Long-term changes in the discharge regime in Finland

Johanna Korhonen and Esko Kuusisto

ABSTRACT

This paper presents characteristics of the discharge regime, long-term trends and variability in Finland. A selection of long-term discharge records including both unregulated and regulated rivers and lake outlets were analysed up to the year 2004. In addition to individual time series, monthly and annual discharges from the territory of Finland were calculated for the period 1912–2004. The observed drought and flood periods are also discussed, as well as the connection between discharge regime and climate. Moreover, the periodicity of the time series is examined for a couple of sites. The Mann–Kendall trend test was applied to assess changes in annual, monthly and seasonal mean discharges, maximum and minimum flows and, in addition, the date of the annual peak flow. The trend analysis revealed no changes in mean annual flow in general, but the seasonal distribution of streamflow has changed. Winter and spring mean monthly discharges have increased at most of the observation sites. The spring peak has moved to an earlier date at over one-third of the sites. However, the magnitudes of spring high flow have not changed. Autumn flow did not show trends in general. Minimum flows have increased at about half of the unregulated sites.

Key words | discharge, Finland, rivers, runoff, time series, trends

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INTRODUCTION

Water resources are highly dependent on climatic conditions. The runoff regime is affected by both precipitation and temperature changes, as well as by changes in radiation balance. Finland belongs to the so-called humid zone; a typical feature is the abundance of water bodies and peatlands. However, the water situation may vary greatly from year to year. Within a year, there is a considerable difference between the winter, when most of the precipitation is stored in the snow cover, and the summer, when a major part of the rainwater evaporates. Overall, slightly over half of the annual precipitation evaporates and the remainder flows into the seas or across the borders.

Annual mean temperatures in Finland increased by about 0.7°C during the 20th century (Jylhä *et al.* 2004). In particular, the springs have become warmer (Tuomenvirta 2004). Climate scenarios predict further warming and increasing precipitation, particularly in winter (Jylhä *et al.* 2004). Both droughts and floods are expected to intensify, at least to some extent. The discharge regime is also expected to change; mean annual and winter flows should increase, whereas summer flows may decrease (Beldring *et al.* 2006). Since discharge can be measured more precisely than other water balance components, it is interesting to study observed changes in the Finnish streamflow regime hitherto. This paper examines whether any changes can already be noticed in the discharge records.

There are several earlier studies concerning long-term changes in the Finnish discharge regime. In the present study, the number of stations and variables in the analysis is higher than in previous studies. Additionally, the connection between climate and discharge regime, as well as periodicity, is looked at in more detail than in the other studies. Earlier studies have shown the increase in spring and summer high flows due to the extensive drainage of

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forest and peatlands (Hyvärinen & Vehviläinen 1981), the increase in winter flows in southern, western and central Finland due to warmer winters (Hyvärinen 1988, 1998, 2003; Hyvärinen & Leppäjärvi 1989; Hiltunen 1994) and the increase in annual flow during certain time periods (Hyvärinen 1988, 1998, 2003). Kuusisto (1992) presented monthly and annual runoff from Finland for the period 1931–1990. No changes in annual runoff were found, whereas winter discharges had increased due to the regulation. In addition, Finnish streamflow records have been included in the Nordic runoff studies conducted by Hisdal *et al.* (1995, 2003, 2004) and Roald (1998). Effects of climate change on water resources in Finland have been presented by, for example, Vehviläinen & Lohvansuu (1991), Hiltunen (1992, 1994), Vehviläinen & Huttunen (1997), and by Beldring *et al.* (2006) in all Nordic countries. Results of these Nordic and Finnish studies are similar to the ones mentioned above.

DATA AND METHODS

The flow regimes in the rivers and lake outlets in Finland were investigated using the records of the Finnish Environment Institute. Among other things, typical annual regime, variation and trends of discharge are discussed in this paper. Twenty-five discharge time series, for both unregulated and regulated rivers and lake outlets, were examined. Many of the watersheds in Finland are regulated. Most of the regulation schemes were started in 1945–1970 in order to reduce flooding, to produce hydropower, to facilitate water transportation and to improve the water supply.

Discharge data from unregulated stations were determined by the rating curve method using the continuous daily water level data. Data of regulated sites were obtained from the hydropower plants or by the rating curve method if the station was not situated at a hydropower plant. All discharge sites at hydropower plants are listed in Table 1 by the abbreviation HP. The original data consist of daily mean discharges from each station. Monthly means were calculated from the original daily data, and these monthly data were used in the analyses. The longest continuous records date back to the mid-1800s. The Lake Saimaa water level time series and the corresponding discharge time series for the River Vuoksi are available since 1847 and the discharge time series at Muroleenkoski since 1863. Most of the observation series examined in this study started in the 1910s–1930s. The study sites and their locations are presented in Table 1 and Figure 1. This paper presents some results of a more extensive study concerning the discharge and water level regime in Finland (Korhonen 2007).

Besides analysing the individual time series, monthly and annual mean discharges from the territory of Finland were calculated for the period 1912–2004. The total discharge was determined according to Kuusisto's (1992) earlier analysis. It was calculated by combining different discharge records from all available drainage basins. Since the different stations had different periods of records, the runoff was estimated by using several combinations of stations. In the year 1911, discharge observations covered about 67% of the present area of Finland. In the early 1990 s, 13% of the country still remained ungauged. The discharge from the ungauged part of each subregion has been estimated by dividing that area among the gauged nearby basins. In most cases this has been rather straightforward, although the accuracy of the results can be questioned. In some cases the replacing station has been located far away, implying the risk of large estimation errors. This is the case particularly for the Archipelago Sea and White Sea subregions until the 1950s. On the other hand, these subregions cover only 4.9% of the country. Many observation series have gaps or station relocations. Each change implies a new set of coefficients for the computation. In a few cases negative coefficients were also involved, either to subtract flow from the territory of a neighbouring country or to take into account large differences in lake percentages. (Kuusisto 1992) A decrease in the number of discharge stations in the mid-1990s caused some adjustment to the coefficients and to the stations used to determine the total outflow from Finland, and therefore these values differ slightly from those derived by Kuusisto (1992). Since the number of stations included in the calculation of the total discharge from the territory of Finland was fewer in earlier years, a weighted trend analysis would have improved uncertainty slightly. However, it was not used since the determination of weights would have been complicated; a number of stations do not correlate linearly with covered subregions.

It is recognised that the trend analysis is highly dependent on the chosen time period. Since the starting year of individual observation time series varied considerably from the mid-1800s to the 1960s, it was decided that all data would be analysed for all the sites until the year 2004 for the longest available period. In addition, for unregulated data the period 1961–2004 was studied in order to obtain one uniform time period. For the regulated data both unregulated and regulated time periods were included in the trend analysis.

