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LONG-TERM CHANGES AND VARIABILITY OF THE WINTER AND SPRING SEASON HYDROLOGICAL REGIME IN FINLAND

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Cover picture: Lake ice melting in the spring 2018 near Kuopio.
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Abstract

The hydrological regime is highly dependent on climatic conditions. In a boreal snow-driven region, such as Finland, changes in the winter and spring climatic seasonal conditions have a large effect on the hydrology. In this study, long-term changes and variability of the winter and spring season hydrological regime are investigated based on long-term ice phenology and river discharge time series in Finland. Ice cover and river discharge observations are among the oldest hydrological records in Finland and in some locations records cover 150–300 years. The analyses show statistically significant changes in both ice cover and discharge regime until the early 21st century. The ice freeze-up has become later, and the break-up is earlier, while the duration of the ice cover has shortened. In recent decades, changes have become even more apparent and the number of extremely early break-ups and late freeze-ups has increased. In ice phenology, new records have been set in the 21st century. Until 2002, there were both increasing and decreasing trends in the maximum lake ice thickness. Updated data until the winter 2017–2018 still show decreasing trends in the south, but no longer increasing trends in Central or Northern Finland. In the discharge regime, the seasonal winter and spring discharges have increased, and the spring peak has moved earlier up to 2004. The mean annual flows or annual high flows have not shown changes in general. Similar tendencies have even continued with updated data until the year 2017 as they did up to 2004. These observed seasonal winter and spring hydrological trends are in line with findings of annual and seasonal air temperature and precipitation changes and also with projected climate change scenarios until the late 21st century. In addition to long-term trend analysis, atmospheric circulation patterns and their relation to the seasonal winter and spring hydrological regimes were investigated. Both ice cover and river discharge are related to large scale atmospheric circulation patterns and show different periodicities. The influence of the North Atlantic Oscillation (NAO) can be seen in both the ice and discharge time series. The strong positive winter NAO is related to shorter ice cover duration and higher winter discharges, and the strong negative winter NAO vice versa.

Keywords: climate change, Finland, hydrology, ice cover, river discharge, trends, variability

List of papers

This thesis is based on the following six articles, which are referred to in the text by their Roman numerals:

I: *Korhonen, J.* 2006. Long-term changes in lake ice cover in Finland. *Nordic Hydrology* **37(4-5)**, 347–363.

II: *Korhonen, J.* & Kuusisto, E. 2010. Long-term changes in the discharge regime in Finland. *Hydrology Research* **41(3-4)**, 253–268.

III: Veijalainen, N., *Korhonen, J.,* Vehviläinen, B. & Koivusalo, H. 2012. Modelling and statistical analysis of catchment water balance and discharge in Finland in 1951–2099 using transient climate scenarios. *Journal of Water and Climate Change* **3(1)**, 55–78.

IV: Benson, B.J., Magnuson, J.J., Jensen, O.P, Card, V.M., Hodgkins, G., *Korhonen, J.,* Livingstone, D.M., Stewart, K.M., Weyhenmeyer, G.A. & Granin, N.G. 2012. Extreme events, trends, and variability in Northern Hemisphere lake-ice phenology (1855–2005). *Climatic change* **112(2)**, 299–323.

V: Helama, S., Jiang, J., *Korhonen, J.,* Holopainen, J. & Timonen, M. 2013. Quantifying temporal changes in Tornionjoki river ice breakup dates and spring temperatures in Lapland since 1802. *Journal of Geographical Sciences* **23(6)**, 1069–1079.

VI: Sharma, S., Magnuson, J.J., Batt, R.D., Winslow, L.A., *Korhonen, J.* & Aono, Y. 2016. Direct observations of ice seasonality reveal changes in climate over the past 320–570 years. *Scientific Reports* **6**, 25061.

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Author's contribution for the papers:

I: Korhonen performed all the work related to the article. She planned the research idea and carried out the selection of data, keyed part of the data from the archives, executed quality control, carried out all the data analyses, prepared graphs, compiled tables and wrote the manuscript and revised it according to the reviewers' feedback.

II: The research idea and planning was done by Korhonen. Korhonen selected the data used in the research. Korhonen mainly carried out all the data analysis, prepared figures and tables and wrote the manuscript. Kuusisto was responsible for determining the discharge stations and their coefficients for the total Finnish outflow discharge calculation based on his earlier paper. He also improved the manuscript with valuable comments. Korhonen made all the revisions according to the reviewers' feedback.

III: Korhonen took part in planning the research question and selecting the data to be used in the research with Veijalainen. Korhonen did the data analysis related to historical data and also performed the trend analysis for the simulated data. Korhonen wrote the chapters related to the trend analysis and data used in it. She also revised other parts of the manuscript with Veijalainen.

IV: Korhonen commented on the research idea provided by the main author. Korhonen provided the Finnish data and was responsible for the quality control and metadata of the data. Korhonen shared her local knowledge of the Finnish data for the research and interpretation of the results. She also contributed to commenting on analysis methods and revising the manuscript.

V: Korhonen commented on the research idea provided by the main author. Korhonen provided data on the River Tornionjoki and was responsible for the quality control of this data during the latest decades. Korhonen shared her local background information on the records to be used in the analysis. She also contributed by commenting on the methods and analysis and revised the manuscript.

VI: Korhonen commented on the research idea provided by the main author. Korhonen provided data on the River Tornionjoki and was responsible for the quality control of the data. Korhonen shared her local background information on the Tornionjoki region which was requested by reviewers. She also contributed by commenting on the methods and analysis and revising the manuscript.

Preface

Nature, water and climate have fascinated me all of my life. I have been surrounded by waters everywhere I have lived. In my youth, living by lake Kallavesi and spending summers at our family cottage by lake Iisvesi. One could ask whether it is a coincidence that these two North Savonian lakes have one of the longest ice records in Finland. I just recently found that my childhood diaries included some observations of weather events and ice phenology from the late 1980s. These observations were indeed focused on winter and spring events such as the first snow fall, the ice break-up and extremely warm spring weather. Certainly, my curiosity about these phenomena has been present for a long time. In hindsight, studying geophysics and meteorology was an obvious choice that combined my interest in nature with physics and mathematics.

The journey towards completing this PhD has been a long one. We will see whether the saying "More haste, less speed" was valid for this. I started my PhD studies after completing my Master's in 2002. During the first years as a hydrologist at SYKE, I had time to focus on analyses and complete my PhD studies during the HYDMET-diploma programme 2004–2005. After starting out as a group leader, the time allocated for research diminished significantly. At some point, I already lost my belief in ever completing my PhD, as there were too many projects and things to be managed. However, in 2017 Professor Leppäranta convinced me to finish the prolonged work, and finally during some very hot weeks in July 2018 I compiled the synthesis.

I am certainly thankful for Professor Matti Leppäranta and Docent Esko Kuusisto that they were persistent in pushing me to complete the project. I also owe them many thanks for improving and commenting on the manuscript and believing in me.

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I owe my deepest gratitude to my dear present and former colleagues in hydrological monitoring at SYKE, in regional ELY-centres and to the observers who have all done a huge amount of work with all the measurements, data collection and quality control related to the data used in this thesis. They have all done and are still doing very important work related to hydrological data. Special thanks for discharge and water level data corrections go to Jarkko Koskela and Heidi Sjöblom. I would also like to thank my retired colleagues Veli Hyvärinen and Matti Ekholm for the earlier discharge data corrections and with help in choosing stations for the analysis. I am grateful for Juha Kajander for doing a lot of work in the 1990s while collecting the world-famous River Tornionjoki time series, which has been continued by SYKE since. I am very grateful to Hannu Sirviö for helping with statistical issues. Mirjam Orvomaa also deserves thanks for cheering me on during the synthesis writing. I would like to thank Simo Riikonen for harmonizing the reference list. Thanks also to the WSFS-group for the fruitful discussions and my entertaining lunch breaks at the Töölö office.

I have been lucky to be part of some amazing international science communities such as Northern Research Basins (NRB). Without NRBs my two first papers would not exist. The NRB community has always encouraged me to carry out hydrological research. Also other international projects, co-operation and networks have motivated me to develop my expertise. Through these networks, I have discovered wonderful colleagues and friends all over the world.

I would especially like to thank my dear long-time friends for their endless support and positive feedback. Without you I would not made it this far. Special thanks go also to the “Rosso group” and the “SYKE Summer 2000 trainee group” for the laughter-rich free time and gatherings, sharing

everything in life over the past 20 years. Thank you also the SPARRU-group for boosting the final sprint of the thesis writing.

Huge thanks also go to my sister and parents who have always supported and believed in me. And finally the greatest thanks go to Sebu, the love of my life – who has always been supportive, loving and proud of my work during all these twenty years together. You lighten my life <3.

In Helsinki
December 8th, 2018

Abbreviations

ACP	Atmospheric Circulation Pattern
ADCP	Acoustic Doppler Current Profiler
AMF	Annual Maximum Floods
AMO	Atlantic Multi-Decadal Oscillation
AO	Arctic Oscillation
DJF	December-January-February
ENSO	El Niño Southern Oscillation
FMI	Finnish Meteorological Institute
HYDRO	Database for hydrological observations (SYKE)
IPCC	Intergovernmental Panel on Climate Change
JJA	June-July-August
MAM	March-April-May
MK	Mann-Kendall trend test
MQ	Mean annual discharge
NAO	North Atlantic Oscillation
NH	Northern Hemisphere
PDO	Pacific Decadal Oscillation
PNA	Pacific North American Pattern
Q	Symbol used for river discharge
RCM	Regional Climate Model
RCP	Representative Concentration Pathway
SON	September-October-November
SWE	Snow Water Equivalent
SYKE	Finnish Environment Institute
WSFS	Watershed Simulation and Forecasting System of SYKE

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1. Introduction

1.1 Background and motivation

The global average air temperature has increased by 0.85°C during the period 1880–2012 and during the last half of the period it has increased even more rapidly (IPCC 2014). Warming has been greater at northern latitudes. Water resources are significantly dependent on climatic conditions to which the snow-melt dominated boreal region is especially sensitive (Woo et al. 2008). The runoff regime is affected by both precipitation and temperature variations, along with changes in radiation. Changes in the precipitation tend to affect the runoff volume and predominantly the maximum snow water equivalent, which usually occurs near the end of the winter. On the other hand, temperature changes mostly affect the timing of runoff (Barnett et al. 2005). Projected climate warming according to several global change scenarios has the potential to significantly alter the water cycle in river basins across northern latitudes. Warming is expected to lead to increases in net precipitation and rises of winter precipitation at high latitudes (IPCC 2014).

Climate change has been one of the most investigated issues in the last decades, due to its vast ecological and socio-economic impacts. The changes in climate have direct and indirect impacts on the natural environment and furthermore on society (IPCC 2014). Water resources are affected too, due to their close linkage to climate. In Finland, the hydrological regime is dominated by temperature-sensitive snow-derived seasonality. Even relatively mild increases in air temperature can result in substantial changes in seasonal runoff regimes in snow-dominated areas (Arnell 1999; Lettenmaier et al. 1999; Payne et al. 2004; Barnett et al. 2005; Veijalainen et al. 2010).

Spring is the most dramatic phase in the northern hydrology. Large spring freshets of water are released, and the clearance of ice and snow makes a huge difference to the heat and radiance balance of land/water/atmosphere, also on a global scale. In northern regions the main water flow occurs during the spring peak (Woo et al. 2008). In Finland, half of the annual runoff is discharged in the springtime (Hyvärinen 1984a).

