common time period is analysed to enable a spatial comparison of trends.

In Hisdal *et al.* (2001) a pan–European study of trends in the severity and frequency of summer drought was carried out. For the period 1962-1990 that included a relatively high density of stations in Norway and Denmark, only one station had a significant trend. However, a tendency towards more severe droughts was seen in southern and northern Norway and Denmark and less severe droughts in the middle part of Norway. The other Nordic countries had too few stations to draw any conclusions. Trends in the low flow indices 7-day annual minimum and 30-day annual minimum of a global dataset were studied by Svensson *et al.* (2005). Only increases in low flows were found in Europe, but this is seen as a result of the increasing number of reservoirs becoming operational in the periods studied. In the present study, trends in droughts are only investigated for stations where there is no effect of reservoirs.

The Nordic countries are privileged to have a good spatial coverage of long time series of observation that have undergone a quality control to avoid stations that are significantly affected by human activity. Especially, a unique selection of pristine basins with a minimum of man-made environmental changes like urbanization, deforestation and changes in storage capacity are available for studies of extremes. The record length enables documentation of changes at inter-annual time scales and testing for trends in common time intervals. Utilizing these data gives a unique opportunity to investigate changes in streamflow in the Nordic region.

The main objective of this paper is to answer the question of whether streamflow has changed in the Nordic countries by means of an analysis of the temporal and spatial variations in annual and seasonal streamflow, floods and droughts. The next section describes data selection and the streamflow variables analysed, followed by a section discussing the trend test applied. Then the results are presented and discussed with respect to the time period and region analysed before the detected trends are compared to expected changes in the future. Finally conclusions are given.

2 Data

A total of 162 streamflow records with an average length of 83 years of daily data from Denmark, Finland, Iceland, Norway and Sweden were collected. The data are stored in a common database, a 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 data were selected to cover the whole Nordic region with a common time period, including 2002. The criteria for selecting series were that the records should be, as far as possible, unaffected by human induced changes in the basin, and that the records should be as long as possible. Even if most catchments in the Nordic region are only subject to minor land use changes and a minimum of water abstractions for irrigation, industry and public water supply, long pristine series are hard to find. 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 only suitable for analysis of trends in annual values;
- series also suitable for analysis of monthly values, i.e. seasonal trends;
- series also suitable for analysis on a daily level, i.e. trends in extremes.

To obtain a good spatial resolution a reasonable and common time period should be selected. However, time series, as long as possible, are important to study long term variability. A best possible Nordic coverage required a relatively short period to be selected (1961-2000). This period encompasses the total data set (162 stations). Two additional sets of stations, 1941-2002 (139 stations) and 1920-2002 (87 stations) were chosen to investigate longer-term trends. Analyses of trends in seasonal streamflow and extremes further reduce the number of stations. A minimum number of stations, 46, are found for analysis on a daily level for the period 1920-2002. The spatial coverage of data is not uniform as a larger number of long records from pristine basins are available in Norway and Denmark as compared to Sweden, Finland and Iceland. This has to be considered when the results are discussed. However, the dataset comprises a good-quality, long-term set of homogeneous series of adequate spatial resolution with a minimum of human influence to detect trends caused by climate changes, natural or human induced.

The trend studies were performed for the following hydrological variables: annual streamflow (calendar years), seasonal values (winter: December-February; spring: March- May; summer: June-August; autumn: September-November), timing (date of flood peak) and magnitude of floods and drought duration and deficit volume.

A rough differentiation of the flood generation mechanism was done by looking at spring and autumn floods separately. The spring flood period was defined to be March 1 to July 15, and the autumn flood period was July 16 to November 11. Timing was defined as the date of the flood peak. In Denmark, parts of southern Sweden and south-western Iceland the major floods usually occur during the winter season. For this region it could therefore be relevant to study floods for a season lasting from late autumn to early spring, but this study is limited to the two periods defined above.

Nordic river flow regimes vary considerably. In Denmark and along the western coasts of Norway and most of southern Sweden with no regular snow cover during the winter, the lowest flows occur during the summer months caused by lack of precipitation and high evaporation losses. In the north, in the east and in the mountainous regions, the lowest flows are found in the winter due to precipitation being stored as snow. There are also transition regions where the lowest flow can be found in all seasons. To perform a consistent analysis of droughts, it is necessary to distinguish between “summer droughts” and “winter droughts”. These two drought types are affected in different ways by climate change. Here only “summer droughts” are considered. Except from Denmark, southern Sweden and groundwater-fed rivers in south-western Iceland most of the basins in this study have a regular spring flood. Plots of maximum, median and minimum values of streamflow were used to identify the average timing of the spring flood. The start of the summer season was defined to be at the end of the spring flood. The end of the summer season was defined to be the date when the average temperature drops below 0^{o}C. This method has previously been applied to define summer drought seasons for basins all over Europe and is further discussed in Hisdal *et al.* (2001). Finally, three seasons were identified and the stations were classified according to these. Season A (all year/no season) includes Denmark, the four westernmost basins in Norway and the two south-western basins in Sweden. Season B (April 15 – November 15) is applied to the coastal zone in Norway, two stations in southern Sweden and the three southernmost stations in Finland. Season C (June 15 to October 15) is used for the northern and inland catchments of Norway, Sweden and Finland and the Icelandic stations.