Trend analysis was applied to annual mean discharges (calendar year), monthly mean and seasonal mean discharges; winter Dec–Jan–Feb (DJF), spring Mar–Apr–May (MAM), summer Jun–Jul–Aug (JJA) and autumn Sep–Oct–Nov (SON), annual maximum and minimum flows and date of the annual highest flow. Trends of low flow and high flow were not analysed for regulated sites. Total outflow from Finland was analysed for the period 1912–2004 on the monthly, seasonal and annual level. Trends were tested statistically with a non-parametric Mann–Kendall trend test. The level of 5% was used for critical significance. Significances of 5%, 1% and 0.1% are shown in the trend tables. Trend magnitude was calculated using a non-parametric linear Sen's slope estimator (Sen 1968). The result of the Mann–Kendall test depends strongly on the autocorrelation. If there is a positive

Table 1 | Discharge observation period, drainage area (A, km^2) and lake percentage of the drainage basin (L, %). HP means that the observation site is a hydropower plant

Observation site	Observations since	A (km^2)	L (%)
Unregulated			
1. Lieksanjoki, Ruunaa (lake outlet)	1931	6,260	14
2. Pääjärvi (lake outlet)	1911	1,210	7
3. Nilakka, Äyskoski (lake outlet)	1896	2,157	18
4. Vantaanjoki, Oulunkylä (river)	1937	1,620	3
5. Aurajoki, Hypöistenkoski (river)	1948	350	0
6. Kitusjärvi (lake outlet)	1911	550	10
7. Muroleenkoski (lake outlet)	1863	6,100	12
8. Lestijärvi (lake outlet)	1921	360	21
9. Lentua (lake outlet)	1911	2,050	13
10. Ounasjoki, Marraskoski (river)	1919	12,300	3
11. Tornionjoki, Karunki (river)	1911	39,010	5
12. Utsjoki, Patoniva (river)	1963	1,520	3
13. Juutuanjoki, Saukkoniva (river)	1921	5,160	5
Regulated			
14. Pielisjoki, Kaltimo (river, HP)	1911	21,080	13
15. Kallavesi, Konnus + Karvio (lake outlet)	1931	16,270	15
16. Vuoksi, Tainionkoski (lake outlet, HP)	1847	61,060	20
17. Päijänne, Kalkkinen (lake outlet)	1910	26,460	19
18. Kymijoki, Anjala (river, HP)	1938	36,280	19
19. Kokemäenjoki, Harjavalta (river, HP)	1931	26,120	11
20. Kyrönjoki, Skatila (river)	1911	4,830	1
21. Lapuanjoki, Keppo (river)	1931	3,950	3
22. Kalajoki, Niskakoski (river)	1931	3,070	2
23. Oulujärvi, Jylhämä (lake outlet, HP)	1896	19,840	13
24. Iijoki, Raasakka (river, HP)	1911	14,190	6
25. Kemijoki, Isohaara (river, HP)	1911	50,680	4

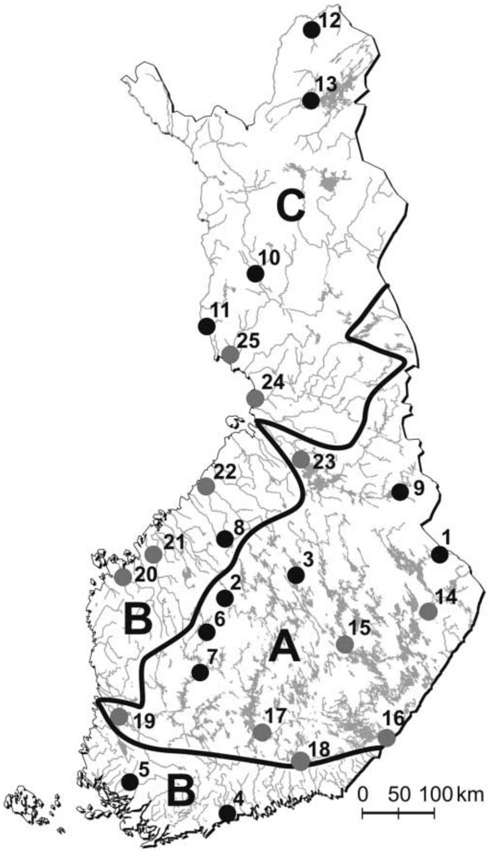

Figure 1 | A map of the locations of discharge gauging stations of this study. Black dots present unregulated sites and grey dots regulated sites. Regions A, B and C will be explained in the text.

autocorrelation in the time series, the test rejects the null hypothesis more often than without autocorrelation (von Storch & Navarra 1995). Thus, the test would increase the apparent level of significance of trend in a time series. Therefore, autocorrelation must be removed if it is statistically significant ($p < 0.05$). Some of the discharge data had a statistically significant autocorrelation at the time lag of one year. If the data were autocorrelated, the pre-whitening procedure presented by Wang & Swail (2001) was applied. The pre-whitening method removes serial autocorrelation from the time series. The trend significance is tested for the pre-whitened dataset. In most of the cases in this study, the differences between trends after and before pre-whitening were insignificant.

Although the Mann–Kendall tests for trend took account of serial correlation within each dataset, no account was taken of spatial correlation between the different sites, nor of correlations between the data sequences for different months within the same site. Both types of correlation, if present, would result in over-estimation of the number of significant trends found using a given level of statistical significance.

The data of annual precipitation and monthly mean temperature of Finland for 1912–2002 were obtained from the Finnish Meteorological Institute, based on Tuomenvirta (2004). The precipitation values are uncorrected, i.e. the yearly gauge corrections have not been made. The average gauge correction for the annual precipitation of Finland for the Wild precipitation gauge (until 1980) is 1.16, for the Tretyakov gauge (1981–present) it is 1.18 (Mustonen 1986). These correction values are used later in this paper when calculating the runoff–precipitation ratio. The NAO index data by Hurrell (1995) were obtained from the website: http://www.cgd.ucar.edu/cas/jhurrell/indices.html

RESULTS AND DISCUSSION

Discharge regime in Finland

This section gives first a short overview of the discharge regime in Finland based on the previous studies. At the end of the section some results of this study are introduced.

Precipitation is, of course, the primary factor affecting the discharge regime. In southern Finland the precipitation is higher than in the north. In the south the growing season is longer and evaporation is higher. Therefore, the runoff coefficient is higher in the north than in the south. The form of precipitation has a huge effect on the seasonal discharge regime. In the winter, precipitation is stored as snow; therefore, water levels and discharges are typically at their lowest in late winter. After that, the highest water levels and discharges are recorded in springtime or in early summer, due to snowmelt (Mustonen 1986).

Water levels and discharges usually decrease during summer when the evaporation is normally greater than the precipitation. If the summer is dry and warm, water levels can even drop below the winter minimum. In northern Finland the lowest water levels are normally reached in wintertime, but in the south, especially now that winter discharges have increased (Hyvärinen & Vehviläinen 1981;

Hyvärinen 1988, 1998, 2003; Hyvärinen & Leppäjärvi 1989), the lowest levels are often recorded in the summer. In autumn, evaporation decreases and rainfall increases water levels and discharges. In the small rivers of the southern and western coast, the annual high flow may also occur in autumn, summer or winter. In the unregulated rivers of northern Finland the highest flow is almost always recorded in spring or in early summer. When the winter period starts, water levels begin to recede again, because of minimal runoff formation when the soil is frozen and the precipitation falls as snow (Mustonen 1986).

