Historical runoff variation in the Nordic countries

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Abstract The regional variability of the runoff in the Nordic countries has been examined by analysing 160 long-term series of daily discharge. The study area was grouped into 13 regions with similar temporal behaviour of the annual runoff. Index series were developed for each region. The series were tested for trend and jumps. An increase has been found in southwest Norway and in Denmark, especially since 1980. Series from southern Sweden show a decrease at the same time. The increase in the maritime exposed areas are most significant in the autumn and early winter. The behaviour of the runoff series has been compared to the behaviour of selected precipitation series. The increase in runoff in southwest Norway is reflected in a similar increase in the precipitation in the same period.

INTRODUCTION

Based on scenarios of future temperatures and precipitation and a modified rainfall-runoff model, simulation experiments indicate changes in the runoff regime of the Nordic countries as shown by Sælthun et al. (1994). A rise in the temperature will reduce the accumulation of snow, which has a dominating effect on the present seasonal regime. The effects should be possible to identify in the long-term time series of runoff data.

The long-term variation of the runoff has been examined in a number of national studies by Roald & Sælthun (1990), Jutman (1991), and Hiltunen & Hyvärinen (1992). Lindstrem (1993) has studied trends in floods in Sweden. Long-term variability in meteorological time series has been studied by Aune (1989), Førland & Bauer (1992), Alexandersson & Eriksson (1989), Frich (1990) and Heino (1994). Hiltunen (1994) has shown that long periodic fluctuations in runoff in Finland are linked to changes in precipitation and evaporation. Tveito & Hisdal (1994) have compared long homogeneous time series of precipitation and runoff to identify variation in time and space. Clark et al (1992) have studied trends in precipitation, evaporation and runoff from nine catchments in Denmark. This paper summarizes results of an ongoing study by the Hydrological Institutions in the Nordic countries (Hisdal et al., 1995, 1996). WMO (1988) has also done a regional study on long-term variability of the runoff.
DATA

The Norwegian Water Resources and Energy Administration, NVE, serves as a regional data centre for the Nordic countries in FRIEND-NE. A subset of the FRIEND database has been implemented as an extension of the national Norwegian hydrological database. The selection of data from the Nordic countries was supplemented with daily flow data from a number of long-term stations, mostly from larger basins than in the original FRIEND database, resulting in a Nordic data set of 160 stations long-term data series. Data was also obtained from Estonia, Greenland and the Faeroe Islands. The data series from Greenland and the Faeroe Islands were, however, too short and too incomplete to be applicable to this study.

Some of the data series are unaffected by reservoirs or diversions for hydropower production or other human activities. These data series were considered as suitable for study of the seasonal variability as well as the extremes. For other series affected by regulations, naturalized flow series have been calculated. These series were considered suitable for study of the seasonal variability, but not for study of the extremes. Some series are affected by reservoirs, but not by diversions in or out of the upstream basin. Because very few reservoirs operate as buffers over several years, these series were considered suitable for analysis of annual values. The data set was thus divided into three quality categories according to their suitability for analysis of extremes, seasonality and annual values.

A map showing the location of the gauging stations included in the study is shown in Fig. 1. The part of the database used in this study is summarized in Table 1.

![Fig. 1 Map of the study area. The centre points of the basins for the stations included in the study are shown on the map.](image-url)
Historical runoff variation in the Nordic countries

Table 1 Summary of the discharge series on the Nordic FRIEND database.

<table>
<thead>
<tr>
<th>Country</th>
<th>No. of series</th>
<th>Record length (years)</th>
<th>Quality category:</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>1</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>2</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>3</td>
</tr>
<tr>
<td>Denmark</td>
<td>25</td>
<td>41-75</td>
<td>23</td>
</tr>
<tr>
<td>Estonia</td>
<td>5</td>
<td>47-67</td>
<td>5</td>
</tr>
<tr>
<td>Faroes</td>
<td>6</td>
<td>4-11</td>
<td>6</td>
</tr>
<tr>
<td>Finland</td>
<td>34</td>
<td>41-144</td>
<td>25</td>
</tr>
<tr>
<td>Greenland</td>
<td>2</td>
<td>10-13</td>
<td>2</td>
</tr>
<tr>
<td>Iceland</td>
<td>7</td>
<td>40-61</td>
<td>6</td>
</tr>
<tr>
<td>Norway</td>
<td>55</td>
<td>41-111</td>
<td>47</td>
</tr>
<tr>
<td>Sweden</td>
<td>25</td>
<td>68-152</td>
<td>18</td>
</tr>
</tbody>
</table>

Quality categories are:
1. Annual values, seasonal values and extremes,
2. Annual and seasonal values and
3. Annual values only.
Some series were later discarded because of unsatisfactory record lengths or because of suspicion of inhomogeneities in the series.