The river flow is considered to indicate drought conditions when the flow is below a specific threshold, Q_0. This method proposed by Yevjevich (1967) was originally based on the statistical theory of runs for analysing sequential time series with a time resolution of one month or longer. The approach has previously been used to select droughts from a daily hydrograph for trend studies (Hisdal *et* *al.*, 2001). The method allows streamflow droughts to be characterised in terms of their duration, d_i, deficit volume (severity), v_i, minimum flow, Q_{min} and time of occurrence (Figure 1). During a prolonged dry period it is often observed that the flow exceeds the threshold level in a short period of time and thereby dividing a large drought into a number of minor droughts that are mutually dependent. To as far as possible pool dependent droughts and remove minor droughts, an 11-day moving average procedure was adopted, as recommended by Tallaksen *et al.* (1997). The threshold level, Q_0, was determined for each station by using the 70-percentile, Q_{70}, from the flow duration curve (flow which is exceeded 70% of the time in the given period and season). Finally, the drought events were extracted for each station for the three time periods. Two drought characteristics were analysed:

- annual maximum drought duration (days)
- annual maximum deficit volume (m^3)

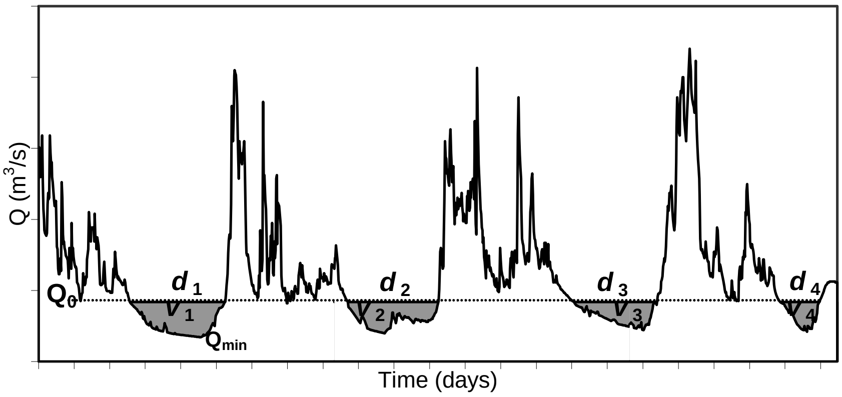

Figure 1 Definition of drought characteristics

Low flow data are especially prone to measurement errors caused by factors such as altered cross-sections, weed growth and backwater effects. This might influence a trend study of daily minimum series. Drought as defined here is more robust in this respect.

3 Trend analysis

According to Yue and Pilon (2004), even if the underlying distribution is known to be approximately normal, the power of a parametric test is only slightly higher than the power of a non-parametric alternative. For non-normal series, rank-based tests, including the Mann-Kendall test, were found to have an increased ability to detect trends as compared to slope-based tests. The distribution of the streamflow parameter to be analysed will differ in space and can be highly skewed. Especially in case of flood and drought there might be many minor and few major events. Hence, a non-parametric test is favourable.

In Kundzewicz and Robson (2004) resampling methods are pointed out as particularly suitable for hydrological data. Hisdal *et al.* (2001) applied two tests, a resampling test and the widely used non-parametric Mann-Kendall test, to investigate trends in streamflow droughts in Europe. It was found that there was a strong agreement between the two tests. In the present study the Mann-Kendall test (two-sided) with a 5% significance level, also recommended by the WMO (1988), is applied. A 5% significance level implies that there is a five percent probability of incorrectly rejecting the hypothesis of no change and detecting a trend, when no trend is present.

The Mann-Kendall test searches for a trend in a time series without specifying whether the trend is linear or nonlinear. An example of an application of the test can be found in Mitosek (1995), who compared different trend tests to detect signals of climate variability and change in monthly and annual discharges of 176 series from all over the world. Further references of application to hydro-climatological time series can be found in Yue and Pilon (2004). A description of the test can be found in Salas (1993).

Time series of annual and seasonal streamflow and to less extent extremes may exhibit serial correlation, because of storage properties in the basin. Yue *et al.* (2003) state that positive serial correlation increases the possibility that the Mann-Kendall test rejects the hypothesis of no trend, when there is actually no trend. Prior to a trend test, removal of autocorrelation, pre-whitening, is sometimes applied. Some of these procedures might remove a portion of the trend and lead to acceptance of the hypothesis that there is no trend even if a trend is present. Care must therefore be taken if pre-whitening is carried out. If serial correlation coefficients generally are low, the differences between the trend tests prior to and after pre-whitening will not be large (Birsan *et al.*, 2005). An estimation of the serial correlation was carried out for the Nordic data set for annual values for the period 1961-2000. For most of the series in the Nordic data set the serial correlation coefficients were low and hence, a pre-whitening was not seen as required. An exception was most of the Icelandic discharge series that appear to have a significant autocorrelation at the time lag of one to four years. Therefore for Iceland, trend results based on original and pre-whitened series are presented for annual and seasonal values. Pre-whitening according to Appendix A of Wang and Swail (2001) as recommended by Zhang and Zwiers (2004) was applied.

4 Results and discussion

The results have been assessed in two different ways: summary statistics of the significant trends (5%); and maps of the spatial variability of the trends (all periods). Because of the quality classification, the results are as far as possible not influenced by human interference in the catchment. Hence, the detected changes are caused either by natural climate variability or human induced climate change. For Iceland the results without pre-whitening are shown for better comparison with data from the other countries, but the differences are explained in the text.

4.1 Summary statistics

The percentages of stations with significant positive and negative trends are summarized in Figure 2 (annual and seasonal flow) and 3 (extremes). A significance level of 5% implies that significant trends at 5% of the stations can be expected, even if no trends are present. Three issues should be kept in mind when discussing the results; 1) only few records are available for the period 1920-2002, 2) the period 1961-2000 is included and therefore influences the results in all periods and finally, 3) the station density is larger in Denmark and Norway than in Sweden and Finland. As stations in the same climatic region will tend to have similar trends, a trend in a region with many stations will result in a larger total percentage of significant trends.