River systems in Finland can be divided into three groups according to their discharge regimes (Mustonen 1986). The first group comprises the watersheds of lake regions mostly in southern and central Finland, where the large storage volume smoothes away seasonal discharge variations. The river systems of Vuoksi, Kymijoki and Oulujoki, as well as a large part of the Kokemäenjoki river system, are included in this category (Region A in Figure 1). Moreover, the waters of the Kuusamo region, which flow into the White Sea, and a few other lake-rich regions, belong to this group.

The second group (Mustonen 1986), small and medium-sized river basins with only a few lakes, is mostly found in the coastal regions along the Gulf of Finland and the Gulf of Bothnia. In these rivers, both floods and drought periods are common (Region B in Figure 1). The third group (Mustonen 1986) includes large rivers in northern Ostrobothnia and Lapland. Here water flows abundantly throughout the year, even though there are not many lakes (Region C in Figure 1).

The runoff regime of a drainage basin is affected by its area, shape and lake percentage (Mustonen 1986). In large and lake-rich drainage basins, water level and discharge variations are moderate compared to small drainage basins with a low lake percentage. In large lakes with large drainage areas, the annual maximum water level often occurs as late as in the end of the summer, e.g. in Saimaa, the largest lake in Finland. Water level and discharge fluctuations in rivers with small drainage basins are very rapid compared to those in lakes (Mustonen 1986).

In this present study we found out that the ratio between the mean annual high flow and mean annual low flow can be several hundreds in small rivers, whereas in lake outlets it is often less than ten. The ratio between the mean annual high flow and mean annual flow in outlets of large lakes can be as low as two, whereas in small rivers it can be more than fifteen. The typical standard deviation of annual mean discharge is 20–40%. It is largest in small southern rivers and smallest in the north. Similar values have been found out earlier by Kuusisto (1975). In Figure 2 three hydrographs are shown, representing different runoff regions (Mustonen 1986) in Finland which were described earlier.

As a result of this present study we found out that the mean annual discharge from the territory of Finland in 1912–2004 was 3,293 m^3/s. The standard deviation of

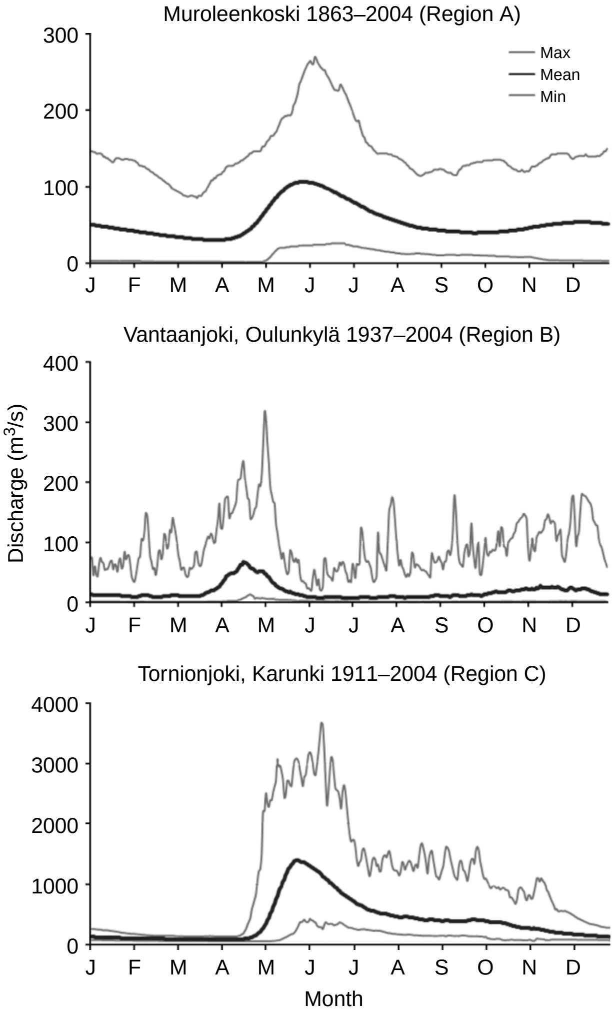

Figure 2 | Minimum, mean and maximum hydrographs for three unregulated discharge sites in different runoff regions. Note the different scales.

mean annual discharge was 18%. The variation percent for the total discharge from Finland was lower than for the individual stations, because regional differences even out. Normally the outflow is lowest in wintertime and peaks up in spring or in early summer. The highest monthly discharges have normally been recorded in May due to spring floods. The standard deviation of the monthly mean discharge was lowest in May (22%) and highest in September (35%). Monthly outflow from the territory of Finland is presented in Figure 3.

Droughts and floods

The interannual variation of annual precipitation is about 12% in Finland (Tuomenvirta 2004). Persistent drought (precipitation) periods are rare, as are prolonged periods with heavy rain. In addition, the role of lakes in streamflow attenuation is considerable. Therefore, extreme droughts and extensive floods are quite rare phenomena in Finland.

However, some serious droughts and floods have been observed in the perspective of extreme discharges. The most intense drought period occurred during the early 1940s. Another drought occurred in 2002–2003. The most memorable flood event was the Flood of the Broken Oath, in 1899, which also led to the establishment of the Hydrological Bureau in Finland (Kuusisto 2008).

In the period 1912–2004, the lowest annual outflow from the territory of Finland was 1,589 m^3/s in 1941 and the highest 4,702 m^3/s in 1981. The highest monthly mean discharge was 10,353 m^3/s in May 1920. On the other hand, the lowest monthly mean discharge was only 640 m^3/s in March 1942.

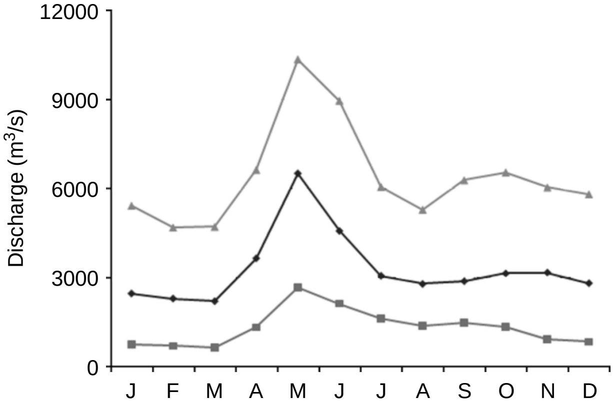

Figure 3 | Monthly mean, minimum and maximum discharge from Finland in 1912–2004.

At almost all observation sites, 1941 was the driest year on the annual level and the absolute minimum flows were recorded during the late winter or early spring of 1942. Only Lieksanjoki (minimum 1960), Kokemäenjoki (1942), Lestijärvi outlet (1942), Vantaanjoki (1940) and Vuoksi (1942) did not have a minimum annual flow in 1941. In Aurajoki and Utsjoki observations started later than 1941.

