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Trends and Characteristics of Hydrological Time Series in Finland

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Hydrological time series analyses made in Finland up to 2001 show the following: 1) Precipitation has been increasing in southern and central Finland, and also in the north in winter, during the period 1911-2000. There are, however, no harmonized analyses of areal precipitation to show the exact increase. 2) The annual maximum of the areal water equivalent of snow has been increasing in eastern and northern Finland but decreasing in the south and west during the period 1947-2001. 3) The winter runoff has generally been increasing strongly in southern and slightly in central Finland during the 20th century. In northern Lapland there are no signs of increase in winter or annual flow. Annual discharge in the south and west has also increased to some extent. 4) The existing analyses show no signs of long-term trends in annual evapotranspiration. 5) Long-term fluctuations of water stage have been observed in the major groundwater formations. 6) The series of the date of ice break-up in the river Tornionjoki – starting in 1693 – shows that in recent decades the ice cover of the river has broken up about two weeks earlier than in the beginning of the period. 6) Lake ice maximum thickness series show no noticeable trend. 7) Lake water temperature in south-eastern Finland seems to have been increasing slightly during the period starting in 1924; in central and northern Finland no trends in water temperature have been observed.

Introduction

The purpose of this paper is to give an overview of hydrological time series analyses made in Finland until 2002 in order to study the possible role of climatic change in hydrological changes. Global climate scenarios predict that the increasing greenhouse effect will cause increasing temperatures and increasing precipitation in northern latitudes, where Finland is situated (between the 60th and 70th parallel). In average, various climate scenarios predict about 10% increase in annual precipitation and 3...5°C increase in annual mean temperature in Finland from the period 1961-1990 to the period 2070-2099. For winter the approximate figures are: precipitation +10...+30% and air temperature +4...+7°C. The predicted changes for summer are smaller, while scenarios for spring scatter between large and moderate changes (Jylhä 2002).

Climatic changes are expected to be reflected in many ways in the hydrology of Finland. Long-term observations and analyses will ultimately show how obediently Nature follows the scenarios and models. The results of hydrological time series, presented in this paper, are mainly based on the analyses made at the Finnish Environment Institute. During the period of SILMU (The Finnish Reserch Programme on Climate Change, 1991-1995), especially runoff/discharge analyses were made to determine possible hydrological changes in the Finnish territory, using both observed hydrological time series and models (Hiltunen 1994a and 1994 b; Roos 1996; Vehviläinen and Huttunen 1997).

This article describes, by selected representative examples, the trends and fluctuations in the Finnish hydrological time series observed up to 2001. The series have been selected so that climate change or variations – whatever their backgrounds may be – are the main reason for the hydrological variations. Thus, for example, discharge observation series strongly or moderately effected by forest draining or regulation of water *etc.* have been excluded in this approach.

Data

Most of the analyses described in this paper are based on the Finnish national hydrological data base (formerly called HYTREK, now HYDRO), which belongs to the major database HERTTA of the Finnish Environment Institute (SYKE) . This data base includes rather long data series of lake water level, river discharge, areal precipitation, areal water equivalent of snow, lake and river ice, water temperature, groundwater level, ground frost *etc.* The longest hydrological observation series in Finland, that of ice break-up in the river Tornionjoki, begins in 1693. The earliest lake level series and discharge series begin in 1847, and there are some ten other series longer than 100 years. From most main rivers there are observation series from 1911. Runoff of small lakeless catchments have been observed mainly from late 1950s; these series are not included in this app.roach. Pan evaporation, groundwater level and soil moisture series are only 25 to 42 years long now.

Discharge

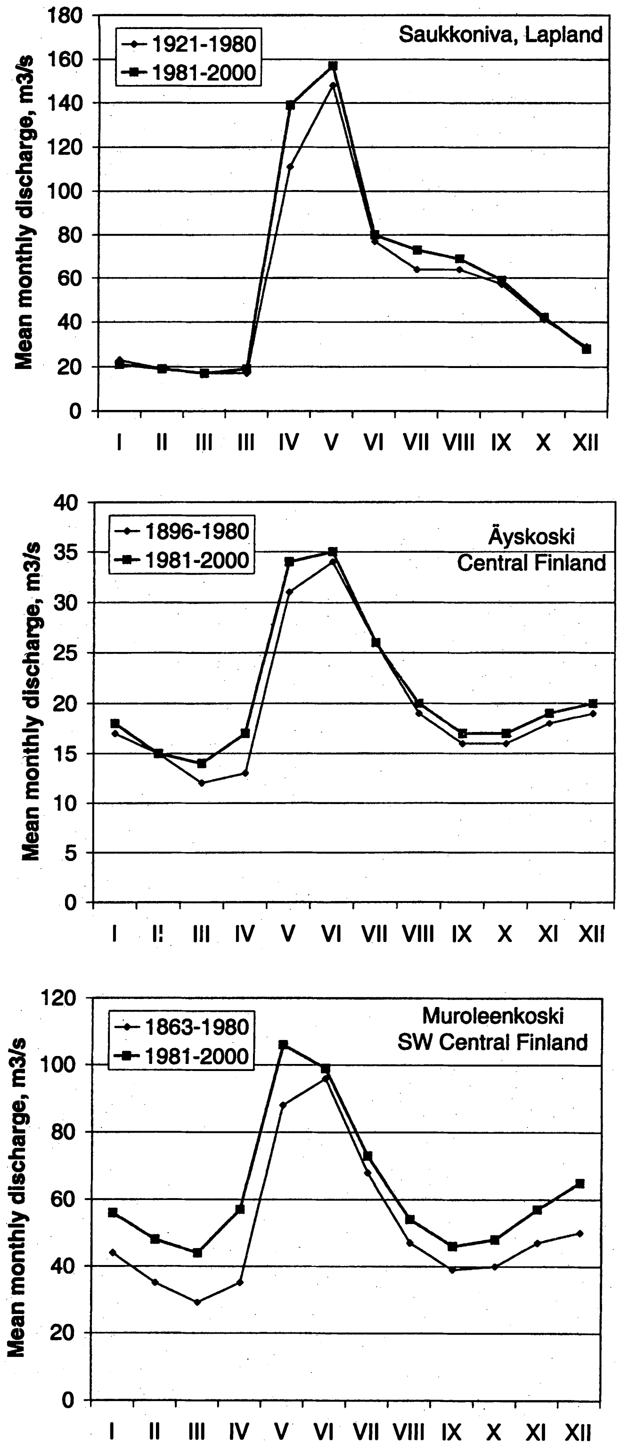
Discharge observation series from lake outlets are rather precise, even during winter, because the lake outlets are ice-free. At river stations ice cover, ice dams and frazil ice jams often disturb the stage-discharge relationship, and they have been excluded from this app.roach – except the stations of southernmost Finland from where undisturbed long term discharge observations from lake outlets are lacking and where ice reduction in river stations is rather low, so that also winter discharge for these stations has been estimated reasonably well.