Except for the autumn season for all periods and the timing of the autumn flood in the periods 1920-2002 and 1941-2002, more than 5% significant trends are found. In general a larger proportion significant trends are found in annual and seasonal values than in the extremes. Overall the number of positive significant trends, towards increasing streamflow, dominates for annual and seasonal flow (Figure 2). Regarding annual discharge a significant positive trend is found for about 20% of the stations in the periods 1961-2000 and 1941-2002. For the longest period, 1920-2002, this number is reduced to 5%. Both the winter and spring seasons are dominated by positive trends in all periods. For the summer season, the positive dominance in the period 1961-2000 is replaced by a negative dominance in the longest period, 1920-2002. Less than 5% of the stations show a significant trend for the autumn season. By pre-whitening of the Icelandic series (11 for the period 1961-2000 and two for the period 1941-2002) the significant negative trends disappeared (one for each of the spring season 1961-2000, the autumn season 1941-2002 and the annual values 1941-2002). None of the trends towards increased flow disappeared.

Concerning floods, the picture is more unclear (Figure 3). For flood peaks (both autumn and spring) and the timing of the autumn flood, the number of positive (increased flood peak) and negative (reduced flood peak) trends strongly depends on the period analysed. However, regardless of the period analysed, there is a clear dominance of negative trends for the timing of the spring flood meaning trends towards earlier spring floods. For drought the number of positive (more severe) and negative (less severe) trends depends on the period analysed.

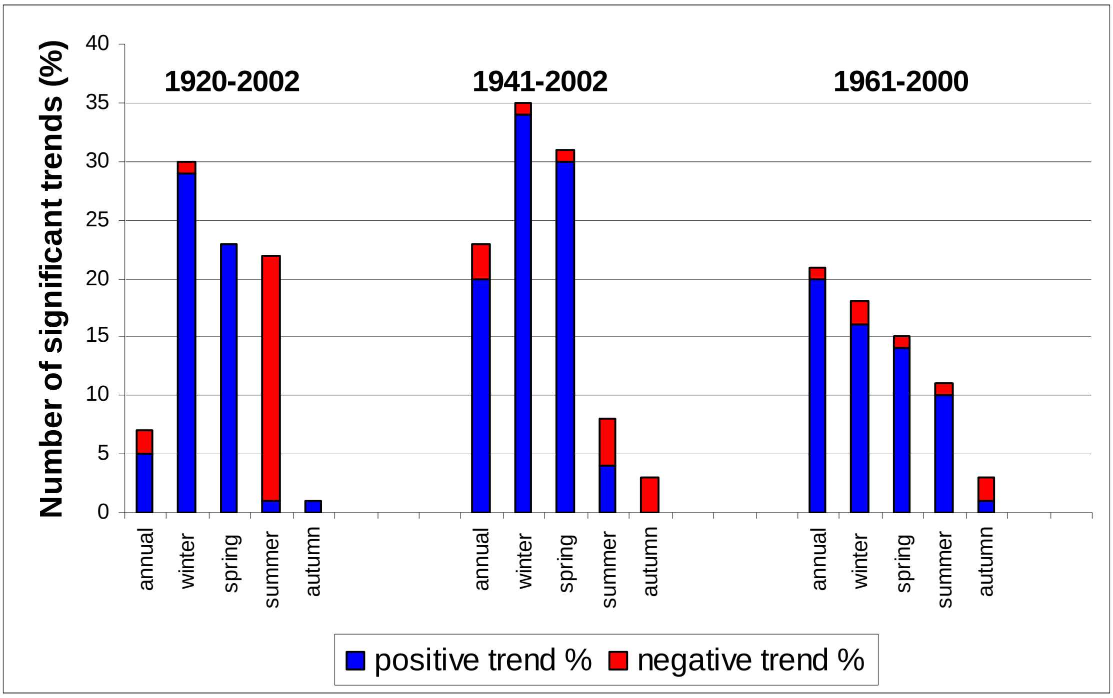

Figure 2 Summary of the significant trends, at the 5% level, for annual and seasonal flow in all time intervals.

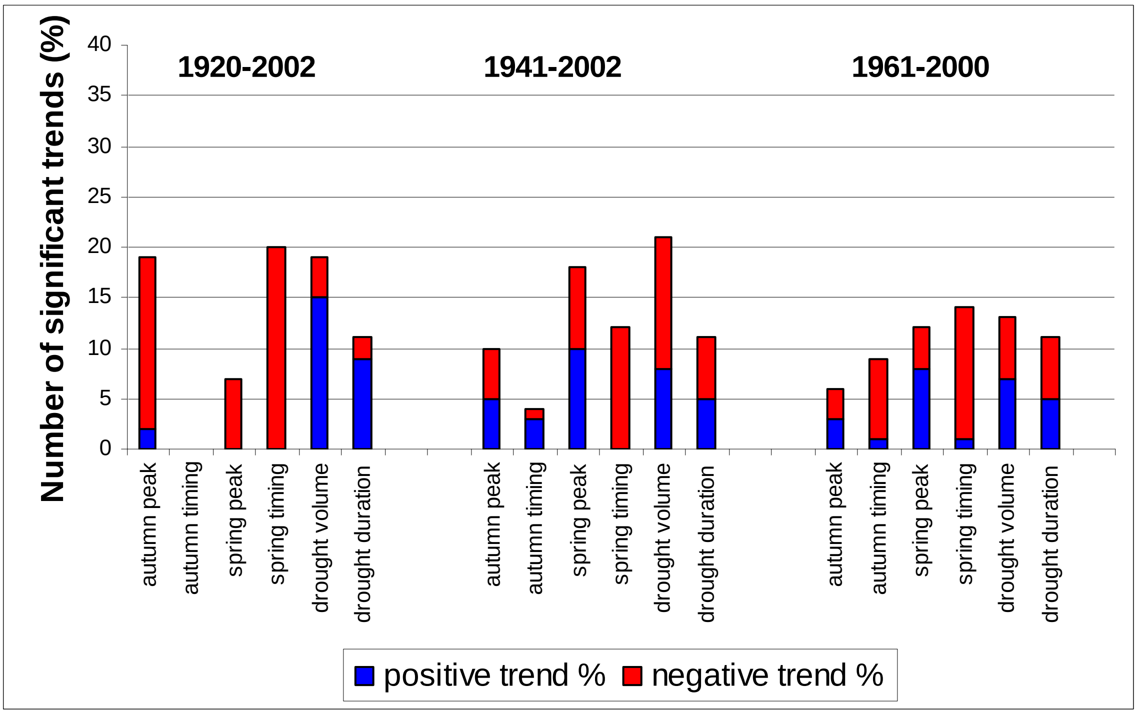

Figure 3 Summary of the significant trends, at the 5% level, for flood and drought in all time intervals.