The year of the highest annual discharge has more variation between sites than the year of the minimum annual value. 1981 was the wettest year in the middle of lake-rich regions such as Pääjärvi, Kitusjärvi, Muroleenkoski and Päijänne, and also in the rivers outflowing from this region, Kymijoki and Kokemäenjoki. In other regions, the year of the maxima of these 19 sites were distributed among 12 different years. The years 1932, 1962 and 1974 were years of highest annual discharge for several sites.

The highest daily discharge recorded in Finland – at least in this database – has been 4,824 m^3/s at Isohaara, Kemijoki in May 1973. The mean annual high flow at this site is about 2,900 m^3/s. In other large rivers, the highest recorded daily discharges have been as follows: 1,170 m^3/s in Vuoksi at Tainionkoski (August 1899, the famous Flood of the Broken Oath), Kokemäenjoki at Harjavalta 918 m^3/s (May 1966), Oulujoki at Jylhämä 881 m^3/s (June 1899) and Kymijoki at Anjala 712 m^3/s (January 1975). All these large rivers in Finland are nowadays regulated, at least in the lower part of the river system.

Connection between discharge regime and climate

It is obvious that discharge variations are mainly caused by climatic factors. Precipitation is the main element affecting runoff. In the winter, snow accumulates in the terrain and it is released to the rivers and lakes in the springtime. Mild winters cause higher discharge due to snow melt and raining instead of snowing. In Finland, warm summers do not contribute to the summer discharge variation as much as warm winters to the winter discharge. Naturally summer temperatures are related to evaporation, which affects the discharge regime, but precipitation is of more importance (Mustonen 1986).

Atmospheric circulation affects the local climate considerably, since it governs the precipitation and temperature conditions. There are several oscillation indices which describe air pressure anomalies in different parts of the world. The North Atlantic oscillation index (NAO) is based on the difference in normalized sea level pressure between the Azores and Iceland. The NAO has an effect on the weather in Europe (Hurrell 1995) so that, when the NAO is strongly positive in wintertime, strong westerly winds bring mild and rainy weather to Northern Europe. Large negative NAO values are connected to weak westerly winds and cold winters. There are studies which show the influence of NAO on air temperatures (e.g. Chen & Hellström (1999)) and on winter precipitation in Northern Europe (Hurrell & Van Loon 1997; Uvo 2003). Several studies have presented a correlation between the NAO and discharge regime (e.g. Peterson *et al.* 2002; Bouwer *et al.* 2006; Danilovich *et al.* 2007).

Since precipitation, air temperature and the NAO index are all related to the discharge regime, connections between them were examined. Approximately half of the precipitation ends up in runoff on a yearly level. There is variation between different years; the runoff percentage from the total territory of Finland varied in 1912–2002 from about 30% to 65%, and the standard deviation was 6%. The runoff percentage was calculated by dividing each annual runoff by annual precipitation. This percentage was estimated from the original uncorrected precipitation data, which was corrected using the average gauge correction value of 1.16 until the year 1980 and 1.18 for 1981–2002 (Mustonen 1986). The proportion of runoff was, as expected, higher in wet years and lower in dry years. The correlation coefficient between annual precipitation (uncorrected) and mean runoff in Finland in 1912–2002 was 0.78 ($r^2 = 0.61$), which is statistically significant ($p < 0.001$). The correlation was higher in northern Finland than in southern Finland. Linear regression between mean runoff and annual precipitation is presented in Figure 4.

The connection between annual air temperature and discharge is much weaker than between annual precipitation and runoff: only 0.19 ($p < 0.10$) in northern Finland and 0.28 ($p < 0.01$) in southern Finland during the period 1912–2002. The correlation was strongest ($r = 0.38$, $p < 0.001$) between winter air temperature and winter discharge in southern Finland. The winter air temperature and discharge relationship was not statistically significant in northern Finland. This was an obvious consequence of the fact that winter air temperature usually remains below zero Celsius in the north, and changes below zero do not have much effect on discharge. In addition, in northern Finland the discharge regulation is implemented mainly in wintertime, thus also affecting the relationship between the discharge regime and temperature. On the other hand, the correlation between summer air temperature and summer discharge was higher in northern Finland ($r = -0.32$, $p < 0.01$) than in southern Finland ($r = -0.20$, $p < 0.05$). Correlations were positive for wintertime and negative for summertime, meaning warm winters generate more streamflow and warm summers less runoff.

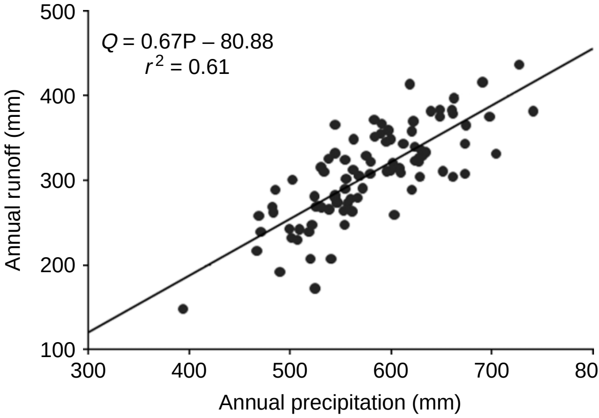

Figure 4 | Relationship between annual precipitation and annual mean runoff in Finland in 1912–2002. The annual precipitation in the regression figure is so-called uncorrected data, since yearly corrected values are not available.

Relationships between the NAO index and total outflow from Finland, and also between the NAO index and discharge at all unregulated sites of this study, were examined. Both annual flow and the annual NAO index, and winter flow and the winter NAO index, were investigated. The correlation coefficient between annual discharge from Finland and the annual NAO index in 1912–2002 was 0.24 ($p < 0.05$). The 20-year sliding correlation was also examined. The sliding correlation means that correlation was calculated for a 20-year time window, year by year. First it was applied for the time period of 1912–1931, then for 1913–1932, etc. There was a large variation in the correlation coefficient; in some of the 20-year periods it was close to zero, but it reached almost

0.6 at its highest. The correlation coefficient between the winter NAO and winter discharge in 1912–2002 was almost the same as for the annual discharge, 0.26 ($p < 0.05$). The 20-year sliding correlation showed remarkable variation, from −0.2 to 0.5. When individual time series of unregulated gauging stations in the period 1961–2002 were examined, the correlation coefficients for annual values varied from 0.03 to 0.42, and for the winter time from 0.05 to 0.58. The best correlation was found for the winter flow at the Hypöistenkoski rapids. In this small south-western drainage basin the winter NAO explained 34% of the winter flow variation. In this region, mild winters with snow melt and rainfall are common, and such winters are usually connected with strong westerly winds and, thus, the NAO.

Discharge trends

The discharge regime has changed over the decades on account of both climatic and human impacts. Human impact predominantly includes regulation, but land use, bog drainage and timber floating have also had some effect on the discharge regime in some river basins. Climate change has particularly affected the seasonal distribution of runoff.