The first time series analyses of discharge have been available since the end of 1970s, made in the Finnish Hydrological Office (Hyvärinen and Vehviläinen 1980). A rather clear increase in winter flow in southern Finland was then detected. Later observations and analyses have confirmed the strong increase in winter flow in south and west – as well as a clear increase in central parts of Finland, too. (Hyvärinen 1988; Hyvärinen and Leppäjärvi 1989; Hiltunen 1994a and 1994b; Hyvärinen 1998). Increasing winter air temperatures and increasing winter precipitation have resulted in increasing winter flows in these areas. Winter temperatures have increased in Finland during the 20th century in average by 1 C°; the largest increase rate was recorded in the 1990s. In northernmost Lapland, where winters have continued to be cold enough to maintain winterly conditions, no marked trends in the winter flows have been observed. Mean annual temperature decreased in Lapland during the period 1961-1990; in 1991-2000 some increase was observed also there. Some examples of changed runoff/discharge regimes are presented in Fig. 1.

Autumn flows have also been increasing in southern and central Finland during the 20th century, although there are no noticeable trends in summer flow or in spring maximum flow. In most of Finland the annual runoff has increased, on average 0.5 mm a^{-1}, but in parts of south-western Finland the average increase of annual runoff has been up to 1 mm a^{-1} during the 20th century (Hyvärinen and Leppäjärvi 1989; Hyvärinen, Solantie *et al.* 1995; Hyvärinen 1998). Some examples of seasonal trends of discharge are given in Fig. 2. – The trend line is drawn in Figs. 2 to 8, whenever relevant to express, as well as the statistical significance of the trend, * ($P < 0.05$), ** ($P < 0.01$), and *** ($P < 0.001$).

The analyses for Äyskoski, from 1896 onwards, show very similar seasonal trends to those of Muroleenkoski, and so do all the existing (shorter) series in southern, western and central Finland. The results of Muroleenkoski have been represented here because of the length of the series.

There is, however, no marked trend in the longest discharge series in Finland, that of Lake Saimaa to River Vuoksi, situated in south-eastern Finland. This series starts in 1847. The reason to the absence of trend, at least partly, is the heavy burn-beating in large areas in the southern parts of the drainage basin (totally 61,060 km^2) in the middle of the 19th century (Hyvärinen, Solantie *et al.* 1995). The deforestation decreased considerably evapotranspiration in these areas for more than half a cen-


Saukkoniva, Lapland
1921-1980
1981-2000
Mean monthly discharge, m3/s
180
160
140
120
100
80
60
40
20
0
I II III III IV V VI VII VIII IX X XII
Äyskoski
Central Finland
1896-1980
1981-2000
Mean monthly discharge, m3/s
40
35
30
25
20
15
10
5
0
I II III IV V VI VII VIII IX X XI XII
Muroleenkoski
SW Central Finland
1863-1980
1981-2000
Mean monthly discharge, m3/s
120
100
80
60
40
20
0
I II III IV V VI VII VIII IX X XI XII

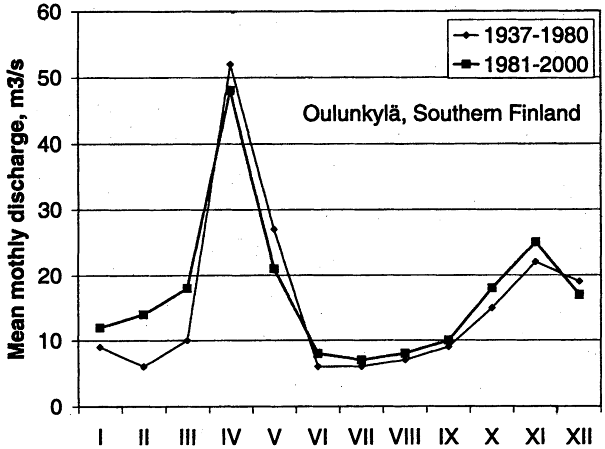


Fig. 1. Mean monthly discharges in Saukkoniva (measuring site: 68°55'N, 26°55'E, F = 5160 km^2, L = 4.7%), Äyskoski (63°23'N, 26°40'E, F = 2157 km^2 , L = 17.9%), Muroleenkoski (61°51'N, 23°54'E, F = 6102 km^2, L = 12.2%) and Oulunkylä (60°14'N, 24°59'E, 1680 km^2 , L = 2.5%). In southern and central Finland especially winter flow has increased during the observation period, in south-western Finland mean annual flow has also increased, and the date of the spring flood peak has shifted earlier. In the north, no trend in winter flow is observed.

tury. As a result, runoff in the middle of the 19th century was higher than in the surrounding areas where burn-beating was of less importance. After the burn-beating was forbidden, the areas became forested again. Moreover, autumn and winter precipitation have increased more in western and southern Finland than in the east.