4.2 Trends in annual discharge

The annual streamflow trends are presented in Figure 4. Trends with a 5% significance level are indicated with large blue circles (significant positive trend) and large red circles (significant negative trend). These are in the following called *significant trends*. Trends that are only significant at a 30% level are indicated with smaller circles, light blue if a positive and orange if a negative trend was found and are in the following called *trends*. Green circles indicate that no trend was found.

A positive trend is seen in a region including Denmark and the western coast of Sweden for all three periods. A majority of the Danish stations, especially in western Jutland and in the south have no trend in the period 1961-2000, but the positive trend is still present in the rest of Denmark. The mountain area of southern Norway has a positive trend in the two periods 1941-2002 and 1961-2000, with significant trends for a large number of stations in the latter period. Stations on the extreme western coast of Norway have only weak positive trends and most often no trends at all. Generally in a zone from mid-Norway over eastern Norway and into central and southern Sweden there are no trends. Some stations, especially in southern Norway have a negative trend in the period 1920-2002. A positive trend appears in northern Sweden for a few stations in 1920-2002, and at most stations in the two shorter periods. The region extends into the northernmost part of Norway in all periods and into western Finland in the period 1941-2002. A couple of coastal stations in northern Norway have a significant falling trend in the two shorter periods.

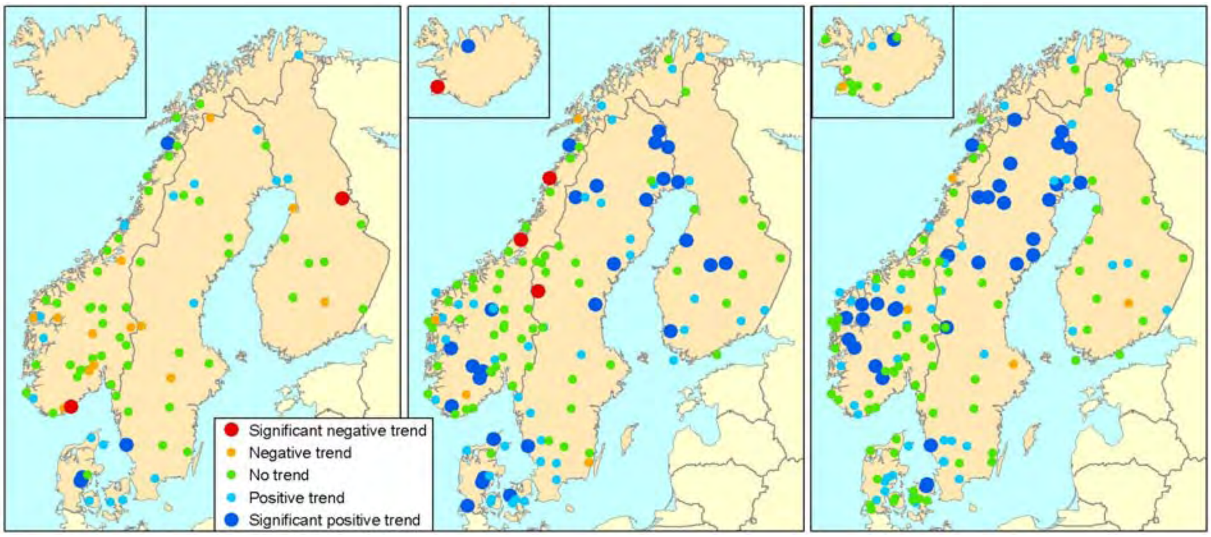

Figure 4 Trends in annual streamflow for the periods 1920-2002 (left), 1941-2002 (middle) and 1961-2000 (right).

A systematic change in the runoff is present in the data from Denmark and the western coast stations of Sweden. By examining the individual series some characteristics appear. There is a pronounced dry period from the late 1960s to around 1980 in most series away from the western coast. The early 1940s were also dry at many locations, but with some wet years in mid-Norway. This explains why mid-Norway is without trends, and why so many series have significant positive trends in the two shorter periods. The 1920s were cool, but with abundant precipitation in many regions, and this explains that most series are without any trend or even slightly declining trends in this period. The precipitation and runoff peaked in western Norway around 1990 and have declined somewhat in the most recent years at some stations. Glacier streams in western Norway peaked in the warm 1930s and have had increasing discharge since the mid 1960s because of rising rainfall and temperature. The recent decline is not present in the series from northern Sweden, and explains why the trend is apparent at so many Swedish stations in the two shorter periods. In Finland, the significant positive trends are found only for the period 1941-2002. These are mainly caused by the occurrence of two very dry years in the early 1940s. In the western and central parts of the country, flows in 1941 generally were 25-40% and in 1942 40-60% of the long-term mean.

Trends in annual streamflow in Iceland are hardly noticeable during 1961-2000. There is only one significant positive trend, one positive trend that disappears after pre-whitening and one negative trend. Most of the rivers do not show any trends. The trends are lower than trends seen in annual precipitation during the same time period (Jónsdóttir *et al.*, 2005). Trends in Iceland during 1941-2002 are apparent but only two stations are of that length. The direct runoff river in the north has a significant positive trend while the one in the south has a negative trend (significant prior to pre-whitening).