Ice cover is a natural winter phenomenon in lakes and rivers in countries of boreal regions (e.g. Kirillin et al. 2012). In the boreal zones, like Finland, the ice cover season has a great effect on the hydrology and at the same time also the ecology (e.g. Assel & Robertson 1995; Hodgson & Smol 2008). The winter season with snow and ice cover restricts the water surface-atmosphere

interaction by insulating the surface layer and altering the surface albedo. The winter season and especially the ice cover period plays an important economical and recreational role in northern latitudes (Kuusisto & Elo 2000; Magnuson et al. 2000; Kirillin et al. 2012; **Paper VI**). Ice cover used to be significant for trade in the past, and also nowadays winter fishing is widely practiced as a trade or hobby in northern latitudes. River ice break-ups are often spectacular events and therefore well-documented (Kajander 1993).

The River Tornionjoki break-up records are also exceptional from a global perspective (**Paper VI**). In the early days, ice conditions were recorded mainly for the purpose of transportation over ice or open water. The long datasets of the ice break-up and freeze-up form an interesting subject of analysis because they are good indicators of climate change and climate variations. Ice break-up datasets of many lakes go further back in time than air temperature records from the same areas. Moreover, several studies (e.g. Ruosteenoja 1986; Assel & Robertson 1995; Livingstone 1997) have asserted that break-up dates are even better climatic indicators than the air temperature itself. Historical Finnish ice cover observations have been used as proxy in the reconstruction of historical air temperature series (Holopainen et al. 2009). Additionally, air temperature records have been used as a comparative tool to test for inhomogeneity issues in ice records as shown in **Paper V**.

There is a causal connection between the ice cover and discharges. Winter season discharges are restricted due to limited surface runoff as the soil is usually frozen while the waters are ice covered. The timing of the spring break-up and peak flows in Arctic rivers are also interrelated (Marsh & Hey 1989). For Finnish data, Korhonen (2007) showed correlations between the River Tornionjoki ice break-up and spring peak discharge. Since there are not so many long river ice records available from Finland as lake records, lake ice phenology has been used to a large extent in many analyses. Nevertheless, spring ice cover break-ups in rivers and lakes are related, even though rivers tend to freeze later and become free of ice earlier than lakes. Many Finnish rivers originate from lake outlets.

1.2 Theme related studies prior to papers of this thesis

Due to the large role of the winter and spring seasons, variability and changes in these seasons have remarkable effects on the hydrological cycle and therefore are important to study. The first studies of cryophenological records in Finland (Hällström 1841a; 1841b) were reported by Kajander (1989; 1993; 1995). After Hällström, Rein (1864) and Moberg (1894) published some ice

records. After that, Johansson (1932) presented a number of river ice records and Simojoki (1940) introduced similar data from many Finnish lakes. Previous studies related to long-term ice cover changes in Finland include, for example, Palecki and Barry (1986), Kuusisto (1987; 1993; 1994), Kuusisto and Elo (2000), Magnuson et al. (2000) and Yoo and D'Odorico (2002). Lake ice phenology is a good climatic indicator due to its sensitivity to the climatic variations and availability of long records (e.g. Robertson et al. 1992; Assel & Robertson 1995; Livingstone 1997; 2000; Magnuson et al. 2000; Duguay et al. 2006; Karetnikov & Naumenko 2008; Adrian et al. 2009; Blenckner et al. 2010; Bernhardt et al. 2012).

There are several earlier studies concerning long-term changes in the Finnish discharge regime. The first studies showed the increase in the spring and summer high flows due to the extensive drainage of the forest and peatlands (Hyvärinen & Vehviläinen 1981), the increase in winter flows in the southern, western and central parts of Finland due to warmer winters (Hyvärinen 1988; 1998; 2003; Hyvärinen & Leppäjärvi 1989; Hiltunen 1994) and the increase in the annual flow (Hyvärinen 1988; 1998; 2003). Kuusisto (1992) presented monthly and annual runoff data from Finland for the period 1931–1990. In addition to these national studies, Finnish streamflow records have been included in Nordic runoff research (e.g. Krasovskaia & Gottschalk 1992; Hisdal et al. 1995; 2003; 2004; Roald 1998; Wilson et al. 2010). Studies on the future effects of climate change on water resources and floods in Finland were started in the 1990s by Vehviläinen and Lohvansuu (1991), Hiltunen (1992; 1994) and Vehviläinen and Huttunen (1997). Later climate change research in Finland has continued by Veijalainen et al. (2010). Studies with the same theme covering the Nordic region have been presented by e.g. Beldring et al. (2006), Wilson et al. (2010) and Bergström et al. (2012).

1.3 Objectives of this study

The materials of this dissertation are based mainly on comprehensive hydrological records of river discharges and ice cover observations collected by the Finnish Environment Institute SYKE, which is the national hydrological service of Finland, and its predecessors (National Board of Waters, Hydrological Office and Hydrographical Bureau) and also regional environment centres. Finland has a long history of hydrological time series. The longest records include cryophenology (the ice cover of both rivers and lakes) followed by lake water levels and river discharges. The formation of ice and its disappearance are among the oldest hydrological observations in Finland because specific instruments are not needed, and the role of such

events has been socio-economically significant in the past. The River Tornionjoki ice break-up records have been documented since 1693.

The focus of this thesis is the winter and spring hydrological regime in rivers and lakes due to the importance of these periods to northern hydrology. There have been earlier studies on changes in the ice and river discharge regime, but this dissertation compiles a comprehensive set of data and a versatile analysis compared to previous studies in Finland and covers the data updated to the 21st century.

The main objectives of this dissertation are:

1) To study long-term changes and variability in the ice and discharge regime of Finnish lakes and rivers. To examine whether there been changes and what their magnitudes are (**Papers I, II, IV, V, VI**).
2) To reflect these changes with projected climate change scenarios and simulations (**Paper III**).
3) To assess changes with previous studies on Finnish data and with changes in other parts of the Northern Hemisphere. To determine the connection with climatic variation (also on a global scale) (**Papers I, II, III, IV, V, VI**).
4) To assess whether there have been changes in extreme ice events (**Papers IV, VI**).

2. Climatic and hydrological conditions in Finland in winter and spring

2.1 Climatic conditions and their trends

The main element influencing Finland's climate is the geographical position between the 60th and 70th northern parallels in the Eurasian continent's coastal zone, which shows characteristics of both a maritime and a continental climate, depending on the direction of atmospheric circulation. The climate is mainly subarctic or boreal according to the Köppen classification. The weather is variable in Finland (Mikkonen et al. 2015). The mean temperature in Finland and surrounding Northern Europe is several degrees higher than in other areas of the same latitudes, e.g. Siberia and South Greenland. The temperature is raised by westerlies from the Atlantic, which are warmed by the Gulf Stream. Additionally, the Baltic Sea and a large number of inland waters even out temperature variations during the year compared to other continental locations at same latitudes.

As Finland belongs to a humid zone in climate classification, a typical feature is the abundance of water bodies and peatlands. However, the water situation may vary greatly from year to year depending on atmospheric circulation. 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 vast part of the rainwater evaporates.

The onset of winter and spring naturally affects the hydrological conditions in Finland. In winter, the mean temperature remains below 0ºC, but warm airflows can raise the daily high values above 0ºC at times. The Finnish meteorological definition of winter is a mean daily air temperature below 0ºC (FMI 2018a). Winter usually begins in mid-October in Lapland (the northern third of Finland) and during November in the rest of Finland, though not until December in the southwestern archipelago. The Baltic Sea and lakes act as a heat storage and hinder the progress of winter. Winter is the longest season, lasting for about 100 days in southwestern Finland and 200 days in Lapland (FMI 2018a). In climatological and hydrological statistics the winter months in Finland are usually during December-February (DJF).

The Finnish meteorological definition of spring is a daily mean air temperature between 0ºC and 10ºC. Spring begins in early April in the southwestern archipelago and later in April elsewhere, except for northernmost Lapland, where it does not begin until early May. Thus, spring begins a month earlier in the south than in the north (FMI 2018a). In

climatological and hydrological statistics spring months in Finland are usually March-May (MAM).

The mean air temperature of Finland has risen over 2°C in the 1847–2013 period (Mikkonen et al. 2015). This trend is stronger than earlier studies showed for the 20th century (Jylhä et al. 2004). The observed warming in Finland is almost twice as high as the global temperature increase (0.74 °C/100 years), which is in line with the notion that warming is stronger in higher latitudes. Within the last 40 years the rate of the temperature increase has varied between 0.2 and 0.4°C/decade. The largest increases have been in November, December and January. Also, the spring months (MAM) have warmed more than the annual average. Tuomenvirta (2004) has also earlier shown that the winter and spring air temperature increases have been the strongest since the 1970s. Winter and spring air temperature anomalies since 1961 for the cities of Tampere (in the south) and Rovaniemi (in the north) are presented in Figure 1 (FMI 2018b).

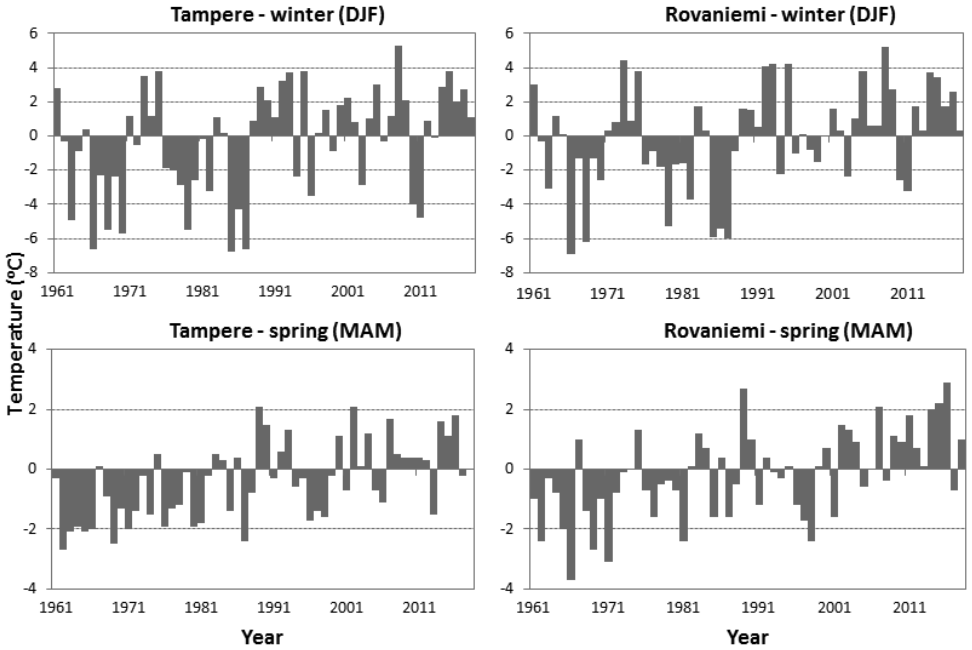


Figure 1. Winter (DJF) and spring (MAM) air temperature anomalies (1961–2018) for Tampere (Southern Finland) and Rovaniemi (Northern Finland). Source: Finnish Meteorological Institute (2018b)

Irannezhad, Marttila and Kløve (2014) found an increasing trend in the annual precipitation of Finland for 1911–2011. Also, the monthly precipitation has increased in the winter and spring months (December,

January and March) according to their study. An earlier study by Tuomenvirta (2004) did not show significant nationwide trends in precipitation during the 20th century, although notable interdecadal variability was detected. Irannezhad, Marttila and Kløve (2014) based their study on the areal precipitation values calculated for drainage basins, while Tuomenvirta (2004) used Finnish Meteorological Institute precipitation stations.