The trend statistics for all the significant changes in total outflow from Finland are presented in Table 2. Time series of mean annual flow from the territory of Finland, as well as time series of mean winter, spring and summer flow in 1912–2004, are presented in Figure 5. There is no statistically significant change in the annual mean outflow from the territory of Finland in 1912–2004, but both the winter and spring mean discharges have increased about 4–5% per decade and summer mean discharges have decreased about 3–4% per decade in June and July. As most drainage basins in Finland are affected by regulation, trends of the monthly outflow from Finland are clearly influenced by regulation.

Changes in seasonal discharges were different in different regions. The influence of regulation was pronounced in northern Finland and in Ostrobothnia. Winter and spring discharges have increased mainly in the north, whereas a decrease in summer discharges was observed in southern Finland.

Table 2 | Statistically significant trends in different regions in 1912–2004, 1912–1960 and 1961–2004. Trends are presented as percentages of the corresponding mean values. Percentage is derived by first calculating the trend slope per year by Sen's method for the chosen time period, dividing the slope value by the mean value of this period and multiplying by ten to get trend per 10 years. Roman numerals refer to monthly mean discharge (I January, II February, etc), DJF to mean winter discharge, MAM to mean spring season and JJA to mean summer season. One plus or minus stands for 5% positive or negative significance, two pluses/minuses for 1% and three pluses/minuses for 0.1%, respectively

	Variable and period	+/−	Trend/10 yr
From the entire territory of Finland	II 1912–2004	+++	+4.6%
	III 1912–2004	+++	+5.1%
	IV 1912–2004	+++	+4.1%
	VI 1912–2004	−−−	−4.2%
	VII 1912–2004	−	−2.7%
	DJF 1913–2004	++	+3.2%
	MAM 1912–2004	+	+1.8%
	JJA 1912–2004	−−	−2.7%
	VI 1912–1960	−	−8.7%
	II 1961–2004	++	+7.0%
	JJA 1912–1960	−	−5.6%

Long-term changes in the individual discharge time series were similar to the changes in the outflow from Finland. Statistically significant trends of mean discharge, seasonal discharges, high flow and low flow found in this study are listed in Tables 3 and 4. Monthly trends were also calculated (not shown). Low flow and high flow trends at regulated sites were omitted due to the effects of regulation. Some graphs of discharge time series and their trends are presented in Figures 6 and 7. In general, there were more trends for the longer time periods than for 1961–2004.

At both unregulated and regulated stations changes were following. At most sites (64%) the winter and/or spring mean discharges have increased. Increase in monthly winter and/or spring discharges was observed at 72% of the sites. The increase of winter discharges was focused on late winter and the increase of spring discharges on early spring. Therefore, the rise of winter and spring discharges can be accounted for by the warming in winter and spring and the earlier snowmelt. The timing of spring peak flow has become earlier at over one-third (36%) of the observation sites. There is no overall change in the magnitude of spring high flow. Annual mean flow and annual high flow did not show statistically significant trends in general, apart from a

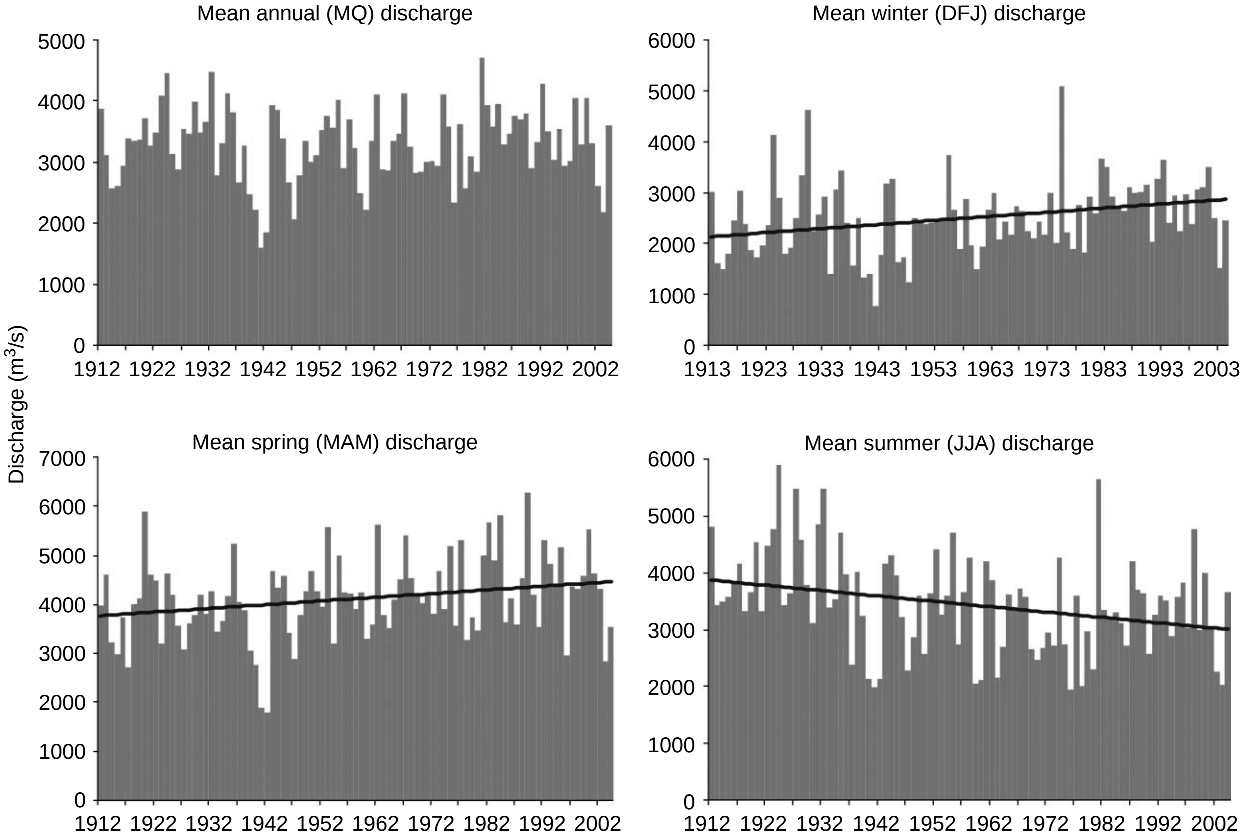

Figure 5 | Time series and trends of mean annual (MQ), winter (DJF), spring (MAM) and summer (JJA) outflow from the territory of Finland in 1912–2004. Only statistically significant trends are drawn in the graph.

few sites. There were no statistically significant changes in autumn flows in general. Changes in mean monthly or seasonal discharges – for those sites where change was statistically significant – were typically 2–10% of the corresponding mean flow per decade, in most cases not higher than 10%. Trends at the regulated sites were stronger than at the unregulated ones.

At unregulated sites in northern Lapland it appears more likely that winter discharges have decreased in some months, although in other parts of the country it was the opposite. At unregulated sites the advance in the spring peak flow date has, in most cases, been 1–3 days per decade. At one-quarter (23%) of the unregulated sites, discharge has increased at least in some summer months. At about half (46%) of the unregulated observation sites the low flows have increased both in winter and summer.