4.3 Trends in seasonal discharge

In the analyses of seasonal trends a total of 139 stations are available for the period 1961-2000, 119 for 1941-2002 and 70 for the entire period 1920-2002. For Finland and Sweden the number of stations is more than doubled when using 1941-2002 as compared to 1920-2002.

For some stations the winter values might be especially uncertain due to the usually very small discharge values. Small deviations from the “true” value might lead to large percentage deviations. Also, ice jamming and ice cover might affect the stage-discharge relationship. Attention must therefore be given when interpreting the winter season results. Figure 5 (upper) shows a clear positive trend for the winter in many regions for all periods. Exceptions are the coast of Norway, the eastern part of Denmark and the south-eastern part of Sweden where there are no significant positive trends (all periods), and Iceland (only series in 1941-2002 and 1961-2000) where there is only one significant positive trend in the shortest period. The two negative trends for 1961-2000 and the positive trend in 1941-2002 disappeared after pre-whitening. The trend toward increase in winter flow almost disappears for the northern parts of Norway, Sweden and Finland and for Denmark for the period 1961-2000. Positive trends in winter runoff might be caused by a general temperature increase during the last decades in combination with an increased winter precipitation in many regions (Førland *et al.*, 2000). It is interesting that the main pattern could also be observed for the period 1920-2002 that includes a period in the 1930s with relatively warm and wet winters.

An even more marked increase in streamflow has taken place in the Nordic countries except Iceland during spring (Figure 5, second uppermost), likely caused by increase in both precipitation and temperature. This is consistent with an earlier snow melt and spring flood for many catchments in the inland of Norway, Sweden and Finland (Figure 6). But also, Jutland in Denmark and the south-western part of Sweden have many stations with positive trends during spring. Again only a few positive trends are found in the coastal region of Norway, the eastern part of Denmark and the south-eastern part of Sweden.

In Iceland a negative trend in spring temperature (Jónsdóttir *et al.*, 2005) delays the snowmelt in some of the watersheds from the spring period into the summer period, therefore an increase in the summer discharge is apparent there and only one positive trend for the period 1961-2000 disappears after pre-whitening.

Different seasons often have opposite trends (Hisdal *et al.*, 1995). This is also the main impression for the periods 1920-2002 and 1941-2002, when looking at the summer season as compared to the winter and spring seasons. In the summer (Figure 5, second lowermost) there is a tendency towards reduced streamflow in the southern and eastern part of Norway, and in the central-western part of Sweden but this tendency only remains for the southernmost part of Norway for the shortest period, 1961-2000. A change in spring flood timing could be the main reason. It should be noticed that by extending the period to 1920-2002, three times as many stations have significant negative trends in spite of the number of stations being reduced by 40 %. Especially this can be noticed at the western coast of Norway, where the longest period has significant negative trend. But also in Denmark, central Sweden and Finland there are additional stations with negative or significant negative trends for the period 1920-2002.

For the autumn season the main pattern is that there are few trends at a 5% significance level (Figure 5, lower). Also in Iceland, one positive trend in 1961-2000 is removed and the significant negative trend for the period 1941-2002 is reduced to a trend after pre-whitening.