2.2 Ice regime in Finland

2.2.1 Ice cover physics

The formation of ice cover in lakes depends on the air temperature, wind speed and also lake morphometry (Stewart & Haugen 1990). The depth of the lake is the most important of the morphological factors as presented in **Paper I**. Finnish lake data presented in Figure 2 shows that very shallow (mean depth <1m) lakes freeze-up already after the negative temperature sum exceeds 20°C, meaning usually a few days after the air temperature drops below zero.

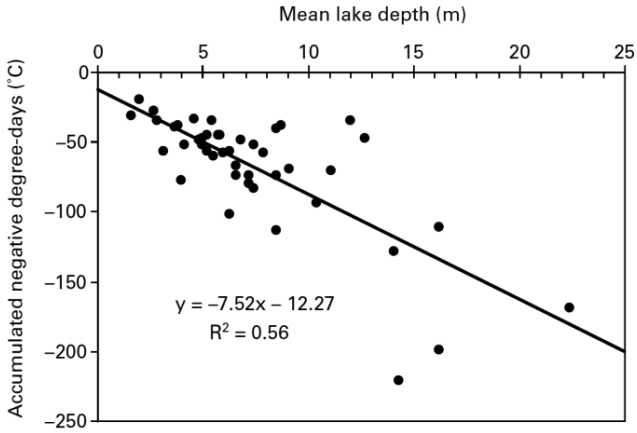


Figure 2. Correlation between the mean depth of the lake and accumulated negative degree-days needed for the freeze-up based on Finnish lake data (**Paper I**). Reprinted with permission of IWA Publishing.

Other studies have shown that the ice-on follows the date of the air temperature falling below the freezing point with a delay, which depends roughly linearly on the lake depth, and that each additional meter of lake depth corresponds to an order of one day of delay (Simojoki 1940; Leppäranta 2010). Leppäranta (2014) showed the relation with the delay and mixed layer depth, showing 2–3 days response for each additional meter. This is in line with finding presented in Figure 2, which illustrates that one

meter added in mean depth equals 7.5 negative degree days. Simojoki (1940) presented that relation between the freezing delay in days and the lake depth was not linear, since in deep lakes all the heat storage of the lower layer is not used. In large boreal lakes, the ice conditions demonstrate a large degree of inter-annual variation (Karetnikov et al. 2017).

Once the whole water body has cooled to 4ºC after the autumn convection, inverse stratification is established, and further cooling stabilizes the upper water layer. When the surface layer has cooled to the freezing point, the air temperature is below zero, and the wind is weak or calm, the first thin layer of horizontal crystals can be formed (called primary ice). As the ice sheet thickens, crystals start to grow downwards, parallel to the heat flux between the lake and the atmosphere. The first mathematical model of ice growth was presented by Stefan (1891). This layer of both primary ice and columnar ice is called black ice or congelation ice (Figure 3).



Figure 3. Schematic sketch of lake ice layers.

Ice cover can also grow within the snow on top of the ice. Snow-ice (superimposed ice) is formed when the snow cover depresses the ice so that water inundates over the ice and freezes within the snow pack. Falling rain or the temporary melting of snow cover on the ice can also cause the development of snow-ice. After the onset of the ice cover, the thickness of the ice grows as long as the released latent heat can be conducted through the ice into the atmosphere (e.g. Leppäranta 2010). The main factors controlling the rate of the ice growth are the heat fluxes and the ice thickness and structure (Kirillin et al. 2012).

The heat balance for ice melting is different from lake cooling and ice growth (Jakkila et al. 2009). The melting season begins once the ice has warmed up to melting point and the heat balance continues to be positive. This is largely determined by the net radiation balance. In winter the balance is negative, and the time it turns positive is a function of the latitude (Leppäranta 2015). Solar radiation is partially absorbed by the ice sheet and partially heats the lake water under the ice. When the snow melts, the surface albedo decreases, and more radiation can be absorbed by the snow. Once the snow has melted, the melting of the ice escalates rapidly. The melt rate of the ice is 1–3 cm per day (Leppäranta 2014). Liquid precipitation and strong winds accelerate the melting (e.g. Williams 1965; Kirillin et al. 2012). Since the solar radiation is the main factor for the timing of the ice-off event, there is a coherency in the spatial context (Magnuson et al. 2000). Snowmelt is most often determined using a temperature index method relating the melt rate proportionally to the air temperature. Also, the melting of the ice can be proportional to the air temperature, even though the process is not linear: it depends both on the radiation balance and the air temperature (Leppäranta 2014). Thus, the disappearance of lake ice can be related to accumulated positive degree-days: the thicker the ice the more accumulated degree-days are required before the ice disappears.

2.2.2 The ice cover season in Finland

Based on the analysis of the ice seasons in the 1961–2000 period (Korhonen 2005 & **Paper I**), on average the freeze-up of lakes occurs in Lapland (Northern Finland) on some small lakes in late October (Figure 4). In southern coastal areas, the lake freeze-up typically occurs at the beginning of December, over a month later than in the north.

Large, deep and lakes in a certain area can freeze as late as one month later than small shallow, ones. The deepest parts of the largest lakes in southern Finland freeze on the average as late as in the end of December, and in some years even as late as January. In Lapland, the largest open areas of Lake Inari freeze up at the end of November on the average. The variation in the freeze-up date is larger in the southern part of the country than in the north, because of the proximity to the Baltic Sea and because of the large lakes that act as heat storage. The atmospheric cooling rate in Northern Finland (more continental conditions) is higher than in the south (Leppäranta 2014). Additionally, freeze-thaw cycles have become common especially in Southern and Central Finland (Korhonen 2005). With data from the Northern Hemisphere data set, Weyhenmeyer et al. (2011) showed that highest interannual variability was observed for water bodies with the latest ice-on dates and the earliest ice-off dates.

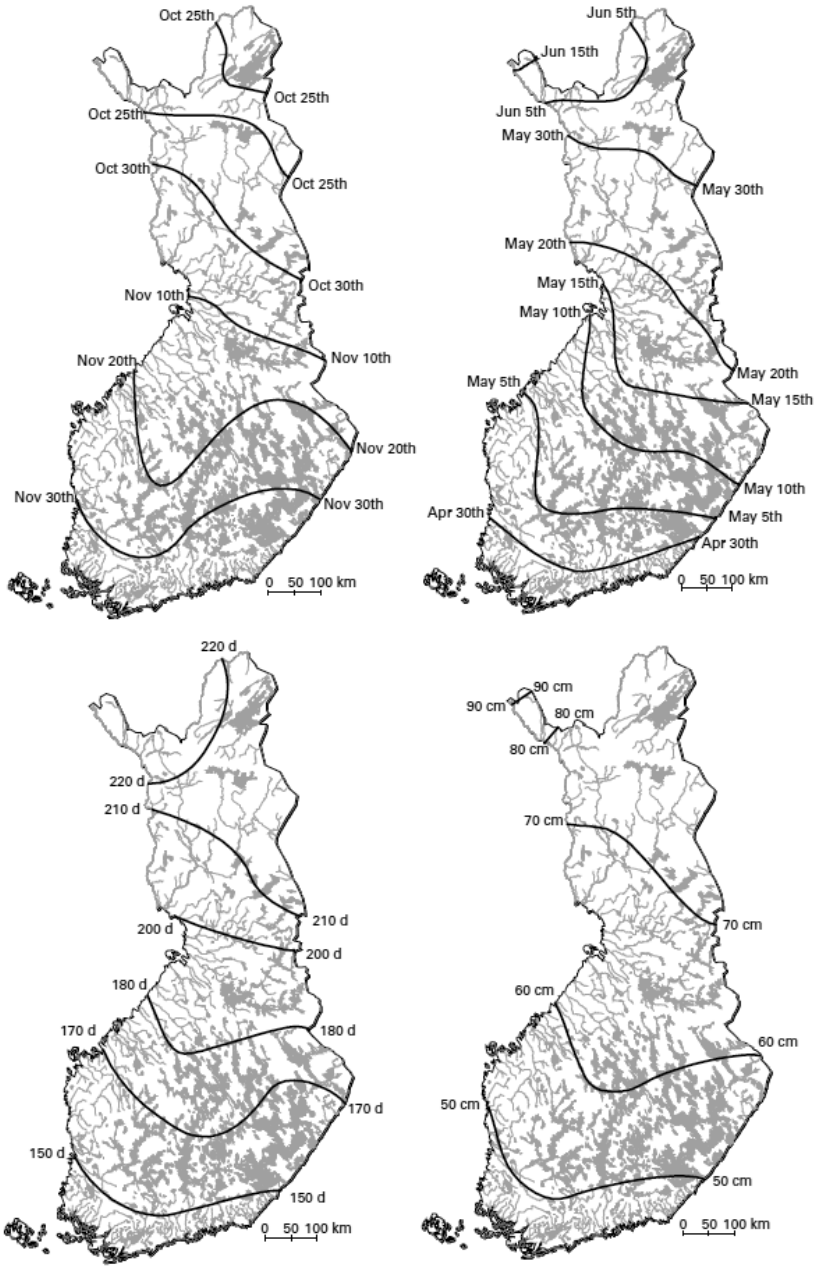


Figure 4. The average date of freeze-up and break-up (at the top), duration of ice cover and the mean maximum ice thickness (at the bottom) in 1961–2000 as presented in **Paper I**. Reprinted with permission of IWA Publishing.

The mean maximum ice thickness in the period of 1961–2000 varied from below 50 cm in Southern Finland to mainly 70–80 cm in Lapland. However, in Lake Kilpisjärvi (in the north-western corner of Finland) the mean maximum thickness is almost 90 cm. The maximum thickness occurs usually in the middle of March in the south and in April in Lapland.

The mean ice cover duration in 1961–2000 varied from the southern coast of less than 140 days to over 220 days in Lapland. The break-up of ice usually occurs at the end of April in Southern Finland, progressing to the north so that in northern Lapland the lakes melt usually at the beginning of June. On Lake Kilpisjärvi, the ice breaks up as late as after mid-June. The ice breaks up simultaneously within a region almost regardless of the size of the lake, as solar radiation is the main driving force behind it. The variation of the break-up date is about half that of the variation of the freeze-up date and can be explained by calendar-related solar radiation.

2.3 The river discharge regime in Finland

Precipitation is the most important climatic factor affecting the discharge regime. In Southern Finland the precipitation is higher than in the north (FMI 2018c; d). In the south the growing season is longer, and the evaporation is higher. Therefore, the amount of runoff compared to the amount of precipitation received (runoff coefficient) is larger in the north than in the south. There is variation also 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% (Korhonen 2007; **Paper II**). The proportion of the runoff is, naturally higher in wet years and lower in dry years.