Groundwater Level

The Finnish groundwater observation sites are mainly situated so that direct human impact in the water level is as low as possible. Soveri *et al.* (2001) analyzed – together with several water quality variables – the groundwater level observation series from 53 stations in Finland, in most cases for the period 1975-1999. One example of the results of the analyses is shown in Fig 3. In some observation sites a seemingly regular fluctuation of groundwater level, with a period of five to seven years, was discovered. In most cases no clear trend was observed; furthermore the Finnish groundwater observation series are generally too short for reliable trend analyses. However, as a curiosity, when looking at May-June groundwater levels in Savo and Northern Karelia, a rather clear decrease is observed in the period 1980-2001 (Mäkinen 2002); see Fig 4. On the one hand this could reflect the fact that in this area the snow melt began earlier in 1990s than previously, or on the other hand it could be due to the several years of very heavy snow cover which occurred in the early 1980s.

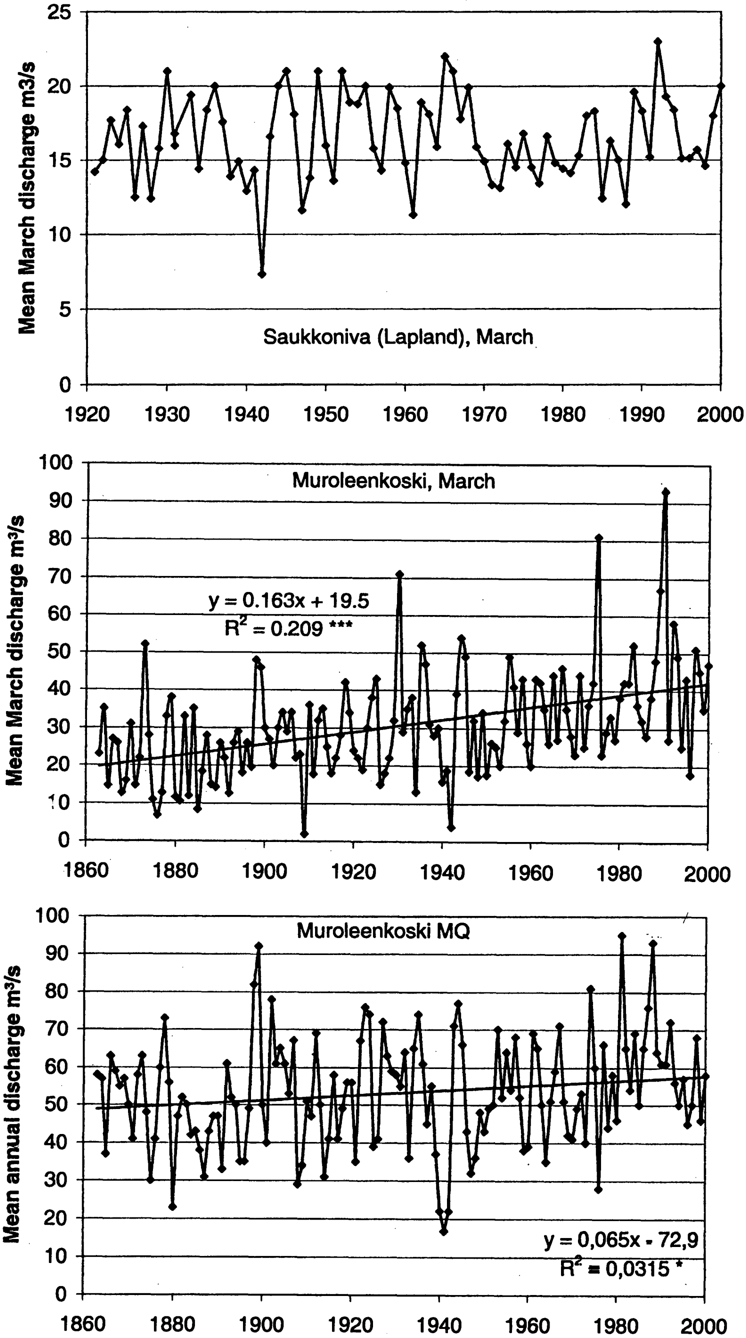
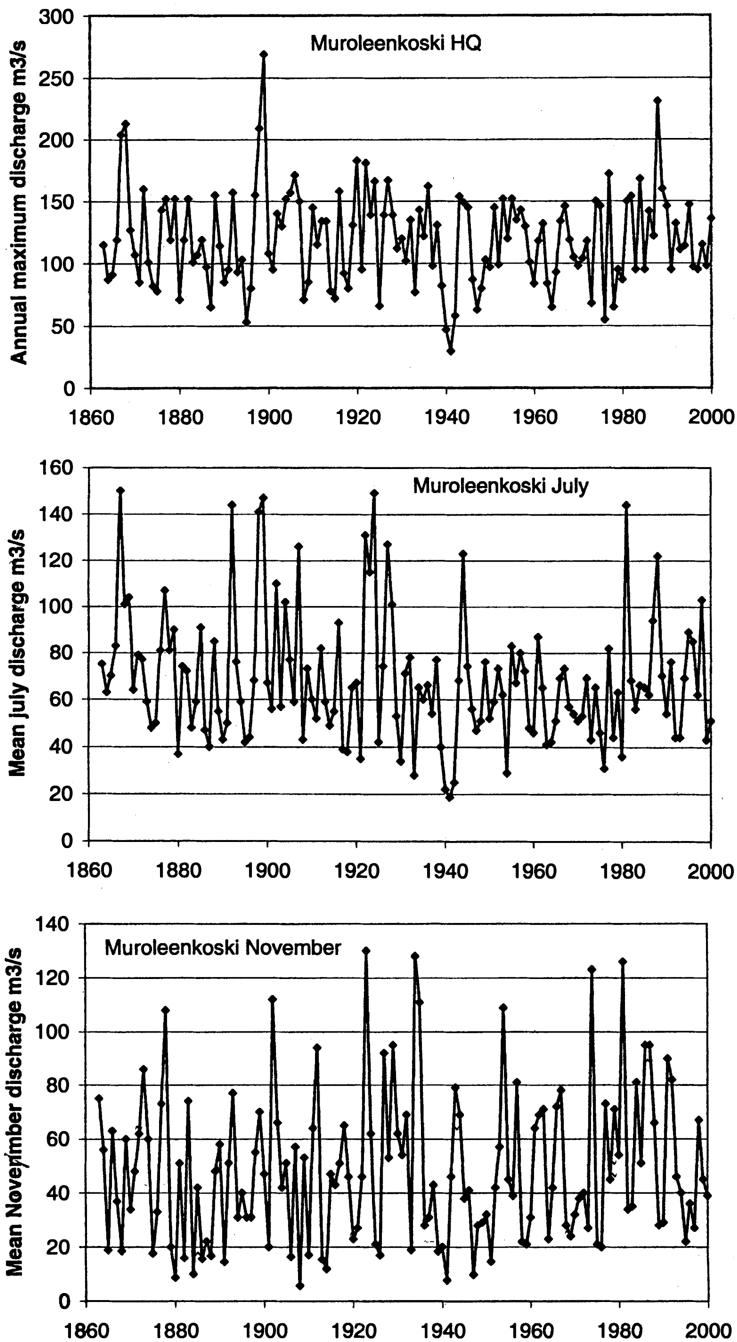