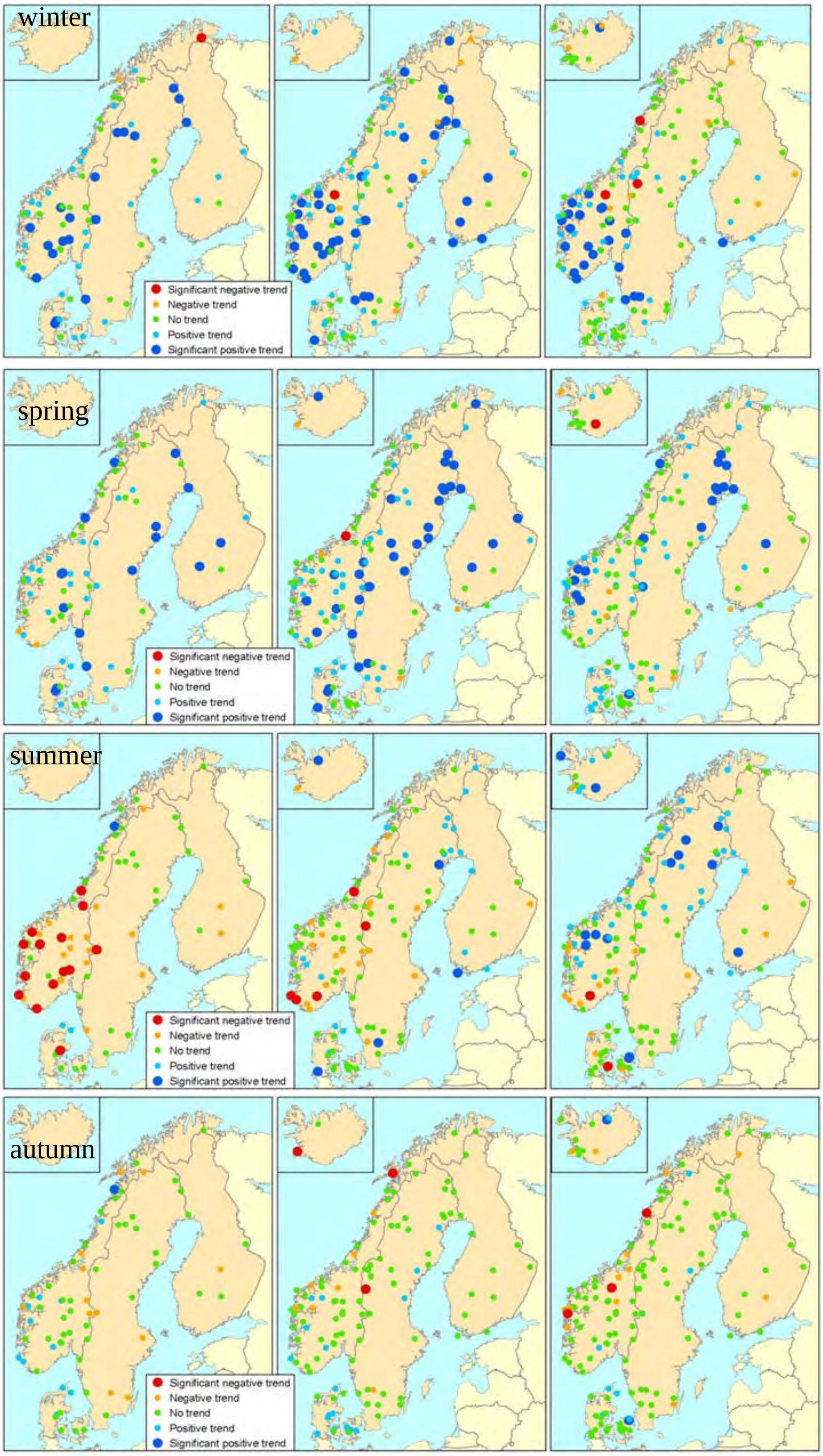

Figure 5 Trends in seasonal streamflow for the periods 1920-2002 (left), 1941-2002 (middle) and 1961-2000 (right).

4.4 Trends in floods

Regarding autumn floods it is hard to find any spatiotemporal patterns in the trends. For the longest period 1920-2002 (46 stations in total) a rather high number of the stations in southern and western Norway have significant trends towards reduced floods. For the period 1941-2002 (78 stations) many of the trends disappear in eastern Norway and instead a tendency towards increased autumn floods is found in Denmark and on the border between Finland and Sweden. For the shortest period with the highest density of stations (106) a mix of significant positive and negative trends is found in western Norway. For the timing of the autumn flood, only the shortest period has more than 5% significant trends at the 5% level.

The magnitude of the spring flood shows no systematic trends neither in time nor in space. However, there is a clear tendency towards an earlier spring flood (Figure 6) both in regions having a snowmelt flood (inland of Norway, Sweden and Finland) and in regions dominated by rain floods (Denmark and south-western Sweden).

This picture is repeated for all three periods even if the percentage of significant trends is largest for the period 1920-2002. The change in timing is likely caused by increased temperature in the inland basins. In Finland the spring temperature has increased in recent decades as shown by Tuomenvirta (2004) who found that the mean temperature in 1963-2002 was 1.8 °C higher than in 1847-1876. The Icelandic stations are the exception to this tendency. The spring floods in Iceland tend to occur later and be larger than earlier. This is caused by a negative trend in spring temperature. During a cold spring the spring flood is delayed, more snow accumulates and the probability of a sudden warming followed by a large spring flood becomes higher. No clear trends appear in the autumn floods except for two watersheds where the melt of the snow pack and glacier extends into the period of autumn floods.

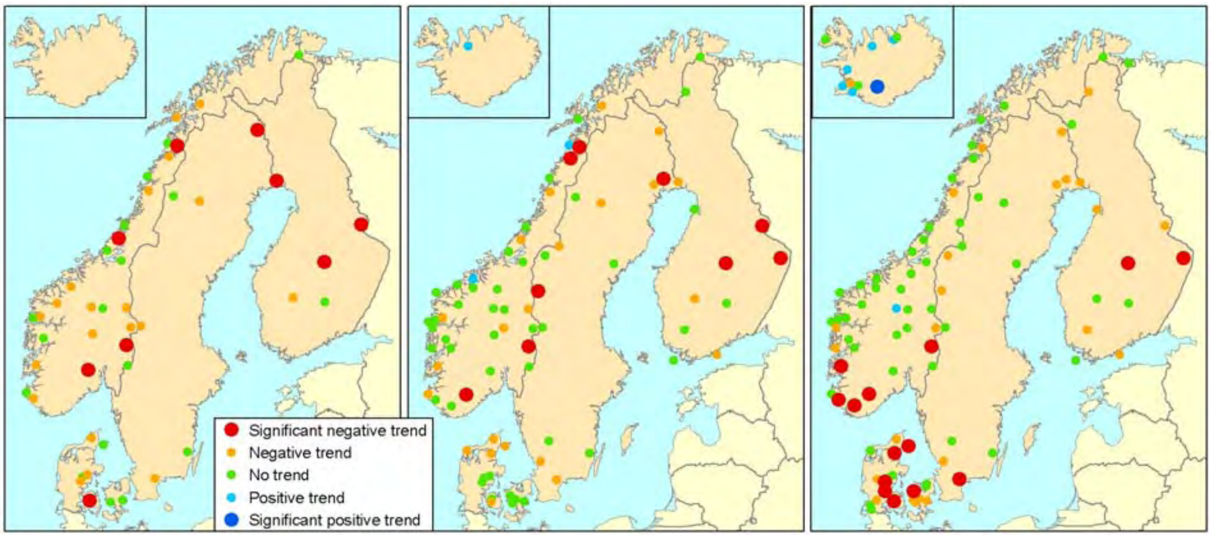

Figure 6 Trends in spring flood date of culmination for the periods 1920-2002 (left), 1941-2002 (middle) and 1961-2000 (right).