The form of precipitation (solid or liquid) has a large effect on the seasonal discharge regime. In the winter, precipitation is stored as snow; therefore, water levels and discharges are typically at their seasonal lowest in late winter before the melting season – at least in the north. After that, the highest water levels and discharges are recorded in springtime or in early summer due to snowmelt (Hyvärinen & Puupponen 1986). Water levels and discharges usually decline during the summer when the evaporation is normally greater than the precipitation. If the summer is dry and warm, water levels can even drop lower than the winter minimum. In Northern Finland the lowest water levels are normally reached in wintertime, but in the south the lowest levels are often recorded in the summer. In the autumn, evaporation decreases, and rainfall increases which leads to higher water levels and discharges. In the small rivers of the southern and western coast, the annual

high flow may occur in autumn, summer or winter. In the unregulated rivers of Northern Finland the highest flow is almost always recorded in spring or early summer. Once the winter period starts, water levels begin to regress again, because of minimal runoff formation caused by the frozen soil and due to the precipitation falling as snow (Hyvärinen & Puupponen 1986).

River systems in Finland can be divided into three groups according to their river discharge regimes (Hyvärinen & Puupponen 1986; Korhonen 2007; **Paper II)** as shown in Figure 5a.

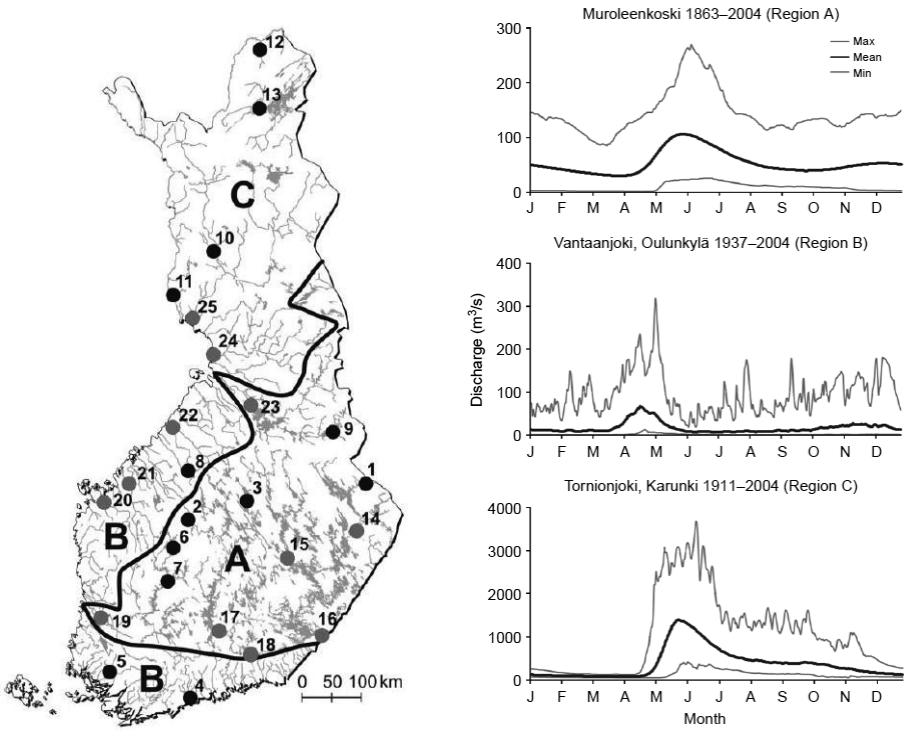


Figure 5. a) (left) A map of the locations of discharge gauging stations from **Paper II**. Black dots represent unregulated sites and grey dots regulated sites. Regions A, B and C refer to different discharge regions in Finland. b) (right) Minimum, mean and maximum hydrographs for three unregulated discharge sites in different runoff regions. Reprinted with the kind permission of IWA Publishing.

The first group covers the watersheds of lake regions mostly in Southern and Central Finland, where the large storage volume mitigates 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, Figure 5). Also, 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 consists of small and medium sized river basins with only a few lakes and these mostly originate 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). The third group contains large rivers in Northern Ostrobothnia and Lapland. Here water flows plentifully throughout the year, even though there are not many lakes (Region C). Many of the largest rivers and lakes in Finland are regulated and the discharge regime is therefore altered.

2.4 Climatic conditions affecting hydrology

Natural discharge variations are mainly caused by climatic factors, as presented in earlier chapters and precipitation is the main element affecting runoff. In the winter, snow accumulates in the terrain and it is released in to the rivers and lakes in the springtime. Mild winters cause higher discharge due to snow melt and rain instead of snow. In Finland, warm summers do not contribute to the summer discharge variation as much as warm winters do to the winter discharge. Naturally summer temperatures are related to evaporation, which affects the discharge regime, but the precipitation is of higher importance (Hyvärinen & Puupponen 1986).

The correlation coefficient between the annual precipitation (uncorrected) and mean runoff in Finland in 1912–2002 was 0.78 (r^2=0.61) and was statistically significant ($p<0.001$) (**Paper II**). The correlation was higher in the north than in the south. The connection between the annual air temperature and discharge was much weaker than between the annual precipitation and runoff during the 1912–2002 period in Finland. The correlation was strongest ($r=0.38$, $p<0.001$) between the 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 the winter air temperature usually remains below zero Celsius in the north, and changes below zero do not have much effect on the discharge.

Naturally, climatic conditions affect the ice season very strongly. There is a connection between ice events (freeze-up, break-up, duration) and air temperature. Figure 6 shows normalized air temperatures in the Northern Hemisphere versus an ice cover time series since 1850 for autumn, winter and spring (**Paper IV**).

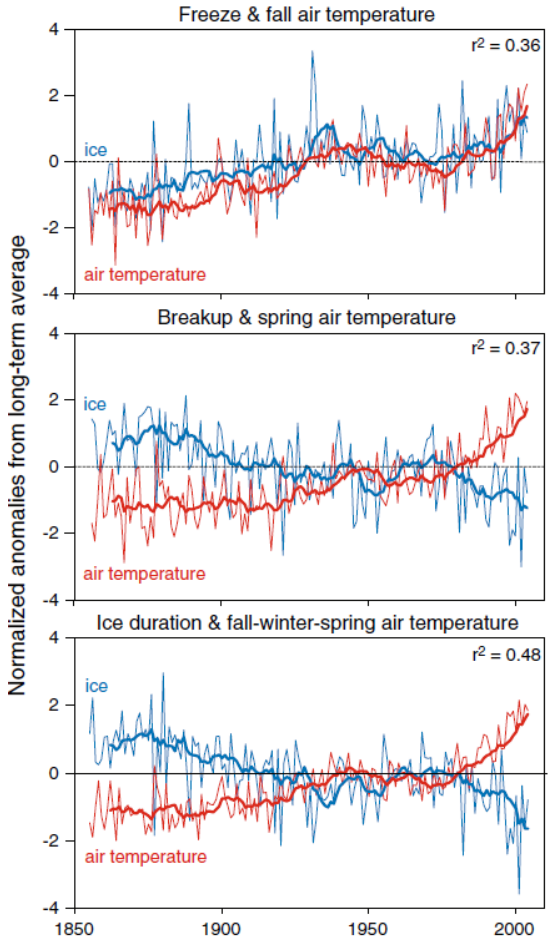


Figure 6. Comparisons of anomaly time series for ice measures and land air temperatures for the Northern Hemisphere from 1855–1856 through 2004–2005. Figure adopted from **Paper IV** and reprinted with permission from Springer Nature.

Moreover, Korhonen (2005, **Paper I**) has also shown correlations between air temperatures and lake ice cover season in Finland. In **Paper I**, correlations between the air temperature and break-up and freeze-up dates were calculated for the longest time series in Finland. Correlations for the break-up and April or April–May mean air temperatures were determined and the r^2 values were 0.59–0.64 for the entire observation period available (until 2002). For the correlations between the freeze-up and the November or November–December mean air temperature, the r^2 values of the entire observation period were 0.41–0.57 for the lakes investigated. The correlations for the break-up dates were higher than for the freeze-up dates. The higher r^2 values for the spring result from the spring mean air

temperatures correlating better with the sum of spring degree-days. In autumn, the water-cooling process depends on the weighted air temperature sum instead of the direct air temperature sum (Leppäranta 2015). Also wind conditions as well as the lake depth have an effect on the process. Furthermore, a warmer spell between below zero temperatures can reset the freezing process. The Finnish data seemed to achieve better r^2 values than in **Paper IV** for the whole Northern Hemisphere. It is of course evident that local data will correlate better than averaged values for larger areas. In **Paper IV** there was no large difference between the spring and autumn r^2 values, but the r^2 value for the ice duration and autumn-winter-spring air temperature was actually higher than the autumn or spring.

2.4.1 Atmospheric circulation patterns

Atmospheric circulation patterns (ACP) affect the local climate considerably since they govern the precipitation and temperature conditions (e.g. Hurrell 1995; Hurrell & Van Loon 1997). There are several ACP indices which describe air pressure anomalies in different parts of the world. In the Southern Hemisphere, the El Niño Southern Oscillation (ENSO) phenomenon has been known for a long time to influence a very large area of the planet, and other Pacific ACPs include the Pacific Decadal Oscillation (PDO) and the Pacific North American Pattern (PNA). In the Northern Hemisphere, the Arctic Oscillation (AO) and the North Atlantic Oscillation (NAO) affect European conditions (Figure 7). The NAO has an effect on the weather in Europe so that, when the NAO is strongly positive in the wintertime, strong westerly winds bring mild and rainy weather to Northern Europe (Hurrell 1995). The large negative NAO values are connected to weak westerly winds and cold winters. There are studies which show the influence of the NAO on air temperatures, e.g. Chen & Hellström (1999), and on precipitation in Northern Europe (Hurrell & Van Loon 1997; Busuioc et al. 2001; Uvo 2003; Jaagus 2006; Irannezhad et al. 2014). Several studies have also presented correlations between the NAO and the discharge regime (e.g. Peterson et al. 2002; Bouwer et al. 2006; 2008; Danilovich et al. 2007; Hannaford & Marsh 2008; Wrzesinski & Paluszkiewicz 2010). Irannezhad et al. (2015; 2017) have presented different ACPs affecting the Finnish climate. The NAO has been probably most researched in Northern Europe and for Finnish conditions.

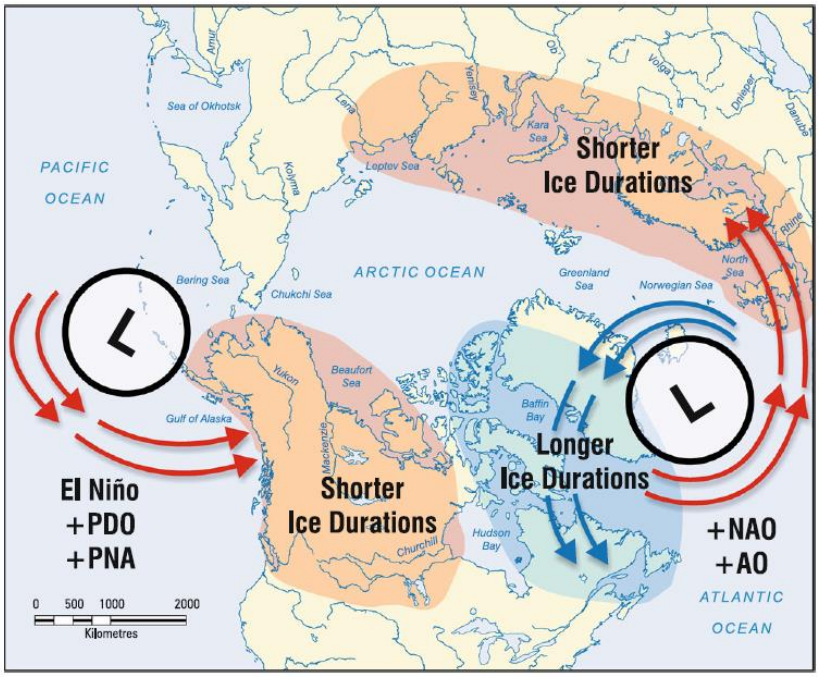


Figure 7. Illustration of different atmospheric circulation patterns and their effects on ice durations. Figure adopted from Prowse et al. (2011) with permission from Springer Nature.