Increases in winter discharges were mainly higher at regulated sites than at unregulated ones. At some regulated sites the release of water has been increased in winter and in early spring in order to create storage capacity for the snowmelt water. This explains the stronger winter and spring discharge trends at some regulated sites. At some regulated sites the advance in the spring peak flow date has been significant, ranging between 1–8 days per decade. There has been a decrease in some monthly summer discharges at slightly less than one-half (41%) of the regulated sites. The decrease of summer discharges at regulated sites can at least partly be explained by higher water release in winter and spring.

Periodicity of time series

There is a pronounced connection between climate and hydrology. The general circulation of the atmosphere is connected to weather conditions and thus also to the discharge regime. Previous studies have shown that NAO

Table 3 | Statistically significant trends of mean annual discharge (MQ), mean seasonal discharge, low flow (LQ) and high flow (HQ) and its timing at unregulated observation sites for the whole observation period and for 1961–2004. Trends are presented as percentages of the corresponding mean values. Percentage is derived by first calculating the trend slope per year by Sen's method for the chosen time period, dividing the slope value by the mean value of this period and multiplying by ten to get trend per 10 years. DJF means winter season, MAM spring season and JJA summer season. Monthly trends are left off due to the lack of space. One plus or minus stands for 5% positive or negative significance, two pluses/minuses for 1% and three pluses/minuses for 0.1%, respectively

Observation site and period	Variable and period	+/−	Trend/10 yr
1. Lieksanjoki, Ruunaa 1931–2004	No trends at all		
2. Pääjärvi, lake outlet 1911–2004	MAM 1911–2004	+	+2.8%
	LQ 1911–2004	+++	+6.1%
3. Nilakka, Äyskoski 1896–2004	Only monthly trends		
4. Vantaanjoki, Oulunkylä 1937–2004	DJF 1937–2004	+	+8.2%
	JJA 1937–2004	++	+6.3%
	LQ 1937–2004	+++	+10.0%
	HQ (spring) 1961–2004	−	−10.8%
5. Aurajoki, Hypöistenkoski 1948–2004	JJA 1948–2004	+	+9.1%
	DJF 1961–2004	+	+17.9%
6. Kitusjärvi, lake outlet 1911–2004	No trends at all		
7. Muroleenkoski, lake outlet 1863–2004	DFJ 1863–2004	++	+2.9%
	MAM 1863–2004	+++	+2.9%
	LQ 1863–2004	+++	+4.4%
	HQ–date (spring) 1863–2004	−−−	−1.0 days
8. Lestijärvi, lake outlet 1921–2004	MAM 1921–2004	+	+2.8%
9. Lentua, lake outlet 1911–2004	MAM 1911–2004	+	+2.4%
	LQ 1911–2004	++	+2.4%
	LQ 1961–2004	++	+6.5%
10. Ounasjoki, Marraskoski 1919–2004	LQ 1919–2004	++	+2.3%
	HQ–date (spring) 1961–2004	−	−2.5 days
11. Tornionjoki, Karunki 1911–2004	DJF 1912–2004	+++	+5.5%
	MAM 1911–2004	++	+3.7%
	MQ 1911–2004	++	+2.0%
	LQ 1911–2004	+++	+4.7%
	HQ–date (spring) 1911–2004	−−	−1.4 days
	MAM 1961–2004	+	+7.0%
	HQ-date (spring) 1961–2004	−	−2.9 days
12. Utsjoki, Patoniva 1963–2004	LQ 1963–2004	−−−	−9.4%
13. Juutuanjoki, Saukkoniva 1921–2004	HQ–date (spring) 1921–2004	−	−1.2 days
	HQ–date (spring) 1961–2004	−−	−3.3 days

and AO (Arctic Oscillation), which are related to the atmospheric circulation, have periodic behavior (e.g. Jevreva & Moore 2001; Jevreva *et al.* 2005). Thus, it is interesting to look at whether any periodicity is found from the longest river discharge and lake water level time series in Finland, since it have been found from other rivers (Pékarová *et al.* 2003) and from the sea level in Europe (Jevreva *et al.* 2005).

Two longest unregulated discharge time series were analysed (Muroleenkoski and Nilakka Äyskoski), as well as two water level time series (Saimaa and Tornionjoki). Data of annual mean values were analysed up to 2004.

Table 4 | Statistically significant discharge trends of mean annual discharge (MQ), mean seasonal discharge and timing of high flow at regulated observation sites. Trends for both the unregulated (UR) and the regulated (R) time periods, as well as for the whole observation period, are presented. Trends are presented as percentages of the corresponding mean values. Percentage is derived by first calculating the trend slope per year by Sen's method for the chosen time period, dividing the slope value by the mean value of this period and multiplying by ten to get trend per 10 years. DJF means winter season, MAM spring season, JJA summer season and SON autumn season. Monthly trends are left off due to the lack of space. Low flow and high flow trends were omitted due to the huge effect of regulation on those. One plus or minus stands for 5% positive or negative significance, two pluses/minuses for 1% and three pluses/minuses for 0.1%, respectively

Observation site and period	Variable and period	+/−	Trend/10 a
14. Pielisjoki, Kaltimo	JJA 1959–2004	+	+5.7%
(UR) 1911–1957	MAM 1911–2004	+	+2.0%
(R) 1959–2004			
15. Kallavesi, Konnus + Karvio	MAM 1931–1971	+	+8.7%
(UR) 1931–1971	HQ–date (spring) 1931–1971	−−	−4.7 days
(R) 1972–2004	HQ–date 1931–1971	−	−4.4 days
	MAM 1931–2004	+++	+5.5%
	HQ-date (spring) 1931–2004	−−	−2.4 days
16. Vuoksi, Tainionkoski	JJA 1950–2004	++	+6.6%
(UR) 1847–1949	SON 1847–2004	−	−0.7%
(R) 1950–2004			
17. Päijänne, Kalkkinen	MAM 1911–2004	+	+2.7%
(UR) 1911–1963	HQ–date (spring) 1911–2004	−−−	−4.2 days
(R) 1964–2004	HQ–date 1911–2004	−	−5.8 days
18. Kymijoki, Anjala	DJF 1939–2004	+	+5.7%
(R) 1938–2004	MAM 1939–2004	+++	+5.6%
	MQ 1939–2004	+	+3.7%
	HQ–date (spring) 1938–2004	−−−	−7.9 days
19. Kokemäenjoki, Harjavalta	DJF 1932–2004	+	+5.9%
(R) 1931–2004			
20. Kyrönjoki, Skatila	DJF 1912–1960	++	+17.2%
(UR) 1911–1960	DJF 1912–2004	+++	+7.4%
(R) 1961–2004			
21. Lapuanjoki, Keppo	Only monthly trends		
(R) 1931–2004			
22. Kalajoki, Niskakoski	Only monthly trends		
(UR) 1911–1970			
(R) 1971–2004			
23. Oulujärvi, Jylhämä	DJF 1950–2004	++	+6.4%
(UR) 1896–1949	DJF 1897–2004	+++	+7.3%
(R) 1950–2004	MAM 1896–2004	+	+2.2%
	JJA 1896–2004	−−−	−10.1%
24. Iijoki, Raasakka	HQ–date (spring) 1961–2004	−	−2.9 days
(UR) 1911–1960	MAM 1911–2004	+	+2.1%
(R) 1961–2004			
25. Kemijoki, Isohaara	DJF 1949–2004	+++	+13.1%
(UR) 1911–1948	DJF 1912–2004	+++	+9.8%
(R) 1949–2004	JJA 1911–2004	−	−2.4%
	HQ–date (spring) 1911–2004	−	−0.8 days