4.5 Trends in drought

The spatial trend pattern in drought duration and deficit volume is coherent even if the number of significant trends is slightly larger for drought deficit volume. Therefore only the drought deficit volume trends are shown (Figure 7). This time the significant positive trend is indicated in red illustrating a trend towards more severe droughts, and significant negative trends are indicated in blue indicating less severe droughts. For all time periods there is a tendency towards more severe summer droughts in southern and eastern Norway. This tendency is not reflected to the same extent in the summer season trends. For the periods 1920-2002 and 1941-2002, Denmark and Finland have trends indicating less severe summer droughts, but this pattern disappears for the period 1961-2000. For this short period Iceland has more trends towards less severe than more severe droughts. For Finland the droughts occurring in the early 1940s are the main explanation for the many trends towards less severe droughts in the period 1941-2002.

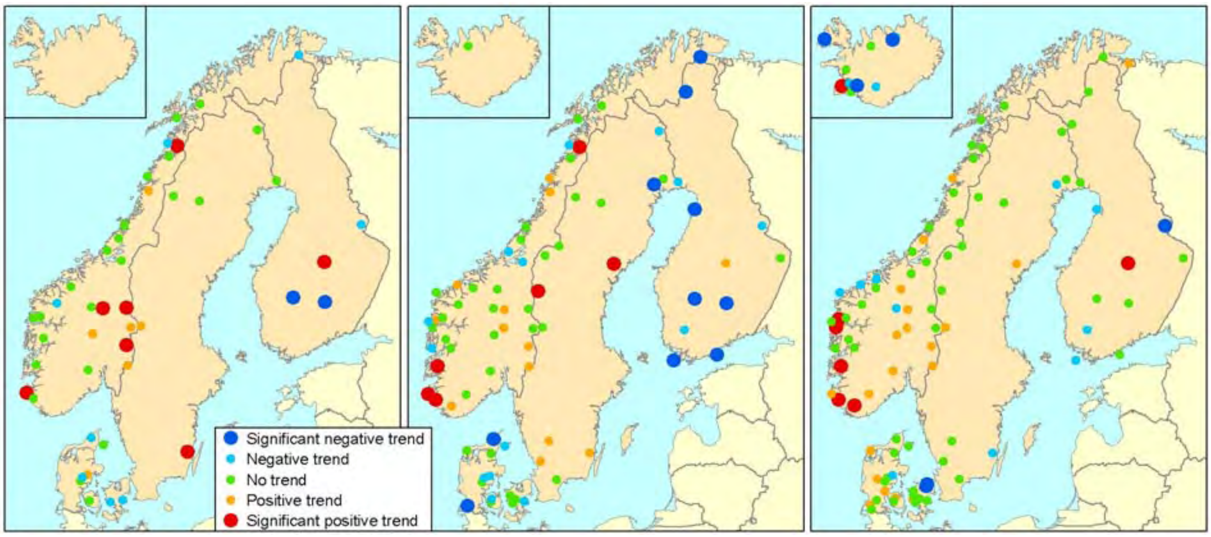

Figure 7 Trends in drought deficit volume for the periods 1920-2002 (left), 1941-2002 (middle) and 1961-2000 (right).

5 Comparison with available scenarios

To assess the effects of future climate changes on basin hydrology, detailed climate information both in time and space is needed. Hanssen-Bauer *et al.* (2005) review statistical downscaling of climate scenarios over Scandinavia (Denmark, Norway and Sweden) based on different climate models. Although the results vary, there are several common features. Regarding the temperature scenarios for the 21st century, the temperature is expected to increase with distance from the coast and with latitude. The precipitation scenarios are less consistent as the projected changes are very much linked to projected changes in atmospheric circulation which differs between models. However, annual precipitation is typically expected to increase. The increasing precipitation tendency is most pronounced for the winter season. During summer the projections tend to show an increase in northern Scandinavia, but several scenarios indicate a reduction in parts of southern Scandinavia. These results also summarise the findings from the RegClim project (http://regclim.met.no) and the PRUDENCE project (http://prudence.dmi.dk/).

For Norway these changes are reflected in streamflow scenarios based on the HadAM3H- (Emission scenario A2 and B2) and the ECHAM4/OPYC3 (Emission scenario B2) Global Climate Models. Possible future streamflow scenarios for 2071-2100 (Engen-Skaugen *et al.*, 2005; Roald *et al.*, 2004; Roald *et al.*, 2006) are simulated by a Gridded Water Balance Model (Beldring *et al.*, 2003). The scenarios vary, but there are some common features indicating increased annual discharge in most of Norway, but a slight decrease for some basins in southern and south-eastern Norway and parts of northern Norway. This disagrees with our findings as the trends found in annual values strongly depend on the period analysed. However, the increase in winter and spring discharge found in the scenarios agrees well with the detected trends. The scenarios show a reduction in summer flow in most of the country whereas a decreasing summer discharge trend is only found for the southern part of Norway. The earlier timing of the spring flood is also indicated by the scenarios.

The major disagreement between the trends and the scenarios are found for the autumn season where the scenarios indicate an increase in flow for the whole country whereas no trends in this direction were found for any of the periods analysed. The predicted reduction in spring flood magnitude in regimes with a dominant snow melt flood and increased autumn floods close to the coast is not reflected in the trend study. It should be noted that the results regarding flood magnitude scenarios are very uncertain. Drought scenarios as defined in this study were not given.

The most systematic change in observed streamflow in Sweden is an increase in winter and spring streamflow, particularly in northern Sweden. This is coupled to unusually high temperatures and precipitation in recent years (Lindström and Alexandersson, 2004). The increases have led to a shorter period for snow accumulation and to an earlier snowmelt. This is reflected in the observed trend towards an earlier spring flood. These observations agree with recent streamflow scenario simulations (e.g. Bergström *et al.*, 2001; Andreasson *et al.*, 2004). Andreasson et al. (2004) presented hydrological scenario simulations based on the A2 and B2 scenarios for 2071-2100, compared to a control climate of 1961-1990. The scenario simulations, however, generally suggest decreasing streamflow during summer in south-eastern Sweden, decreasing spring flood peaks and increasing autumn flood peaks, whereas these patterns are not evident in the observed trends.