Interannual and interdecadal variabilities in lake ice dates have many drivers on local and global scales. Time series of lake ice events have statistical correlations with large scale climate drivers such as the ENSO (Anderson et al.1996; Livingstone 2000; Robertson et al. 2000; Magnuson et al. 2004; Bonsal et al. 2006; Sharma & Magnuson 2014), NAO (Livingstone 1999; 2000; Yoo & D'Odorico 2002; Magnuson et al. 2004; Blenckner at al. 2007; 2010; Karetnikov & Naumenko 2008; Sharma & Magnuson 2014), PDO (Magnuson et al. 2004; Bonsal et al. 2006), PNA (Benson et al. 2000; Bonsal et al. 2006), the Western Pacific Pattern (WP) (Benson et al. 2000), the North Pacific index (NP) (Magnuson et al. 2004), and the AO (Bonsal et al. 2006). Prowse et al. (2011) summarized different studies concerning ACPs and their effects on Arctic lake and river ice (Figure 7).

2.4.2 Climate change effects

As presented in the introduction of this thesis, changes in the precipitation tend to affect the volume of runoff and particularly the maximum snow water equivalent (SWE), which usually occurs at the onset of the melt season. On the other hand, temperature changes mostly affect the timing of runoff

(Barnett et al. 2005). Projected climate warming according to several global change scenarios has the potential to significantly modify the water cycle within river basins in northern latitudes. Warming is expected to lead to increases in the net and winter precipitation (IPCC 2014) at high latitudes.

Global warming projections for Finland show that substantial changes will take place in the Finnish climate. According to Ruosteenoja et al. (2016), under the high-emission RCP8.5 forcing scenario for the period 2040–2069, surface air temperatures in winter are projected to increase by 2–7°C relative to 1981–2010, while precipitation would increase by 4–30%. The projected changes are most notable in the winter: the mean surface air temperature is estimated to rise 1.6–1.7 times as much, and in the summer, precipitation may increase by several tens of percent by the end of this century. According to the RCP8.5 scenario, mid-winter temperatures in Finland would increase by 2–7°C and precipitation by 3–36% by the mid-21st century. Changes in climatic conditions are reflected in discharge regimes, as seen from the past studies (presented in Introduction) and can also be seen from the results of this thesis and several other studies across the Northern Hemisphere.

Changes both in the mean condition and in variability around the mean condition can alter the probability of extreme events as presented by the IPCC (2001) (Figure 8). Based on air temperature analyses, both decreasing and increasing variability have been found in different studies and for different time spans (IPCC 2001). As addition to an increase in mean air temperatures, an increase in the number of extreme hot events and a decrease in number of extreme cold events have been observed (IPCC 2001). The IPCC (2013) present observed changes in both the mean daily minimum and daily maximum air temperature anomalies relative to a 1961–1990 climatology for two periods: 1951–1980 and 1981–2010. **Paper IV** presents that for example, a trend toward earlier ice break-up increases the probability of extremely early break-up events and decreases the probability of extremely late break-up events. Similarly, if the variability of the ice break-up dates increases, the probabilities of both extremely early and extremely late events may increase owing to the change in variability alone. Extreme events in the context of lake ice dynamics include, for example, extremely late freeze-ups, extremely early break-ups, and, for lakes that usually freeze, years of no ice cover.

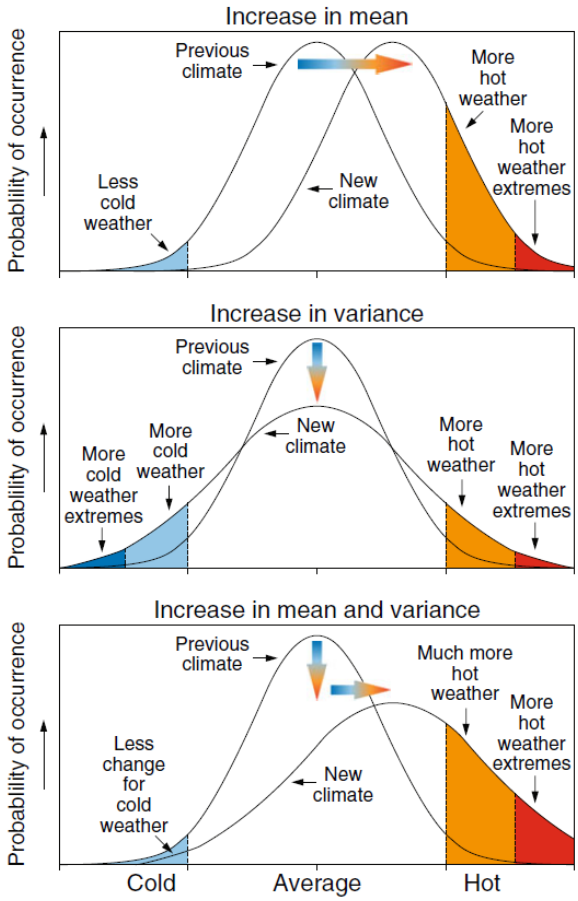


Figure 8. Diagram of changes in the frequency of extreme events if the mean increases (top), the variance increases (middle), or both increase (bottom). Modified from Figure 2.32 in the Intergovernmental Panel on Climate Change (IPCC), Working Group I report (2001) adopted from **Paper IV** with permission from Springer Nature.

3. Observations and measurements

The data used in this dissertation mainly comprises records gathered by the Finnish Environment Institute SYKE, its predecessors and regional environment centres. The data is stored in the HYDRO database. Since both ice and discharge data have been collected in Finland for over a century, also the measurement techniques and data processing procedures have changed over time. Observation and measurement methods and practices related to them are presented and discussed in this chapter.

The papers in this thesis include different kinds of observation data. Different sources of data are marked in Table 1. Numbers in parenthesis refer to the number of stations included in the papers. This was applied only for ice cover and river discharge stations which are main scope of this thesis, not for meteorological or climatological data or models.

The observation sites of river discharge and ice cover stations used in this study are presented in Figure 5 and Figure 9, respectively. The largest number of stations was included in **Paper I** as shown in Table 1. Subsets of these Finnish discharge and ice cover data sets were also used in **Papers III** and **IV**, and the River Tornionjoki break-up series was used in **Papers V** and **VI**.

Table 1. Data used in the different papers of this thesis. The number of stations used in the analysis are marked in parenthesis when applicable (ice cover and discharge stations).

Data	Paper I	Paper II	Paper III	Paper IV	Paper V	Paper VI
Ice freeze-up or break-up	**x (88)**			**x (75)**	**x (1)**	**x (2)**
Ice thickness	**x (34)**					
River discharge		**x (25)**	**x (4)**			
Climatic or weather data	**x**	**x**	**x**	**x**	**x**	**x**
ACPs (NAO)		**x**				**x**

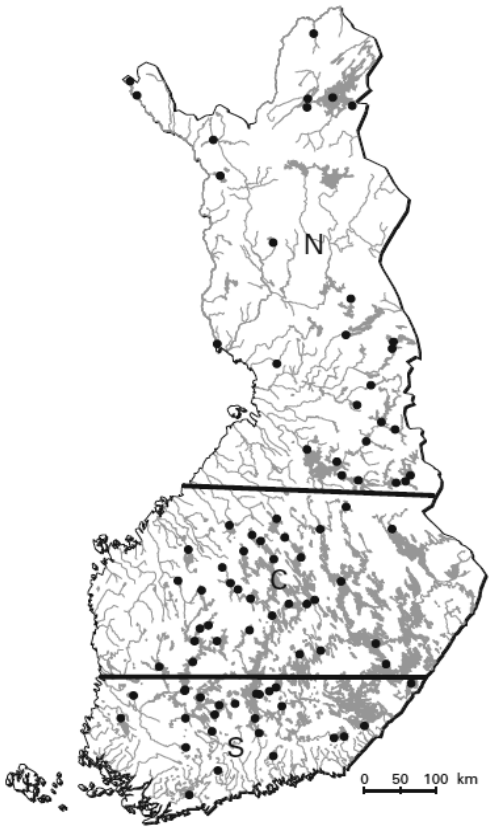


Figure 9. Map of ice observation stations used in this study (**Paper I**) and Finland divided into southern (S), central (C) and northern regions (N) for that study. Reprinted with permission from IWA Publishing.

3.1 Ice cover observations

Ice conditions in lakes and rivers have been observed in Finland for a long time. The record for the date of ice break-up for the River Tornionjoki, defined as when the ice was generally moving, was started by a merchant named Olof Ahlbom in 1693. The ice break-up time series has been preserved because of Torne's important role in trade and transportation (**Paper V** and **VI**). Kajander (1989; 1993; 1995) thoroughly documented the ice break-up dates and observations from multiple sources.

The longest freeze-up and break-up series of lakes are from Lake Kallavesi, Lake Näsijärvi and Lake Oulujärvi. For these lakes, observations had begun by the middle of the 19th century. There are also some other lakes for which there are records since the late 19th century, but the majority of ice

phenology time series started in 1909–1910 when hydrometric networks were established in Finland (Korhonen 2005; Puupponen 2008; Korhonen 2008). Continuous ice thickness observations begun in the 1910s at some lake sites in Central and in Southern Finland. Most of the ice thickness measurements commenced in the 1960s. Ice phenology and ice thickness observation practices have been described in detail by Korhonen (2005) and they are shortly presented in following paragraphs.

3.1.1 Freeze-up and break-up of lakes

Both freeze-ups and break-ups are observed at four stages according to SYKE observation instructions, depending on the extent of the ice cover within the horizon of the observation site. The four stages of freezing are the: "freezing of the shores", "freezing of the bays", "freeze-up of the lake within sight" and "freeze-up of the whole lake".

Only a few observation sites display a clear sequence of these four stages. Sometimes severe cold causes all four stages to occur during the same night. At some sites it is not possible to distinguish between the stages. “Within sight” at a small lake often means the whole lake. On the other hand, it is hard for an observer to get information about the freezing of all the parts of a large and complex lake and therefore within sight has been used. The date of the permanent freeze-up of the whole area visible from the observation site was taken as the official freeze-up date in this study.

The four stages of break-up are: “thawing of the shores”, “thaw areas out of the shore”, “ice in movement” and “no ice within sight”. The break-up date was chosen as the date when ice was no longer visible from the observation site. For the River Tornionjoki, break-up was defined as when the ice was moving.

If there were several records for the same year from different data sources, the earlier date was used. The duration of ice cover in days was defined as the difference between the break-up and the freeze-up dates. Timing records contain some uncertainties. Usually an observer has lived nearby a station and when daily water level observations have been made, records of ice-on and ice-off timing are made at the same time. During the last decades when the stations have been automated, observers have no longer visited the gauge daily. Sometimes defining the exact date of a freeze-up or break-up is a difficult and subjective definition by a person.