REGIONALIZATION

The study area was divided into 13 regions with similar behaviour of the annual runoff based on the following procedure (Arnell et al., 1989):
(a) Calculation of annual values.
(b) Standardization of each series in order to remove scale effects due to differences in the size of the drainage basin. Each annual series was standardized by subtracting the long-term mean value and by division by the long-term standard deviation.
(c) Identify spatially coherent groups of series with similar temporal behaviour based on the cross-correlations between the series.
(d) For each region an index series was derived based on the annual values expressed as percentages of the long-term average of each series. The regional mean value was calculated by averaging the percentages for all series within the region for each year. Since the individual series comprising a region was of different length, a correction was applied. This correction was based on two averages: The average for the common period of all series in the region and the average for the common period of the series for the specific year.

The resulting regionalization is summarized in Table 2.

The timing and degree of the snowmelt contribution to the seasonal cycle differ from basin to basin and from region to region. One or two "typical" series were therefore chosen for each region as basis for an analysis based on seasonal and extreme values. Each of the selected typical series was analysed for four seasons, based on a division of the year into seasons, depending on the seasonal regime in each region.

STATISTICAL ANALYSES

The following analyses were applied to the regional index series and the seasonal runoff series: Visualization of the general behaviour by Gauss filtering, as shown in
Table 2 Summary of the regionalization.

<table>
<thead>
<tr>
<th>Region</th>
<th>Name</th>
<th>No. of series</th>
<th>First year*</th>
<th>Last year</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>Iceland</td>
<td>6</td>
<td>1947</td>
<td>1991</td>
</tr>
<tr>
<td>II</td>
<td>Northwest Norway</td>
<td>25</td>
<td>1901</td>
<td>1991</td>
</tr>
<tr>
<td>III</td>
<td>Southwest Norway</td>
<td>9</td>
<td>1892</td>
<td>1991</td>
</tr>
<tr>
<td>IV</td>
<td>Central Scandinavia</td>
<td>15</td>
<td>1872</td>
<td>1991</td>
</tr>
<tr>
<td>V</td>
<td>Northern Finland, Sweden and northeast Norway</td>
<td>8</td>
<td>1911</td>
<td>1991</td>
</tr>
<tr>
<td>VI</td>
<td>Central and southern Finland</td>
<td>29</td>
<td>1871</td>
<td>1991</td>
</tr>
<tr>
<td>VII</td>
<td>Estonia</td>
<td>5</td>
<td>1922</td>
<td>1989</td>
</tr>
<tr>
<td>VIII</td>
<td>Southeast Norway and Central Sweden</td>
<td>20</td>
<td>1871</td>
<td>1991</td>
</tr>
<tr>
<td>IX</td>
<td>Southern Sweden</td>
<td>7</td>
<td>1871</td>
<td>1991</td>
</tr>
<tr>
<td>X</td>
<td>Eastern Denmark</td>
<td>13</td>
<td>1918</td>
<td>1991</td>
</tr>
<tr>
<td>XI</td>
<td>Western Denmark</td>
<td>12</td>
<td>1918</td>
<td>1991</td>
</tr>
<tr>
<td>XII</td>
<td>Glaciers Iceland</td>
<td>2</td>
<td>1939</td>
<td>1991</td>
</tr>
<tr>
<td>XIII</td>
<td>Glaciers Norway</td>
<td>2</td>
<td>1900</td>
<td>1991</td>
</tr>
</tbody>
</table>

* This is normally the first year of the longest series. Some series start earlier (1847 in Region VI, 1807 in Region VIII and 1858 in Region IX), but have not been included in the analysis.

Fig. 2. The following trend tests were applied: Spearmann and Mann test. Schumann (1994) has developed a jump test based on split sample techniques to identify sudden shifts in a time series. The jump test includes: (a) Mann-Whitney-Wilcoxon (rank) test, (b) chi-square test (on the assumption of normal or log-normal distribution), (c) $F$-test (on differences of the variances), and (d) $t$-test (on differences of the mean). The non-randomness of the index series was examined by the run test and by calculating the autocorrelations. A significance level of 5% was chosen for all tests.

RESULTS

The regional annual index series are shown in Fig. 3 for all the regions. Figure 4 summarizes the regional distribution of changes in the annual runoff for the period.
1930–1980. The seasonal index series for the autumn are shown in Fig. 5. Figure 6 summarizes the regional distribution of changes for all four seasons.

The only region with a significant trend for the annual index series is region IX—southern Sweden. This decreasing trend is also significant for all the seasons. The positive trend in region III—southwest Norway and in region XI and X—Denmark is not significant for annual values, but is strongly significant from 1960 onwards. The positive trend in the autumn series is significant for region III and significant for all seasons in region XI. The jump test indicates a clustering of positive jumps from 1960 to 1980, with negative jumps in earlier periods. Combining the results of the trend test, the jump test and the Gauss filtered values, we conclude that the runoff has increased in regions III, XI and X, and has decreased for region IX and XI. The runoff in Iceland seems to decrease when it is increasing in other parts of the study area. The higher flow values at the start and at the end of

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**Fig. 3** Gauss filtered regional series (filter width approximately 27 years) for all regions.
the period for Estonia seems also to be present in some degree in series from Finland. This pattern is also found in Russia by Semyonov & Alexeyeva (1994).