Fig. 2. Mean March discharge for Muroleenkoski and Saukkoniva as well as annual (MQ), annul maximum (HQ), July and November discharges for Muroleenkoski, compare with Fig. 1.



Muroleenkoski HQ
Annual maximum discharge m3/s
300
250
200
150
100
50
0
1860
1880
1900
1920
1940
1960
1980
2000
Muroleenkoski July
Mean july discharge m3/s
160
140
120
100
80
60
40
20
0
1860
1880
1900
1920
1940
1960
1980
2000
Muroleenkoski November
Mean November discharge m3/s
140
120
100
80
60
40
20
0
1860
1880
1900
1920
1940
1960
1980
2000

Fig. 2. cont.

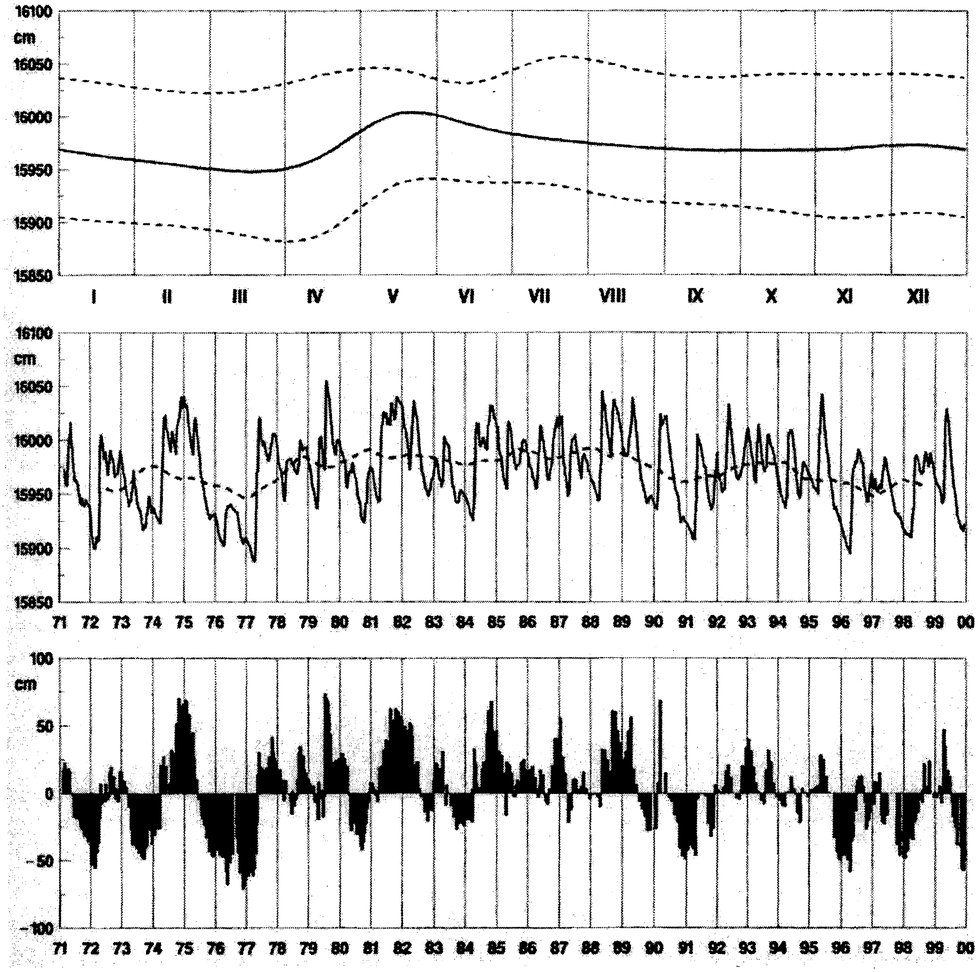


Fig. 3. Groundwater stage at Tullinkangas, southern Finland, 1971-1999. A: mean and extreme groundwater levels I-XII. B: annual variations and 3 year moving average of groundwater level. C: deviation from the mean level (Soveri *et al.* 2001).

Precipitation and Evaporation

As was indicated above, annual river flows have been increasing in many parts of Finland during the 20th century, possibly already during the second half of the 19th century. Has this been due to a simultaneous increase in precipitation and/or decrease in evapo(transpi)ration – if the minor influence of reservoir changes is neglected?

Although simple to ask, this is a rather difficult question to answer.