For Finland, Denmark and Iceland there are no publications on streamflow scenarios. The discussion for these countries is therefore based on precipitation and temperature scenarios. All climate scenarios for Finland anticipate an increase of precipitation, particularly in the winter and in the spring. Consequently, mean annual flow would increase, but due to milder winters spring floods would decrease in southern and also central parts of the country. Summer and autumn floods are going to become more severe; on the other hand, summer droughts might become more frequent and intense. The analysis of the Finnish time series included in this study does not reveal clear indications of these changes. Even if there are increasing trends in winter and spring streamflow, the number of significant trends in all variables studied was below the 5% threshold in the period 1961-2000. One reason might be that this period was characterized by rather large interannual variability in many of the variables.

For Denmark (http://prudence.dmi.dk/) temperature is expected to increase in all seasons. Precipitation increases are seen for annual, winter, spring and to a less extent autumn values. Summer precipitation scenarios indicate reduced rainfall. Hence, especially increased winter and spring flow and decreased summer flow can be expected. The trends show an increase in winter flow for the two longer periods, but not for 1961-2000. The spring flow has increased, whereas no change is seen in the summer period.

The trends seen in the Icelandic 1961-2000 historical streamflow and precipitation series do not fully agree with trends indicated by two climate scenarios simulated by the HIRHAM model with boundary conditions from global simulations from the Hadley centre, based on A2 and B2 emission scenarios. The scenarios do not predict large precipitation changes on an annual basis in Iceland, which agrees with low trends in annual flow in Iceland. The climate scenarios indicate that precipitation may increase substantially in NE-Iceland from 1961-1990 to 2071-2100 during mid-winter (Rögnvaldsson and Ólafsson, 2005), which the 1961-2000 historical trend agrees with (Jónsdóttir *et al.*, 2005). The scenarios indicate, however, an increase in precipitation in S-Iceland in the autumn (Rögnvaldsson and Ólafsson, 2005), the only season where the historical trend indicates decrease in precipitation and to some extent in streamflow in SW-Iceland.

The general increase in winter and spring streamflow seen in the historical time series and predicted in the scenarios will influence the hydropower sector by reducing the importance of large reservoirs to ensure the energy demand during late winter and early spring. Thus, there might be a change in the operation of reservoirs during the year. For example, it would be economical to reduce the water level in the late autumn and the beginning of the winter, to reduce the risk of flood loss in these periods. However, even though there are some trends towards increased annual discharge, there are no signs of less severe dry years or series of dry years. Therefore the reservoirs with hyper-annual storages will still be important.

6 Conclusions

A Nordic analysis of trends in streamflow is described based on annual as well as seasonal and extreme values. In most catchments there are no changes, but distinct regional patterns are found for all time periods. Radziejewski and Kundzewicz (2004) comment that statistical tests are not able to detect weak trends, but that this cannot be seen as a proof of no change. Based on this statement and the fact that in general more than 5% significant trends were found, it appears likely that the streamflow in the Nordic countries has changed, even though the trends found will depend on the period analysed.

There are large areas with increased annual discharge for the periods 1941-2002 and 1961-2000. This increase is mostly absent in 1920-2002 due to some wet, but cold years in the beginning of this period. It should be noted, however, that none of the periods include regions with significant trends toward a decrease in annual flow. This is a result of all periods ending in 2000/2002, where the last decade includes many mild and wet years. Studying other periods could have changed this picture as the trends found are a result of the period analysed.

The winter and spring seasons have a distinct increase in streamflow in large parts of the Nordic region. This is again a result of the warm and wet period after about 1990. However, the positive trend is also present for the longest period. This can be explained by the low temperatures leading to precipitation being stored as snow in these seasons in the 1920s; hence even if the annual discharge was high, the winter and spring discharge was not. However, the summer discharge in the 1920s was high, either due to snowmelt, abundant precipitation or a combination of both, leading to a distinct negative trend in summer streamflow for the period 1920-2002 that is not found for the two other periods. Also 1941-2002 has a decrease in summer flow, whereas there is an increase in central and northern Norway and northern Sweden for the period 1961-2000. For the autumn period no trends are found.

Recent flood and drought events are often seen as an effect of human induced climate change. Our findings do not support a theory of increasing rain floods and decreasing snowmelt floods as for example found in the scenarios for Norway (Roald *et al.*, 2006), as no clear patterns are found related to the magnitude of the flood peaks. However, the fact that the 1920s were cool is also reflected in the flood timing as the signal of an earlier timing of the spring flood is maintained for the period 1920-2002.

It can also be concluded that if the observed temperature increase is a result of human induced climate change, then also the increase in winter and spring streamflow and the earlier timing of the spring flood is a result of human induced climate change. This impact of continuing rising temperatures on snow-cover dynamics will in turn alter the hydrological regimes and thereby water management in general, including the hydropower potential.

A further study should include trend studies of precipitation and temperature. The authors would like to emphasize that 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.

Acknowledgements

The research described in this paper was supported by the Climate and Energy project funded by the Nordic Energy Research, the Nordic energy sector, the Norwegian Water Resources and Energy Directorate and the Swedish Meteorological and Hydrological Institute. The organisations that contributed data to the database; the National Environmental Research Institute – Denmark, the Norwegian Water Resources and Energy Directorate, the Finnish Environment Institute, the Swedish Meteorological and Hydrological Institute and the National Energy Authority in Iceland, are gratefully acknowledged. We thank T. Tonning at the Norwegian Water Resources and Energy Directorate for producing the maps and T. Fjeldstad and E. Klausen for loading the data into the database.

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This series is published by Norwegian Water Resources and Energy Directorate (NVE)

Published in the Report series 2010

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