3.1.2 Ice thickness

Ice thickness is measured in the winter every 10th, 20th and 30th of the month, usually at least 50 meters from the shoreline. This measuring practice has been used since the late 1970s (Korhonen 2005). Before that, measurements were made twice a month, on the 15th and 30th. Nowadays, manual gauges and a drill are used when measuring the ice thickness and the average value from three different holes is defined as the official observation. Before the 1982 only one ice drill hole was made (Korhonen & Koskela 2017). Since the late 1970s, the snow-ice thickness and snow thickness have also been measured in addition to the total thickness of the ice cover. The effect of the change in measurement practices from one to three drilling holes is discussed by Korhonen and Koskela (2017). In general, during the time of maximum ice thickness, areal differences level off, as Bengtsson (1986) has already proved. Usually during this time, the differences are only a few centimetres at Finnish observation sites. However, the measurement practice change might have affected the homogeneity of early winter records (Nov-Dec), but this data is not within the scope of analysis of this thesis.

3.2 River discharge

Water level and discharge observations in Finland already started at a couple of the largest lakes (Lake Näsijärvi and Lake Saimaa) in the mid-1800s (Puupponen 2008). Large numbers of river gauges were built in the 1910s after the establishment of the Hydrographical Bureau in 1908 (Puupponen 1998). Many of the largest rivers in Finland have discharge records starting from 1910. The first discharge measurements with Woltmann current meters were performed already in the 1860s (Sirén 1974).

The discharge data from unregulated stations was determined by the rating curve method (described in paragraph 3.2.2) using the daily water level data. Data from the regulated sites was obtained from hydropower plants, regulation dams or by the rating curve method if the station was not situated at a hydropower plant or dam. The dissertation focuses more on unregulated river gauging sites that present natural variations.

3.2.1 Water level and discharge measurements

Water levels are observed as distances in centimetres from the gauge zero, and in this specific level of the gauge the water level values are also given in the database. When a gauge is established, its gauge datum, i.e. its elevation above the sea level, is determined by levelling from a national network

benchmark. If needed, the water levels can be given according to one of these standard levels. There have been four level standards: NN, N43, LN and N60. A new level standard, N2000, was introduced just recently. According to Finnish practice, levelling of a water level gauge against the benchmark is done at least every three years or more often if the gauge is suspected to be moving.

The water level is observed daily and a major part of the stations have continuous automatic registration at hourly intervals at least (pressure transducers with loggers). At many river stations, water levels were registered using chart recorders (limnigraph) before the time of automatic devices. A limnigraph is a mechanical recorder which draws the curve of water level fluctuations on a paper by registering the movements of a flute floating in a stilling well, connected to the water system. The chart papers are changed every 1–4 weeks and the daily mean values of the water level can be read from them. Even though most of the stations are automated nowadays, once a month control measurements are still made manually, by either reading the gauge or by measuring the level using a funnel-top measuring stick placed on a bottom pole. Automatic pressure transducer values are calibrated against these manual control readings.

Water level measurement techniques have changed over time. At the start of water level observations in the 1800s, one gauge reading was taken at 8 a.m. in the morning. Until the 1986 the daily discharge data was based on a single water level reading at 8 a.m. (Korhonen and Koskela 2017). After that, values in the time series have been daily averages (0–24-hour values) from a chart recorder or averaged from momentary values (pressure transducers, during the recent decades). In addition to changes in the way the daily value is estimated, also the accuracy of the water level reading may have been different over the years. Manual readings have been done at resolution of 1 cm, but also automatic values are rounded to the nearest centimetre integer value when converting to discharges. These irregularities over time in determining the daily water levels have some effect on the peak values at river stations.

In Finland, normally 5 to 10 discharge measurements are needed for establishment of a rating curve (Ekholm 2012). Moreover, frequent measurements are needed to check the validity of the rating curve, as the channel may change due to human activity or natural processes - e.g. as a result of hydrotechnical construction, or erosion, or the growth of vegetation.

Before the 1990s all the measurements were made with traditional mechanical current meters, and measuring spring peak discharges in large rivers was time consuming (Hyvärinen & Ekholm 2008; Hyvärinen 2008). Since the 1990s Acoustic Doppler Current Profilers (ADCP) were introduced for larger river measurements. However, during the early 2000s still less than half of the Finnish national hydrological network's discharge measurements were made with ADCPs (Koskela 2017, personal communication).

3.2.2 Discharge rating curves

Discharge is the volume of water moving down a stream or river per unit of time. In Finland the unit used for measuring water discharge is m^3/s. In general, river discharge is computed by multiplying the area of water in a channel cross section by the average velocity of the water in that cross section: Q = v*A (Figure 10).

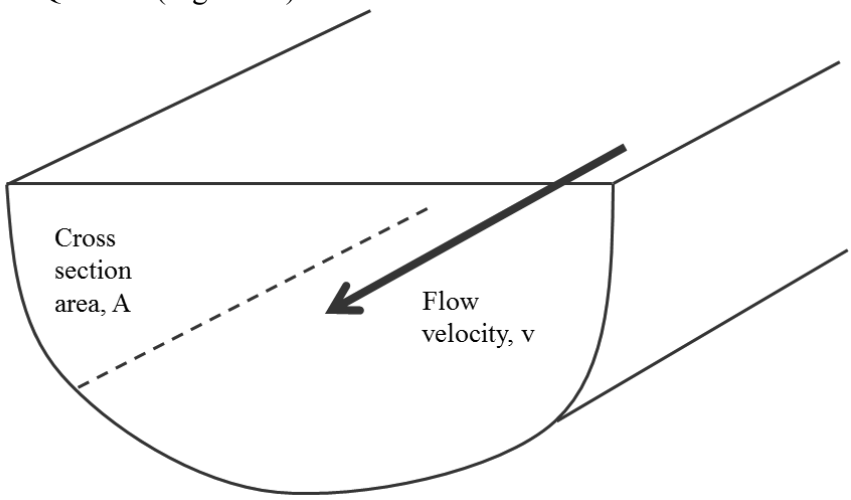


Figure 10. Schematic drawing of river discharge determination.

The discharge rating curve describes the relationship between water level and flow in natural streams. In Finland, river discharges are mainly derived from rating curves in natural state streams. Rating curves can be used for estimating discharges when the discharge depends on the water stage alone. The rating curves can be drawn based on concurrent discharge measurements and water level observations, if the river bed meets certain hydraulic conditions. Conditions are met, if the river bed remains unchanged over time and there is a hydraulic control in the stream. With good measurement site selection, the same rating can be used for years.

There are also very stable rating curves, such as for Muroleenkoski, the outlet of lake Palovesi in Central Finland, which has been valid from the 19th century until the present day (Figure 11). Most of the discharge stations with solid bedrock bottoms in Finland are very stable. Scandinavian river bed conditions are very stable in the case of rating curves compared to other parts of the world with vegetation and erosion problems.

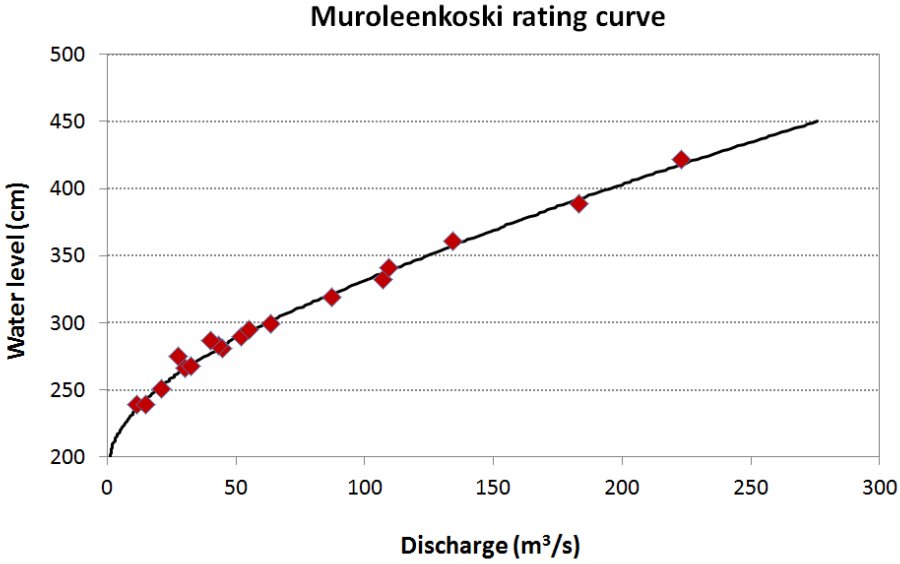


Figure 11. An example of a stable rating curve from Muroleenkoski, valid from 1863. The red dots are actual discharge measurements from 1910–2016.

Kuusisto (1975) stated three sources of uncertainty related to discharges that are: errors in discharge measurements, errors in water level measurements, and errors in rating curves. Korhonen and Koskela (2017) also discuss the uncertainties related to daily discharges. They point out a possible inconsistency in the time series related to the different rating curves used. Based on the careful analysis of the actual discharge measurements of some of the Finnish stations, it is possible to argue that at some places instead of many there has actually always been only one rating that should have been used for the whole observation period (there is an example in Figure 12). Changes in the ratings especially affect the highest flows because the rating curves have been extrapolated well beyond the highest ever measured discharge and these parts of the various curves have big differences. The same applies also to very low flows (Korhonen & Koskela 2017).

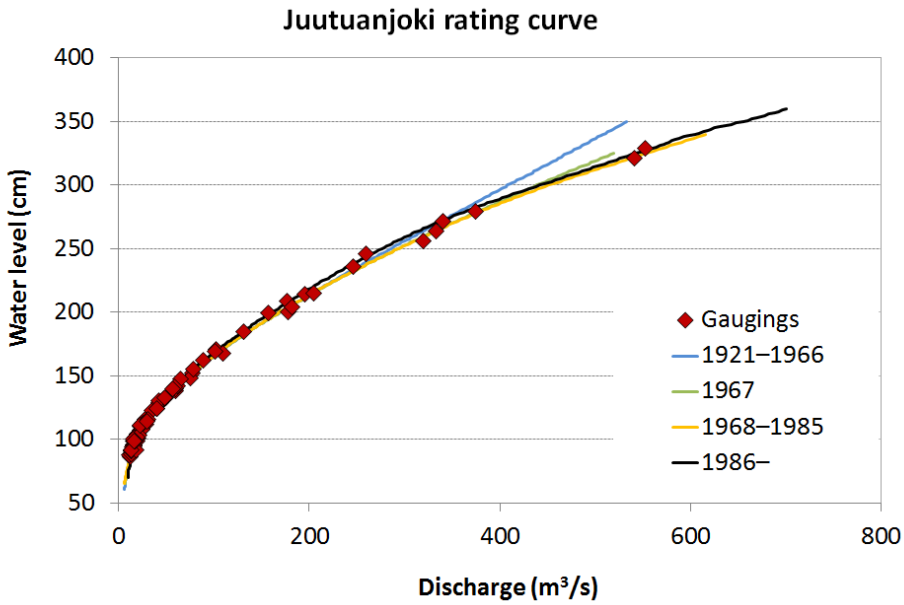


Figure 12. An example of the Juutuanjoki site with four different rating curves defined by a hydrologist, and actual gaugings (red dots).

The stations included in the analysis of this dissertation were selected by criteria with reliable data. However, the extrapolation problem applies to many of rating curve stations, since the mobilization of discharge measurement personnel in the time of extreme events has been challenging and measurement conditions may have been too dangerous or difficult for a current meter measurement. The main analysis of this thesis relies on the timing of spring peaks and seasonal flows that are not so much affected by extrapolation problems. The same applies also for water level measurement method changes, because when using monthly averages this issue does not have much effect.