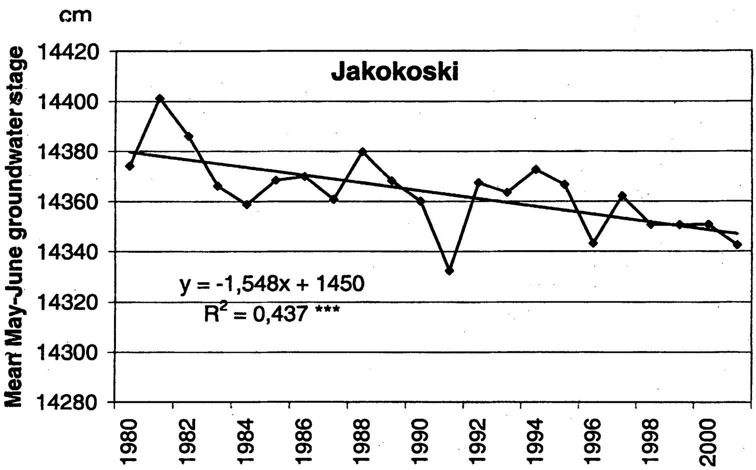


Fig. 4. May-June groundwater stage in 1980-2001 in Jakokoski, Northern Karelia (Mäkinen 2002)

Class A pan observation series for 1961-1990 show no clear trend (Järvinen and Kuusisto 1995). The1980s were rather wet in Finland; this might have affected evaporation. Cloudiness has been increasing, which might have decreased evaporation slightly, although the annual mean air temperatures have simultaneously been increasing, by 0.5 to 1°C during the period 1901-1995 (Tuomenvirta and Heino 1996). During the1990s, there were several very hot summers with rather high evaporation.

In any case, the changes in evaporation can hardly have been sufficient to explain the runoff increases. This suggests that precipitation must have been increasing.

Heino (1994) corrected and analysed 36 long-term precipitation series from the rain gauge records of the Finnish Meteorological Institute. The longest precipitation series in Heino's research (Kuopio) began in 1884, although most series started at the beginning of the 20th century. In many series there is no visible trend. A few stations in western Finland show an increase of up to 1 mm a^{-1}. The increase in annual precipitation of several stations is about of the magnitude 0.5 mm a^{-1} during the 20th century. This seems to agree with the increase in runoff in some areas.

The nationally-averaged analysis of annual mean precipitation in Finland for the period 1910-1996 (Tuomenvirta and Heino 1996), including homogeneous data from 24 stations, shows no clear trend.

However, neither measured point precipitation nor the existing selection of homogenized series provides correct precipitation estimates for water balance calculations in large drainage basins.

In Finnish conditions, the rain gauges gather only about 80...90% of the true annual precipitation, depending on factors such as type of precipitation, wind and location of the gauge. The gain is lowest during winter. The mean annual precipitation, corrected for water balance in Finland in the period 1961-1990, is 660 mm, *i.e.* 14% higher than the uncorrected value (Hyvärinen and Solantie 1995).

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

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

Snow Cover

Increasing winter temperatures have intensified snow melt in western and southern Finland in the middle of winter towards the end of the observation period 1946-2001. This and the increasing rainfalls in the middle of winter have decreased the snow cover in these areas (Fig. 5). As a result, autumn and winter flows have increased in southern and central Finland, as was described above. Precipitation in the form of snow or rain on lake ice also increases flow from lakes downstream, according to Archimedes' law.

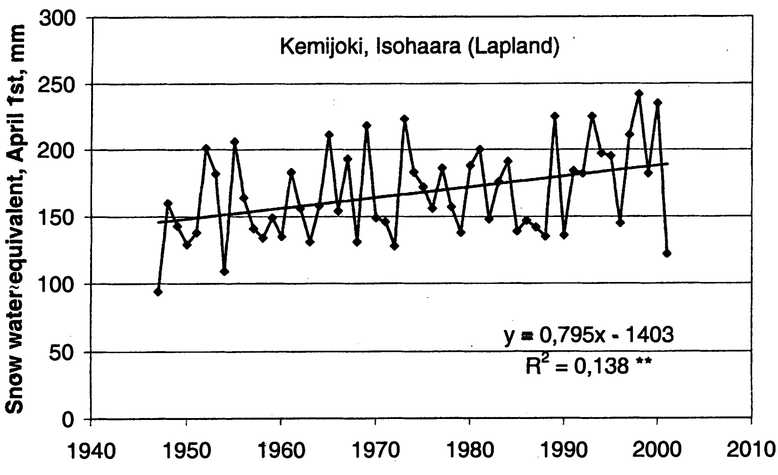


Fig. 5. Water equivalent of snow in some drainage basins in Lapland, northern Finland, central Finland and southern Finland on April 1st, 1947-2001.