**COMPARISON WITH METEOROLOGICAL TIME SERIES**

A number of long-term monthly precipitation and temperature series has been
selected and added to the database. The series were selected to be representative for the basins of the “typical” series. For the Finnish basins area precipitation series were obtained, otherwise the series were observed at locations within or near each basin. Some of these series have been homogenized. Linear trends were fitted to the precipitation and runoff series in order to quantify the magnitude of the trends for two standard periods: (1921–1990) and (1960–1990). The series were also tested for jumps for the same periods. The results have been compared, and the results are summarized in Table 3. The difference between observed precipitation and runoff was also examined. For Iceland and Norway the specific runoff expressed in mm per year exceeds the observed precipitation considerably, in particular in the mountainous areas, where the precipitation stations are located at low altitudes.

Fig. 6 Gauss filtered regional series (filter width approximately 27 years) for the autumn season.
Table 3 Summary of the comparison of trends and jumps in the precipitation and runoff series.

<table>
<thead>
<tr>
<th>Period</th>
<th>No. of series</th>
<th>No. of series with matching trends*</th>
<th>Significant trends either parameter</th>
<th>Matching jumps</th>
</tr>
</thead>
<tbody>
<tr>
<td>1921–1990</td>
<td>15</td>
<td>8</td>
<td>7</td>
<td>7</td>
</tr>
<tr>
<td>1961–1990</td>
<td>28</td>
<td>17</td>
<td>7</td>
<td>13</td>
</tr>
</tbody>
</table>

* Not necessarily significant.

DISCUSSION

A regional index series will be smoother than the individual index series within the region. Since few series are contributing to the early part of the series, compared to the latter, this smoothing will be most pronounced towards the end of the series. By applying trend tests, it is expected that there will be a less significant trend than by analysis of single series. The results do not indicate that a linear trend is a realistic model for describing the variability of the time series. Trend analysis is dependent on the start and end value of the series under consideration. By simply moving the period one year, the sign of a linear trend can be reversed as shown by Jutman (1991). The seasonal analysis is based on “typical” series, where man-induced redistribution of the seasonal flow is not expected to occur. Trends occur more significant in these series, and this reflects to some degree real seasonal redistribution, but some noise will be generated by the procedure of splitting the year into fixed seasons.

By looking at the longest series within the data set we see that each series comprises humid periods with spells of dryer years in between. The humid periods are often characterized by more floods and droughts than in other parts of the series. In southern Norway and Sweden, such a spell can be found in the 1860s and into the 1870s, from the mid 1920s to 1940 and from the 1980s. Comparison of dry and wet spells in different regions, demonstrates that a wet spell in one region is frequently accompanied by a dry spell in a region on the other side of a mountain range. The run test indicates significant non-randomness in regions I, II, VII, VIII, IX and XI. The autocorrelations of the regional series differ from region to region, but few significant autocorrelations have been found. The jump test indicates that the shift from a humid period to a dry period, occurs as one or more jumps rather than as a gradual trend. A possible explanation of this may be found in a change of the general circulation over the study area, a topic which is studied by Førland (ed., 1996). The Scandinavian Peninsula is characterized by mountain ranges to the west, with lowland to the east. A small change in the circulation can therefore easily lead to significant changes in the precipitation and runoff as found in this study.

The analysis of annual precipitation series for standard periods of 1921–1990 and 1961–1990 indicates that the recent trend occurring in the flow in west Norway is reflected in the trends of the seasonal series of the annual precipitation. Most regions did not have significant trends in the runoff. The lack of similarity in the trends is also caused by lack of representativity of the precipitation station selected for the study. Some basins are quite large (up to 68 000 km²). One or two precipitation stations are obviously insufficient to define an index of the area precipitation for such basins. The precipitation series may also be affected by changes in exposure and measuring procedures over time. The Norwegian meteorological institute has applied
corrections to homogenize a number of long series, but there may still be inhomogenities in the series. The flow series does also most likely contain some inhomogeneities because of gradual land use changes and errors in the rating curves. Hanssen-Bauer et al. (1996) have shown that the measuring error of precipitation is likely be reduced by increasing temperatures. The loss caused by catch deficiency is considerably higher for snow than for rainfall. This could result in false trends in precipitation series.

The annual runoff is not only dependent on precipitation but also on the evapotranspiration, which is likely to have more effect in the eastern drier lowland. Examples of this have been found in eastern Sweden. This is expected to be more related to the air temperature in the warm season. The study includes also some basins with a considerable fraction of glaciers. The annual discharge is also more dependent on the temperature of the melting season for these series. The dependencies on the temperature will be examined in the next phase of the project.

CONCLUSION

The long-term variability of number of long-term runoff series from the Nordic countries has been analysed. Based on annual flow indices, 13 regions with similar temporal flow patterns have been identified for the study area. Although a significant long-term trend has been found for only one regional series of annual values, clear regional patterns can be identified for parts of the study area, in particular the western part where a rise has occurred in recent years. Similar increases have also been noted for series in parts of UK, Arnell et al. (1990), in the Netherlands and in the Rhine basin.

By analysis of seasonal averages of “typical” series more significant trends can be found. There are some indications of a seasonal redistribution of the flow with a significant increase in autumn flow, in particular in southwest Norway and in western Denmark which can be explained by a similar increase in the precipitation.

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