3.2.3 Ice correction of ice-covered streams

In winter, the hydraulic properties of rivers are affected by ice cover and therefore the open water rating curve cannot be used during ice-cover season. In 2012, there were about 90 stations for which the rating curve was not valid in the wintertime due to the backwater effect caused by ice in the channel (Ekholm 2012). Discharge observations in the database during ice-affected periods are post-processed values. The discharge values at lake outlets are reliable also in winter time since they usually stay free of ice cover and do not need ice correction (Hyvärinen 2003).

Winter discharge computation methods differ in northern countries (Pelletier 1990). The Finnish ice correction procedure before computers was introduced by Hyvärinen (1984b). In Finland, ice correction has always been a subjective process carried out by the responsible hydrologist. There is no guarantee that two individual hydrologists would correct values exactly the same way, and it has been shown that they do not (e.g. Melcher & Walker 1992, Hamilton et al. 2000). This issue is extremely likely to cause big uncertainties in the annual maxima in Northern Finland as in some years the maximum flood must be ice-corrected. Uncertainties related to ice cover corrections should also always be carefully studied before drawing conclusions on long-term changes in winter discharges.

In Finland the estimation of river discharges during the winter season is still a subjective process. Nowadays, a graphical interface is used providing a visual tool with all the relevant data. In this process, the winter discharge during ice cover season is subjectively interpolated by utilizing winter season discharge measurements, simulation results of the conceptual hydrological model, temperature and precipitation observations, and stage observations. Furthermore, streamflow observations from nearby gauging points and stage-discharge curves for winter season are used whenever available. Additionally, freeze-up and break-up observations are available for some sites. Despite all of the data available, the process of estimating the winter streamflow is still subjective and time-consuming. Over the years there have been at least three different hydrologists carrying out ice corrections for the study sites. On the other hand, a conceptual hydrological model has been available to assist estimates only for about 15 years. (Korhonen & Koskela 2017).

Winter discharges are corrected at nine of the 25 stations included in **Paper II**. Unregulated ice corrected stations include: Lieksanjoki – Ruunaa, Vantaanjoki – Oulunkylä, Ounasjoki – Marraskoski, Tornionjoki – Karunki and Juutuanjoki – Saukkoniva. Regulated ice corrected sites include the Ostrobothnian rivers: Kyrönjoki – Skatila, Lapuanjoki – Keppo and Kalajoki – Niskakoski. Hydropower, regulation dam or lake outlet stations do not need to be ice corrected.

3.2.4 Hydropower station data

Hydropower plants are obligated to provide water level and discharge data to SYKE based on their permits, but these permits do not give any instructions on the data quality control or related procedures. Uncertainties in

hydropower station data are usually larger than for the rating curve stations but this data can be used on the yearly or monthly level.

Since many of the largest rivers of Finland are regulated, some hydropower stations were included in the study. Data quality control procedures at different hydropower companies are just currently under review by SYKE. There are a lot of differences between power companies concerning their procedures. Some companies have relevant methods and others do not. Obvious errors and outliers are scanned by SYKE and station data is compared with nearby stations as well. The hydropower stations selected for analysis in **Paper II** were assessed to be rather reliable even on daily level.

3.2.5 Simulated discharge data

In **Paper III,** the data analysed were model simulated discharge values. These daily discharges were simulated with the Watershed Simulation and Forecasting System (WSFS) hydrological model (Vehviläinen 1994; Vehviläinen et al. 2005) using temperature and precipitation from regional climate models (RCM) for the period 1951–2099.

3.3 Meteorological data

The data on the annual precipitation and monthly mean temperature of Finland for 1912–2002 was obtained from the FMI, based on work by Tuomenvirta (2004). The precipitation values used in **Paper II** and by Korhonen (2007) were uncorrected, i.e. 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, while for the Tretyakov gauge (1981–present) it is 1.18 (Kuusisto 1986). These correction values were used in **Paper II** when calculating the runoff–precipitation ratio.

3.4 The NAO index

In **Papers II and VI,** an index related atmospheric circulation pattern, the so called teleconnection index of the NAO was used in the analysis. The NAO index is defined as the wintertime (December–March) difference between normalized pressure anomalies in Portugal and Iceland. The NAO index data by Hurrell (1995) was used in **Paper II** and by Hurrell (2015) for **Paper VI**.

4. Methods

A schematic illustration of data flow from observations and notes to the final analysis of this thesis is presented in Figure 13.

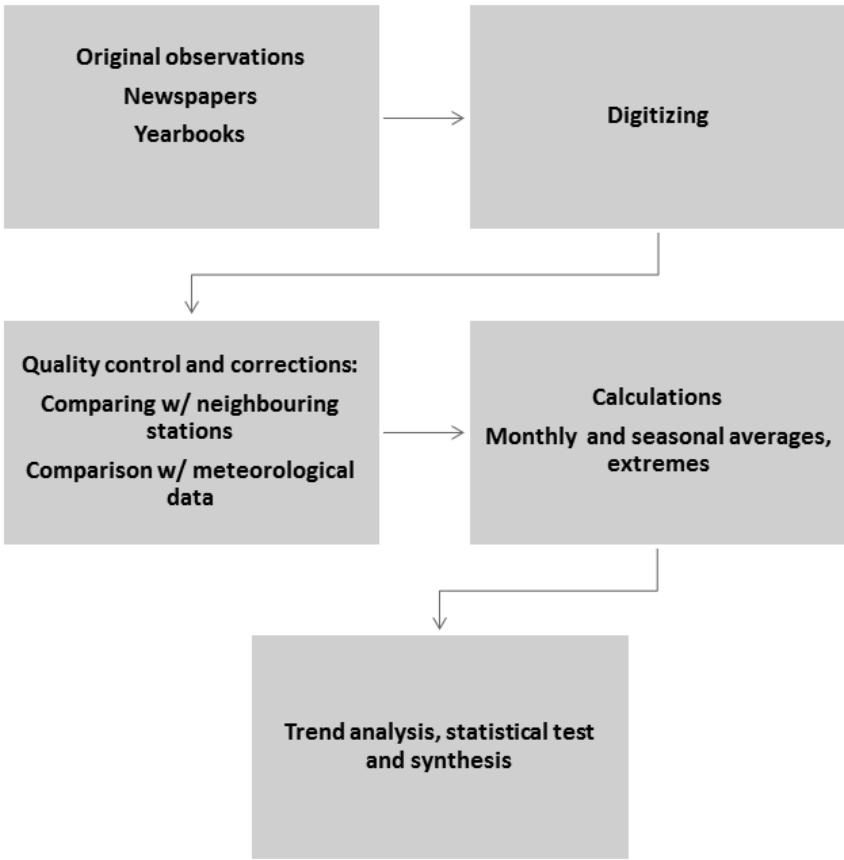


Figure 13. A schematic diagram of the different steps included in this research process.

The first two steps were mainly done by acting hydrologists and research assistants at the time of collecting, controlling quality and digitizing the water level, and calculating river discharge and ice thickness data. A large part of ice phenology data was collected and stored by Kajander (1989; 1993; 1995). Some of the ice phenology (freeze-up and break-up) data of this study (**Paper I**) was digitized and quality controlled by author herself during the research process. After digitizing and verifying the data, records were stored in SYKE database (HYDRO) and since then made available openly to other users. Additionally, the discharge data used in the study was routinely checked for out of range values or outliers before doing the analysis. The

selection of stations was done together with the responsible hydrologist in charge of discharges.

The methods used in this dissertation include mainly statistical data analysis methods as described below. The following paragraphs present some of the research methods used in the different papers. Only the most relevant methods for the scope of this thesis and regarding the role of the author are presented.

4.1 Data pre-processing and corrections prior to data analysis

Data collected by SYKE and its predecessors has been keyed in by research assistants and quality controlled by the hydrologists in charge at the time the data was produced. Data quality assurance procedures include checking obvious outliers and out of range values, filling in the gaps, comparing time series with neighbouring stations, or with other relevant data sources such as meteorological data or metadata provided by observers or technicians taking measurements. Data quality control procedures have varied over the decades and not all practices are documented. Additionally, metadata and flags for data in the early days are incomplete. In the 19th century and until the late 20th century, observations were made manually and then stored as they were as observation papers. After start of data registers and databases, these records were digitized and transferred into digital databases. While the data was transferred to the registers via punch cards some misinterpretation of the data could have happened and this has been corrected when noticed. Some of the quality flags have disappeared during the transfer from the punch cards to the digital archives. Unfortunately, there is always a chance of miskeying the data while during data conversion and storage. Lately, automatic data quality control procedures have been used and these detect easily evident mistakes or errors in the data. Also modelling and water balance comparison with other stations is easier nowadays than it used to be in the past.

Prior to the data analysis, the sites were selected together with the hydrologist in charge of the observations. Sites that were considered to have reliable data were included in the study. Some cross-correlations with neighbouring stations and quality checks with meteorological data were made in order to find outliers (Korhonen 2005, 2007 and **Papers I & II**). In some cases, suspicious values were verified from the observation archives and corrected. Data used in all **Papers I–VI** are as they were in the database at the time of the data retrieval for analysis. For example, the discharge rating curves are usually updated back in time when new measurements confirm

that there has been a change in conditions. However, there have been minimal changes to the data of the rating curve stations since publishing **Paper II,** because reliable stations were selected for the study.

In chapter 3, inhomogeneities related to ice cover and discharge measurement methods were introduced. These inhomogeneities include changes in measurement methods both concerning the ice thickness and water level measurements, ice correction of discharge data and rating curve changing procedures. However, these inconsistencies do not have a large effect on the data when analyzing monthly, seasonal or yearly discharge values and using only stations that are known not to have remarkable inconsistencies in data. In this thesis, the discharge data used in the analyses are mainly monthly or seasonal and these inconsistencies tend to disappear or become insignificant when averaged out. Also ice cover thickness variations even out during the winter, and in times of maximum ice thickness the differences are not as large as they are in the early winter. This dissertation's analyses focus mainly on changes in the maximum ice thickness and the timing of the freeze-up and break-up of the ice.

4.2 Statistical methods

The data of the thesis was analysed using several statistical methods. In addition to basic arithmetic means and standard deviations, correlations, sliding correlations and autoregression were used. Trend analysis and autocorrelation methods are explained in following paragraphs.

4.3 Trend analysis (I, II, III)

Long-term changes in the ice cover (**Paper I**) were investigated by linear regression. Trends were tested to determine whether changes were statistically significant. The 2-tailed t-test was used to determine the level of significance. The significances of trends were categorized to levels of 5% ($p<0.05$), 1% ($p<0.01$) and 0.1% ($p<0.001$).