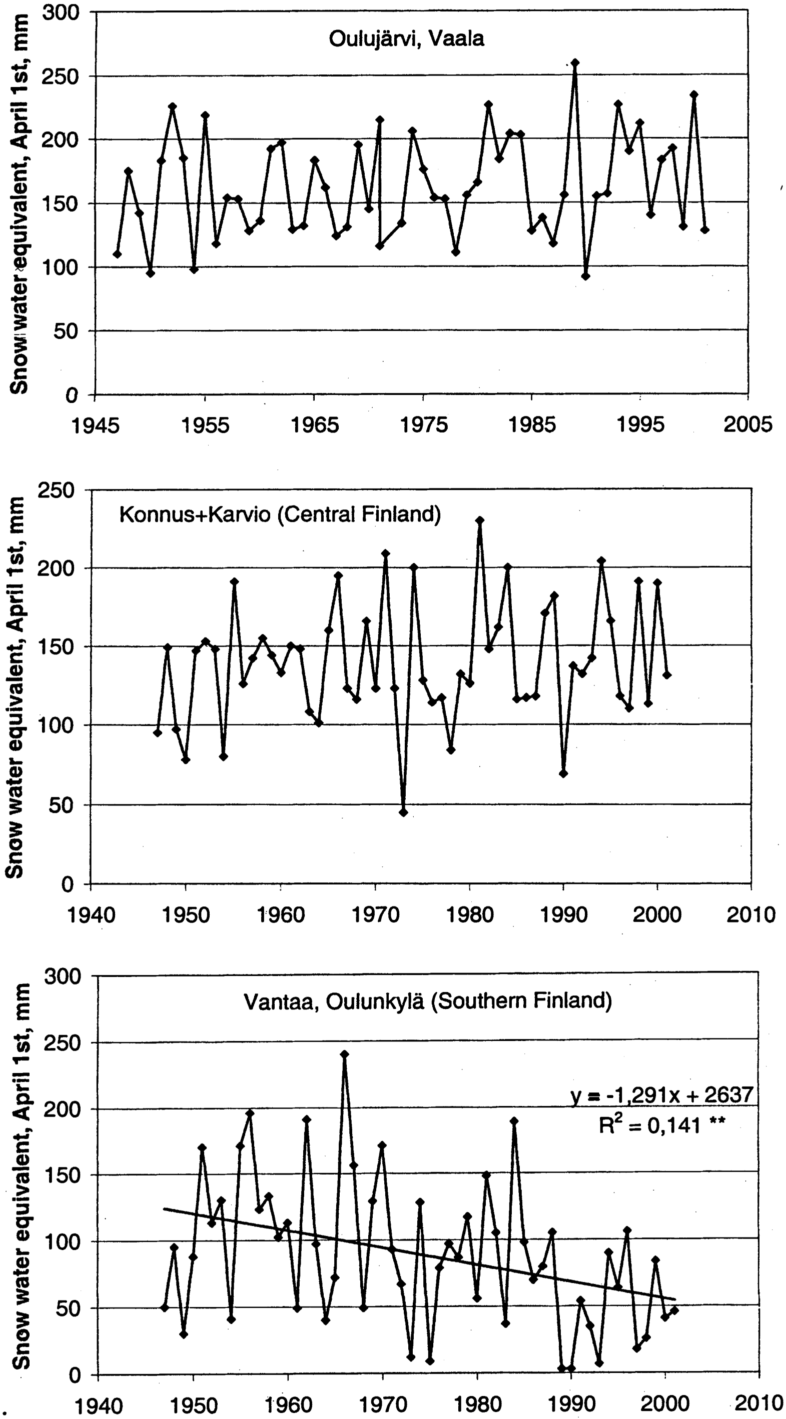

Oulujärvi, Vaala
Snow water equivalent, April 1st, mm
300
250
200
150
100
50
0
1945
1955
1965
1975
1985
1995
2005
Konnus+Karvio (Central Finland)
Snow water equivalent, April 1st, mm
250
200
150
100
50
0
1940
1950
1960
1970
1980
1990
2000
2010
Vantaa, Oulunkylä (Southern Finland)
Snow water equivalent, April 1st, mm
y = -1,291x + 2637
R2 = 0,141 **
300
250
200
150
100
50
0
1940
1950
1960
1970
1980
1990
2000
2010

Fig. 5.

In central Finland there is a zone where no trend is observed in the annual maximum of the water equivalent of snow. In eastern and northern Finland, the maximum water equivalent of snow has been growing quite clearly since 1947 (Fig. 5).

The increase in number of snow survey sites during the observation period 1946/1947 to 2001 causes some inhomogenity in the existing snow cover time series – a matter that requires more detailed analyses. The snow survey method itself has remained unchanged throughout the whole observation period, and the changes in the calculation method of areal water equivalent of snow during the observation period do not have a marked effect (see Perälä and Reuna 1990).

From Fig 5 it can be seen that the snow cover is very unstable in the south and rather stable in the north. The highest water equivalent of snow in the south during the period 1947-2001 was observed in 1966, in the central parts of Finland in 1981, and in the north during the very last years of the1900s. In 2001 the snow cover was exceptionally thin in Finnish Lapland.

Solantie (2000) thoroughly analysed the snow depth observations of The Finnish Meteorological Institute and also the water equivalent of snow as a function of air temperature and geostrophic winds (Solantie 2001). Long-term snow depth observation periods (the longest periods are from 1919 onwards) cover Finland from the south to the Arctic Circle. In Solantie's study a slight increasing trend can be seen in the snow depth in northern Finland on March 15th, and a sligh decreasing trend in the south. On the basis of his studies there are reasons to believe that if there were reliable areal water equivalent observations for longer periods than those starting in 1946/1947, the trends might not be as steep as those presented in Fig 5. On the other hand, the water equivalent of snow cannot be calculated from snow depth observations alone. Milder winters at the end of the observation period may have increased the snow density.

Water Temperature

In most Finnish water temperature observation sites, the surface water temperature has not changed remarkably during the observation periods. In the southern part of the large lake Saimaa system, in Lauritsala (S-E Finland), the summer and autumn water temperature have slightly increased since 1924 (Korhonen 2002), see Fig 6. This may have led to increasing lake evaporation; however, no analyses are available of the trends of lake evaporation in Finland. Besides increased air temperature, one reason to rising water temperatures may have been the increased turbidity of water in the measuring site.