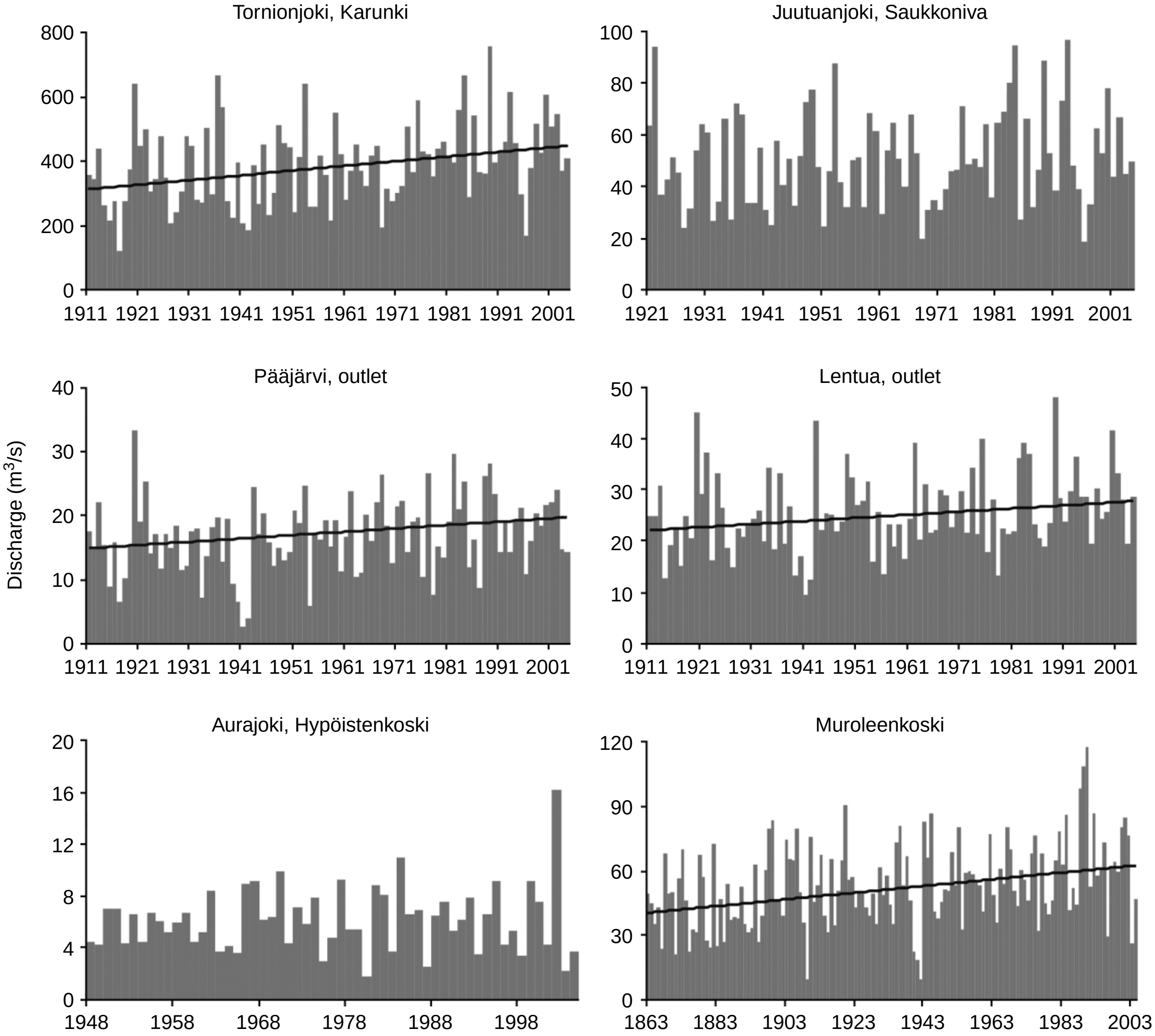

Figure 6 | Time series and trends of mean spring (MAM) discharge at some unregulated observation sites. Only statistically significant trends are drawn in the graph.

The longest of these time series was over 150 years and the shortest over 90 years. It is possible to identify the cyclicity in the time series by finding peaks in periodograms and autocorrelations. Both these methods were used by the ITSM program (Brockwell & Davis 2002). The analysis revealed that there is short- and long-term periodicity in these time series. The short-term cycle was 3–6.5 years and long-term cycle 27–31 years. Pékarová *et al.* (2003) found cycles of 3.6, 7, 13–14, 20–22 and 28–32 years in runoff time series of the major rivers of the world. In their study the nearest river to Finland was the Neva, in St. Petersburg, Russia. In this river, the peak of 28-year periodicity dominated, which is very similar to the Finnish data. Grötzner *et al.* (1999) found an approximately 30-year periodicity in North Atlantic Circulation. Jevreva & Moore (2001), as well as Jevreva *et al.* (2005), found both high-frequency (roughly 2–8 years) and low-frequency (13–30 years) signals in the Arctic Oscillation and North Atlantic Oscillation. Accordingly, the roughly 3–7 year and 30-year cycles in discharges and water levels in Finland might be explained by the atmospheric circulation periodicity pattern.