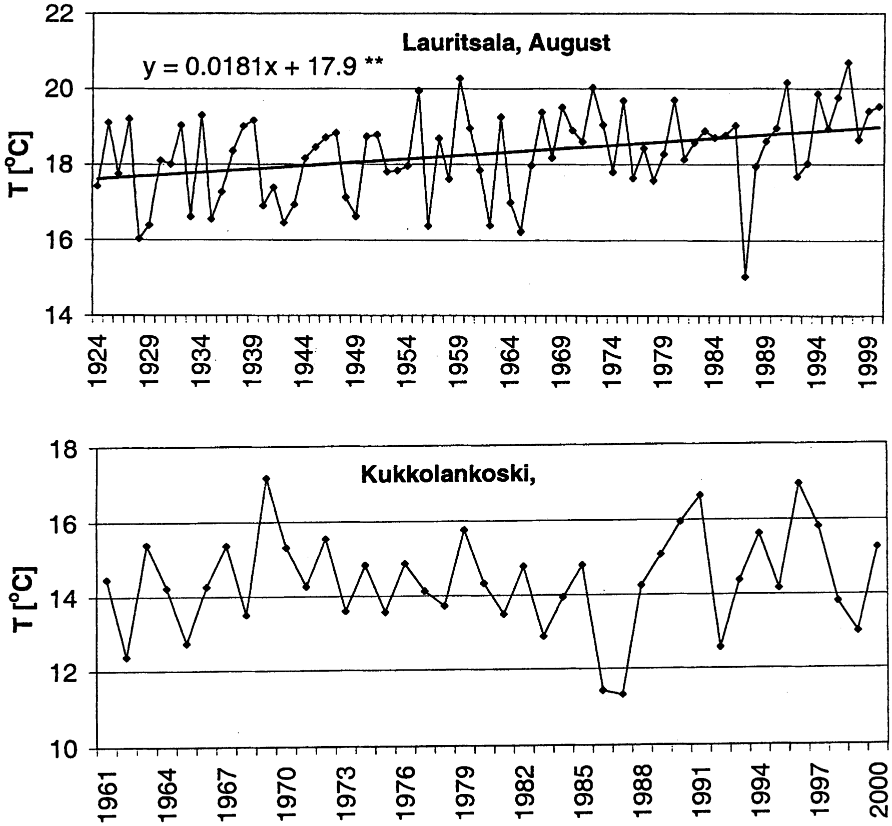


Fig. 6. Mean surface water temperature in August. Saimaa, Laurıtsala (S-E Finland) 1924-2000 and Tornionjoki, Kukkolankoski (N-W Finland) 1961-2000 (Korhonen 2002).

Ice Cover

Records of the date of freezing and break-up were started on Lakes Kallavesi and Näsijärvi in 1830's, and on Lake Oulujärvi in the 1850'es (Kuusisto 1987). A shortening of the ice cover duration by about ten days has occurred on all these lakes, mainly between 1900 and 1920. The series analysed by Kuusisto end in the beginning of 1980s, and newer analyses are needed. No trend can be seen in the mean maximum thickness of lake ice in the Finnish lake district for the period 1912-1992 (Kuusisto 1994). Even in southern Finland, where the air temperatures have been increasing during winter, the annual maximum of ice thickness has generally remained unchanged.

The stability of the annual maximum ice thickness of the Finnish lakes is due to the complex dynamics of ice cover formation. In cold winters, especially if the snow

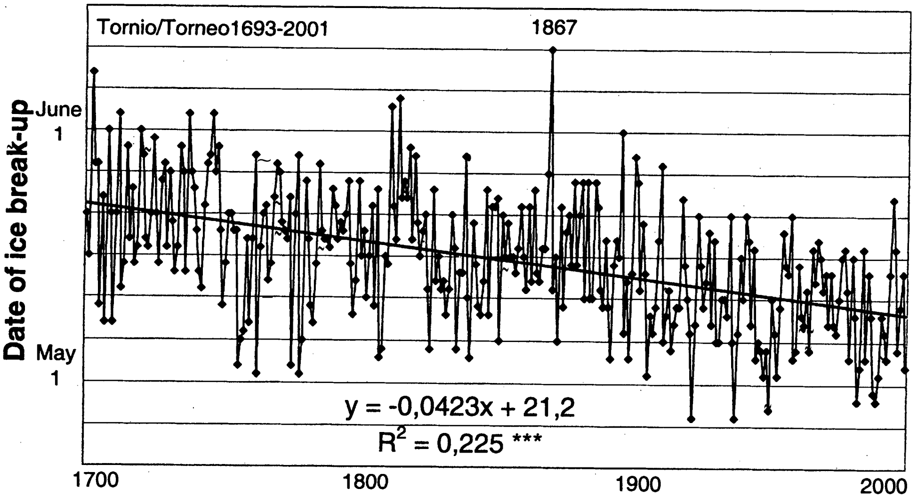


Fig. 7. Date of ice break-up in the lower reach of the river Tornionjoki (Tornio/Torneå) in the period 1693-2001 (Kajander 1995 and SYKE 2001). The Years of Great Famine in Finland culminated in 1867.

cover on the ice is thin, the ice formed is mostly or totally blue ice, *i.e.* the ice grows only downwards – and very slowly when the ice cover is already thick. In mild winters, with heavy snowfall or rains, the ice grows upwards as snow-ice from slush or from rain falling on the ice. Even light frosts are able to freeze the slush and water on ice, and the ice thicknesses increase rapidly. Some features of these processes are described in Hyvärinen (1987).

Melting of snow from lake ice in the middle of winter has been increasing in southern and central Finland in recent decades. As a result, unisolated ice is exposed to air temperature variations, diurnal and others, and thermal expansion of lake ice causes ice shove more often than previously. There are no scientific studies of this phenomenon, but many reports reaching the authorities support this interpretation.

Kajander (1995) collected the longest hydrological observation series in Finland. The series of the date of ice break-up in Tornio/Torneå, situated in the lower reach of the river Tornionjoki, starts in 1693. It shows that in recent decades the ice cover of the lower reach of the river has broken up about two weeks earlier, on average, than at the end of the 1600s. The trend has been rather linear and strong (Fig. 7).The Little Ice Age has receded since the 1700s, and air temperature in April and May has increased during the period from which temperature records are available (Haparanda, 1860 onwards). Due to land uplift, the difference of water levels between the observation site and the sea has increased during the period 1693-2001 by some 1.5 m. This process may have contributed to the trend, as the sea ice to some extent may have prevented early break-up at the observation site some hundred yeras back. However, this theory is not quantitatively proven.

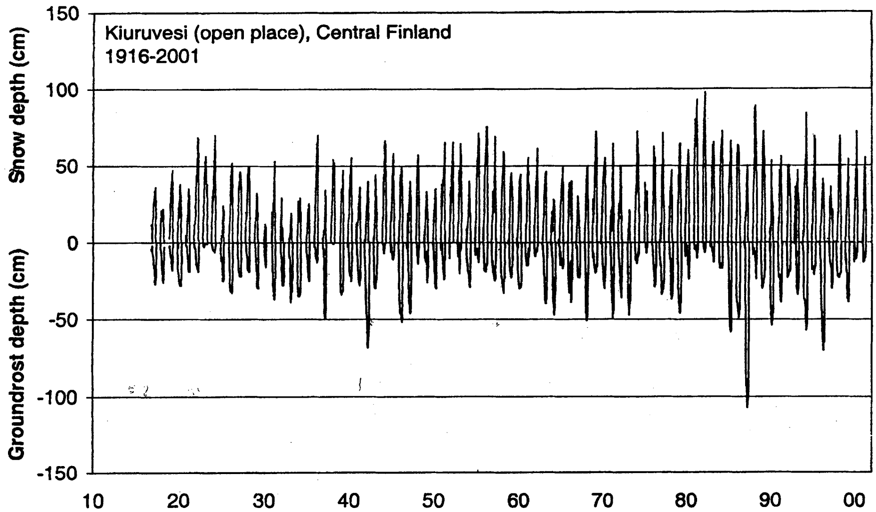


Fig. 8. Groundfrost depth and snow depth in Kiuruvesi, central Finland, during the period 1917-2001. The observation site is situated in an open place. Groundfrost was measured by digging at the beginning of the series, then by a rod, and starting from the 1960s by methylene blue tubes. Groundfrost depths for the years 1977-2000 are estimates (Mäkinen 2002).

Soil Frost

The longest soil frost observation series in Finland dates back to the early 1900s. Soil frost depth observations are subject to several sources of inhomogenity. The observation method has changed; in the early 1900s the lower edge of frozen soil was dug up, later soil frost rods were used, and finally, starting from the 1960s, methylene blue tubes. The changes of vegetation *etc.* in the close vicinity of the observation site strongly affect snow cover, and soil frost depth is strongly dependent on snow depth, many times even more than on air temperature. Also soil moisture affects strongly the formation of groundfrost. The example in Fig. 8 shows clearly for instance the extremely deep groundfrost during the very cold winter of 1987, and the thin frost layers during the snowy winters of 1981 and 1982.

Discussion and Conclusions

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

A Nordic analysis of runoff (Hisdal *et al.* 1995) showed that river flow regime changes may differ considerably in different parts of Nordic countries. It is quite natural: the physico-geographical conditions in the study area – extending from Iceland over Faroe Islands, Norway, Denmark, Sweden and Finland to Estonia – vary considerably. Nine types describing the different runoff regime were classified in the area. The most remarkable trends were increasing annual, autumn and winter runoff in south-western Norway (see also Roald, 1998) and increasing winter runoff in Estonia and southern Finland during the latter part of the 20th century.

In Sweden, which is physico-geographically more close to Finland than the Atlantic and mountaneous Norway, the runoff trends have been rather weak until early 1990s (Jutman 1991). This result was conformed by Brand and Ehlert (1996) who studied the runoff of coastal waters of Sweden. Lindstöm (1993 and 1999) has analysed floods in Sweden and concluded that neither the results from statistical trend tests nor visual inspection of the data suggest any change in flood fequency. The longest of his flood series start in the first part of the19th century and end in 1995. In northern Sweden, a trend towards later freezing and earlier break-up of lake ice has been observed (Ekelund 1999). The longest Swedish ice cover duration series, partly estimated, that from the Bay of Västerås in Lake Mälaren, central Sweden, shows a break in 1988: the mean break-up date has been April 24 during the period 1712-1988 and between 1988-1999 the date has been April 7. Mean annual precipitation has increased in Sweden as much as about 100 mm during the years 1900-2000 (SMHI 2002).

Krasovskaia (1996) analysed the stability of river flow regimes in northern and central Europe. The results of her studies are in agreement with the results presented here, *i.e.* that the runoff regime in south-western Finland is rather unstable.

Filatov *et al.* (2001) have summarized the trends of water balance variables in Russian Karelia for the period 1880-1999. According to their estimates, the mean annual values of both precipitation and runoff have increased there some 20 mm during the 20th century, while evapotranspiration showed no trend. Precipitation and runoff increased most quickly at the very end of the 20th century. These results agree quite well with the results obtained from Finland so far – except for the series of Vuoksi; see above.

In Estonia, average values of annual precipitation during 1966-1998 were about 50 mm higher than during 1891-1980. Precipitation has increased mostly during the cold half-year, during the period 1950-2000 the increase of the precipitation sum of the winter months December to March has been as much as 75 mm or 47% (Jaagus 2002). Snow cover duration has decreased in Estonia by 5 to 10 days during the 20th century (Jaagus 1995 and 1999). Increase in winter flow has been rather similar to the increase in southern Finland. However, the maximum ice cover thickness of Lake Võrtsjärv has not decreased even if the winters have become milder also in Estonia (Järvet 1999). Surprisingly, the ice cover period of Lake Võrtsjärv has become 12 days longer during the period 1923-1998, mainly on account of earlier ice formation in autumn.

In Denmark, the annual mean runoff in most of the Danish streams shows an increasing trend over the observation period starting around 1917. Also for the annual maximum and minimum runoff the trends are predominantly increasing (Ovesen *et al.* 2000).

Some parts of Canada are situated climatologically and geographically in conditions that resemble those of Fennoscandia. A major difference is that Canada is greatly dominated by continental climate and Fennoscandia partly by marine, partly by continental climate. The Gulf Stream warms up the Fennoscandian climate so that the app.roximately similar climatological zones of Canada are situated about 10 degrees (of latitude) southwards compared to Fennoscandia. Zhang *et al.* (2001) have reported of trends in Canadian streamflow, computed for the past 30-50 years. The annual mean streamflow had generally decreased during these periods, especially in the south, and most in August and September. The exceptions are March and April, where significant increases were observed – as those of winter flow in some parts of Finland. The breakup of river ice occurs nowadays significantly earlier than before, especially in British Columbia.

It can be concluded that a considerable amount of work is required in Finland for estimating the representativity of the existing areal precipitation series, of areal snow water equivalent, the possible changes in evapotranspiration, in groundfrost observation series *etc.* Furthermore there are hitherto only a few investigations of ice cover duration. Even runoff series need more investigations.

Acknowledgements

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