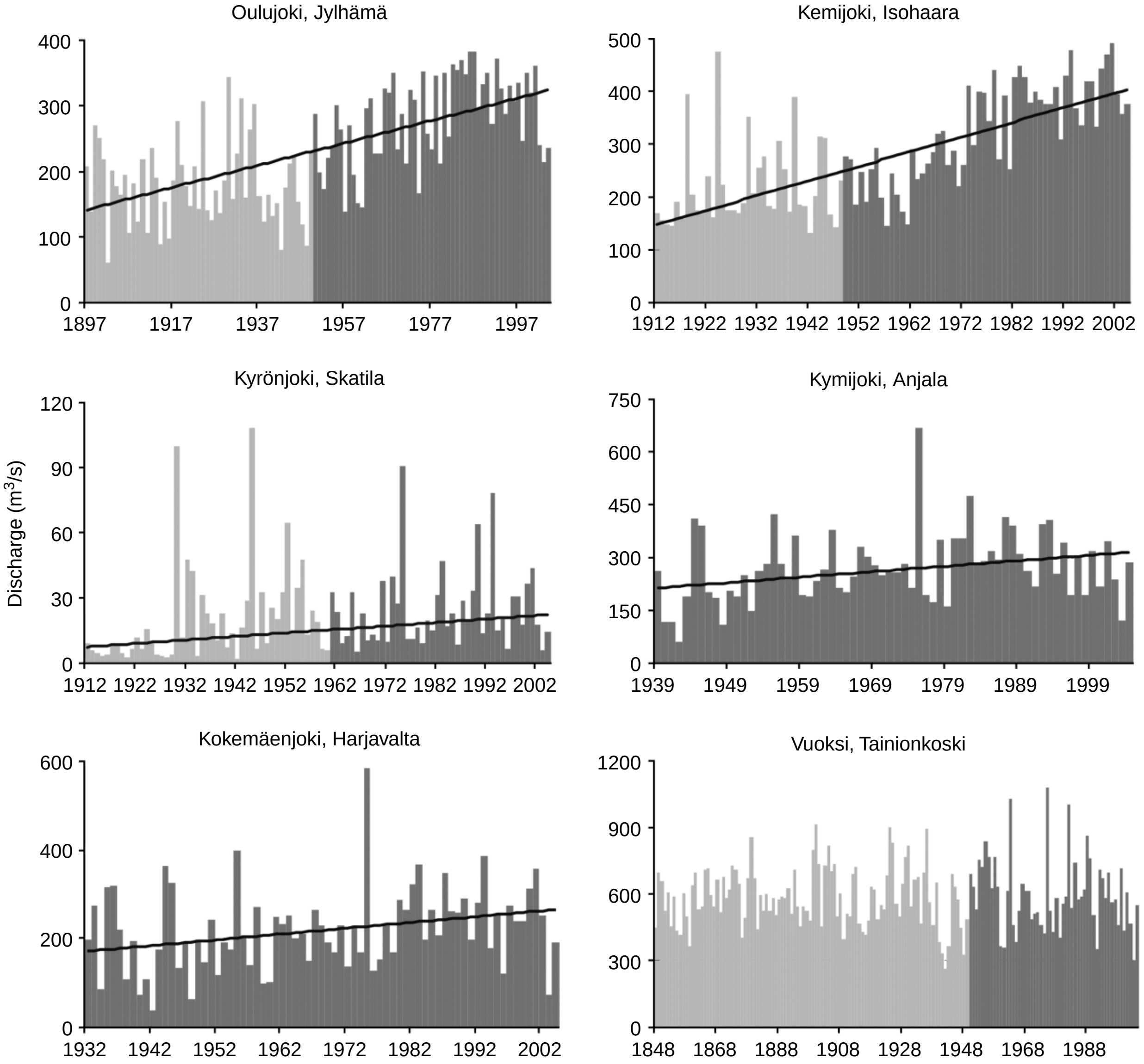

Figure 7 | Time series and trends of mean winter (DJF) discharge at some regulated observation sites. Different colours present the unregulated (light grey) and regulated period (dark grey). Only statistically significant trends are drawn in the graph.

Comparison with other trend studies

There are a number of earlier studies concerning long-term changes in runoff in Finland and in the Nordic and Baltic countries. Anterior studies of long-term changes in runoff or discharge regime have shown rather similar patterns to those observed in this study. The increase of winter discharges in southern and central Finland was presented first by Hyvärinen & Vehviläinen (1981). Later observations and analyses confirmed these findings (Hyvärinen 1988, 1998, 2003; Hyvärinen & Leppäjärvi 1989; Hiltunen 1994). Kuusisto (1992) presented the increase in winter discharges due to regulation. Differently from this present study, the increase of mean annual discharges in Finland were found for certain time periods by Hyvärinen & Leppäjärvi (1989) and Hyvärinen (1998). The Nordic studies of trends in runoff regime have revealed considerable differences in different parts of Fennoscandia (Hisdal *et al.* 1995, 2003, 2004; Roald 1998; Lindström & Bergström 2004). Mean annual discharges have increased, especially in some regions in Denmark and Sweden. Positive trends have also been found in Norway and Finland, depending on the chosen time period (Hisdal *et al.* 2004). In the period 1941–2002, statistically significant trends are found in Finland probably because the first year of the period (1941) was the driest ever observed in many places in Finland. In Iceland, annual values of discharge do not show clear trends (Jónsdottir *et al.* 2006). In Karelia, northwest Russia, the river runoff decreased during the 20th century (Filatov *et al.* 2005). In the Baltic countries, increases in winter and annual discharges have been observed (Reihan *et al.* 2007; Klavins & Rodinov 2008). It should be borne in mind that time periods in these separate studies differ from each other. Trends are naturally dependent on the chosen time period.

As mentioned earlier, discharges are naturally highly dependent on precipitation and evaporation. Long-term changes have not been detected for the precipitation time series in Finland (Tuomenvirta 2004), although in the other Nordic countries (Sweden, Norway, Denmark, Iceland) an increase has been observed (Hisdal *et al.* 2003; Jónsdottir *et al.* 2006). In Karelia, northwest Russia precipitation increased during the 20th century (Filatov *et al.* 2005). In the Baltic area especially the winter precipitation has increased (Reihan *et al.* 2007; Klavins & Rodinov 2008). The evaporation observations begin mainly in the late 1950 s in Finland, and therefore long time series as for precipitation and discharge are not available for Class A pan evaporation. However, for the period 1961–1990 no statistically significant trends were reported by Järvinen & Kuusisto (1995). Neither precipitation nor evaporation show remarkable long-term trends in Finland. Although changes in the streamflow have been observed in this area, the annual mean flow in unregulated streams has not changed in Finland in general. The main issue is the change in the seasonal distribution of the discharge regime; similar changes are also clearly evident from the climatic time series.

CONCLUSIONS

Long-term changes and variability in the discharge regime in Finland were investigated in this study. The discharge regime is highly dependent on the climatic conditions; precipitation is the main factor affecting runoff. The discharge peak flow usually occurs in the spring in the south and early summer in the north. In northern Finland the maximum flow of the year is always due to snow melt, but in southern Finland summer, autumn and winter high flows are also possible. The driest period in the 20th century concerning discharges within the territory of Finland occurred during 1941–1942. The highest outflow from the territory of Finland since 1912 was recorded in 1981.

This paper shows that statistically significant overall changes have not been observed in mean annual discharge, with the exception of a couple of time series. The most significant change has occurred in the hydrological regimes of winter and spring. Winters and springs became milder during the 20th century, and in consequence the late-winter and the early-spring mean discharges have increased. However, the magnitudes of spring high flow have not changed. The peak of spring flow has become 1–8 days earlier per decade at over one-third of all studied sites. The advance in peak flow date was larger at regulated sites than at unregulated. Regulation has increased the winter and spring mean discharges in some places. In addition, the regulation has, in some cases, decreased the summer flow. In contrast, at some unregulated sites summer flows have increased. Low flows have increased at about half of the unregulated sites due to an increase in both winter and summer discharges. There were no statistically significant changes in autumn flows in general. Changes in discharges were mainly 2–10% per decade at the stations where statistically significant trends were found, but at regulated sites somewhat more.

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