In **Papers II and III,** trends were tested statistically with a non-parametric Mann–Kendall trend test (MK) (Mann 1945; Kendall 1955). The test is distribution free and robust to missing data and outliers (Helsel & Hirsch 1992). The MK test is the most widely used of the discharge trend analyses in Europe (Madsen et al. 2014). The computer software program MAKESENS was used for calculating trends (Salmi et al. 2002). The level of 5% was used for critical significance. Significances of 5%, 1% and 0.1% were shown in the results. The trend magnitude was calculated using a non-

parametric linear Sen's slope estimator (Sen 1968). The Theil–Sen estimator is more robust than the least-squares estimator because it is much less sensitive to outliers. The result of the MK test depends strongly on the autocorrelation. If there is a positive autocorrelation in the time series, the test rejects the null hypothesis more often than without autocorrelation (von Storch & Navarra 1995). Thus, the test increases the apparent level of significance of a 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 with a time lag of one year. This is typical especially for discharge stations based near the lakes as lake acts as a storage. Similar autocorrelations have been found e.g. in Icelandic discharge data (Jónsdottir et al. 2006) and earlier for Finnish data by Kuusisto (1975). If the data was autocorrelated, the pre-whitening procedure presented by Wang and Swail (2001) was applied. The pre-whitening method removes serial autocorrelation from the time series. The trend significance was then tested for the pre-whitened dataset. In most of the cases in this study, the differences between trends before and after pre-whitening were insignificant and the trend remained the same as it was without pre-whitening.

Although the MK tests for trends took account of serial correlation within each dataset, no account was taken of the spatial correlation between 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-estimations of the number of significant trends found using a given level of statistical significance. It was evident that observation sites located near each other have spatial correlation as presented by Korhonen (2005; 2007).

4.4 Periodicity and autocorrelation analysis (II)

In **Paper II**, the periodicity and autocorrelations for a couple water level and discharge time series were investigated. The two longest unregulated discharge series were analysed (Muroleenkoski and Nilakka Äyskoski), as well as two water level time series (Lake Saimaa and River Tornionjoki). Data on the annual mean values was analysed up to 2004. The longest of these time series was over 150 years and the shortest over 90 years. The analysis was performed with the ITSM software developed for time series analysis (Brockwell and Davis 2002). It is possible to identify the cyclicity in the time series by finding peaks in the periodograms and autocorrelations. The results of the cyclicity are presented in Chapter 5.5.2. The method and results are also described in detail in the publication by Korhonen (2007).

5. Results from the papers included in the thesis

5.1 Ice cover variability and trends in Finland (I)

The ice cover variability and changes in Finland were investigated in **Papers I, IV, V** and **VI**. **Papers I** and **V** included data until 2002, while **Paper IV** included the data until spring 2005 and **Paper VI** had the data until 2013.

Paper I summarises the ice cover variability and issues related in the following way: the air temperature is the most important factor affecting ice conditions such as the freeze-up date, ice thickness, and break-up date. There are considerable variations in the freeze-up date due to the area and depth of the lake. Large, deep lakes can freeze as much as one month later than small, shallow ones in the same area. The variation of the freeze-up date is greater in the southern part of the country than in the north. The average standard deviation of the freeze-up date is approximately two weeks, which is about twice as high as that of the break-up.

The negative air temperature sums needed for a lake to freeze vary depending on the area and depth of the lake. For very small and shallow lakes, the sums of 20 degree-days are sufficient whereas the deep large lakes require more than 200 degree-days. Ice breaks up simultaneously within a certain region almost regardless of the size or depth of the lake. This is because the ice thickness differences between lakes of different sizes even out the ice cover maxima by winter. In the spring, solar radiation is the main factor, as in the autumn the heat storage of the lakes has effects not only the air temperature. Therefore the energy needed to melt the ice cover is same regardless of the lake size. Ice disappears a little bit later from large lakes than from small lakes. This is because in lake reaches, the air remains cooler than in nearby land areas that absorb spring solar radiation because of the lower albedo of the forest and land areas than ice cover. There are no major differences between the south and north of Finland concerning the standard deviation of the break-up date, since the break-up is driven mostly by solar radiation.

The positive air temperature sum needed for the break-up of the ice is less clearly dependent on the lake morphometry than the negative sum for freeze-up. The average temperature sum for the break-up of medium-sized lakes is 100–160 degree-days. The break-up date of a given site correlates strongly with those of the neighbouring observation sites. The maximum ice thickness also correlates with that at neighbouring sites, although there can be rather large differences (10–20 cm) between sites and within a lake. These

differences can be related to different freeze-up dates. However, the differences tend to even out over the winter.

The duration of the ice cover can be predicted rather well by the freeze-up date. When the freeze-up occurs early, the ice cover period is very likely to be longer than the average value, and the ice is likely to be thicker than the mean thickness. Thicker ice cover obviously needs more energy to melt than a thinner one. Thus in the years of thick ice cover the break-up occurs usually later than in average years.

5.1.1 Break-up and freeze-up in Finland (I, V, VI)

In **Paper I,** long-term trends for break-ups and freeze-ups of Finnish lakes were presented. According to **Paper I,** ice break-up had become earlier, and freeze-ups had commenced later in the last few decades at many observation sites from the start of the observations until 2002. The trends were statistically significant mainly in those sites with records at least since the late 19th century. In most cases, trends of series shorter than 100 years were not statistically significant. In the longest series that started in the late 19th century, the ice break-up had become 6–9 days earlier in one hundred years. The freezing had delayed since the late 19th century, in general by 0–8 days per century. Also the duration of ice cover had significantly reduced at sites with the longest records. Not all of the longest freezing and duration trends were statistically significant until 2002. The break-up trends were more statistically significant, partly because the variation of break-up date is smaller than of the freezing date. The large variation in the freeze-up dates masks the trends of freezing. There were no statistically significant trends in Northern Lapland but the time series from this part of the country were relatively short. Combined trends of the break-up, freeze-up and duration of the ice cover for Southern, Central and Northern Finland are presented in Figure 14. These series were constructed for the 1885–2002 period from those time series which had records at least since the late 19th century. According to Figure 14, the trend towards later freeze-ups varied between regions from 3.6 to 7.9 days per century in the 1885–2002 period. The trend towards an earlier break-up varied between regions from 6.6 to 8.6 days per hundred years for the 1886–2002 period. The trend towards a shorter duration of ice cover varied between regions from 11.2 to 16.8 days per hundred years for the 1886–2002 period. All of the trends were statistically significant except the freeze-up trend in Central Finland. In general, the trend slopes were steepest in Southern Finland. Surprisingly, the Northern Finland trends were a little bit steeper than trends in Central Finland, although in general from individual time series the south underwent the largest changes

and the north the lowest. The difference in regional series might be connected to number of time series included in the region set. The north had a smaller number of series included and Lake Oulujärvi dominated results in that region.

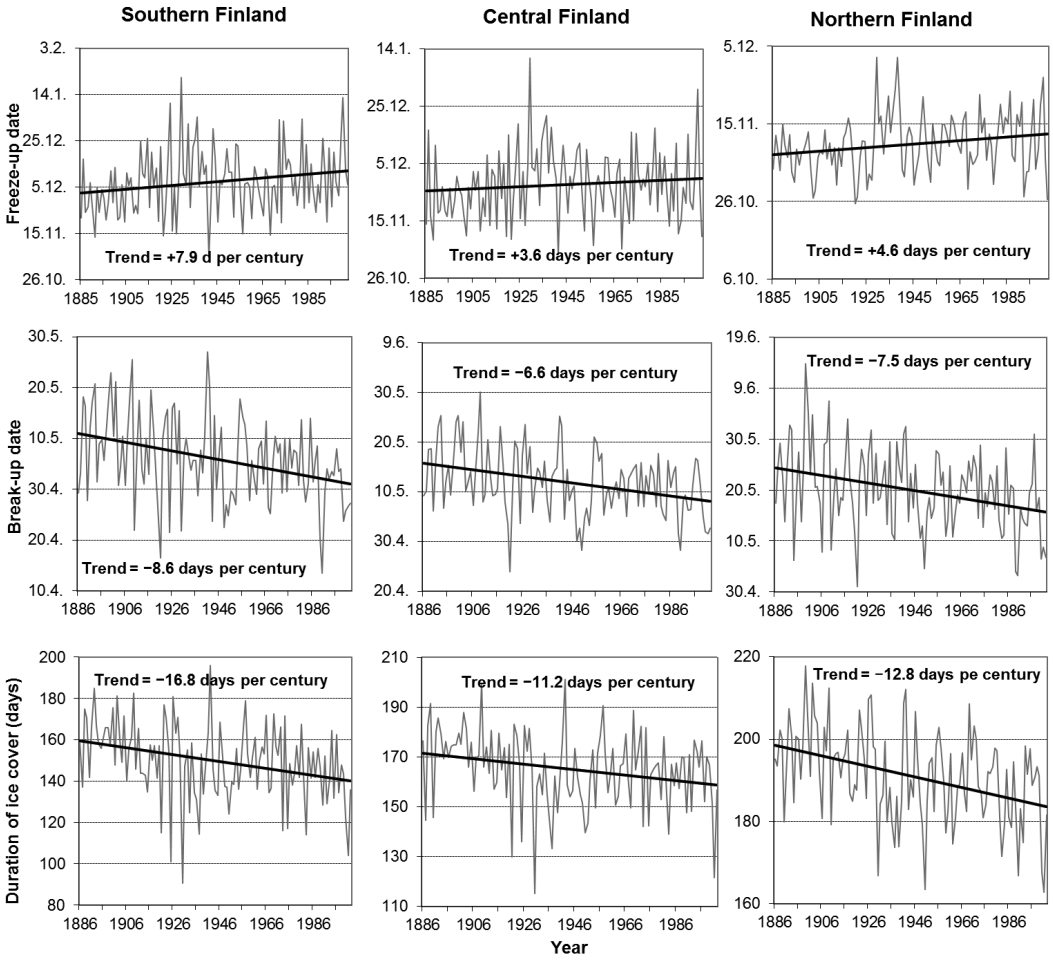


Figure 14. Trends in the break-up, freeze-up and duration of ice cover for southern, central and northern Finland adapted from **Paper I**. Reproduced with permission from IWA Publishing.

Paper V compared Tornionjoki river break-up records with the air temperature of the region, and the synchrony in change points between the temperature and river ice break-up records ruled out the possibility that the changes would have occurred due to the quality of the historical series. The temporal changes quantified for the early 19th century occurred exactly during the very same years, 1821 and 1845, in both series, implying no artificial signals during this period. Subsequently, **Paper V** detected a shift

from colder to warmer conditions through the late 19th century, with coinciding and statistically significant trend-like changes in both the break-up and air temperature series between the 1880s and the1920s. The shift towards warmer spring temperatures in 1974 was followed by a corresponding shift towards earlier river ice break-ups in 1980. These findings were connected to the increased anthropogenic activities within the Tornionjoki river-system, which may have caused the described asynchrony over these recent years.

Paper VI looked at changes in the standard deviation of River Tornionjoki break-up and interannual variability among some 30-year non-overlapping windows. On the River Tornionjoki, the variability appeared to be decreasing from 1700 to 2013. A segmented regression defined two time periods with different slopes and a breakpoint (shift in slope) in 1867. The trend in the ice break-up date for Tornionjoki decreased from −0.30 days per decade before the breakpoint (1693–1866) to −0.66 days per decade after the breakpoint (1867–2013). Mudelsee (2012) found same changing point for 1867 in the Lake Näsijärvi data.

5.1.2 Maximum ice thickness (I)

Both decreasing and increasing trends were found in the maximum ice thickness time series for Finnish lakes (**Paper I**) up to 2002. At about half of the sites the trends were statistically significant. The maximum thicknesses had mainly increased in eastern and Northern Finland and decreased in Southern Finland. The series with records since the 1960s had a significant trend of 2–3 cm per decade, for longer series the trend was mainly 1–2 cm per decade. The time series of snow-ice and snow thickness until 2002 were rather short, about twenty years, thus no long-term analysis could be performed in **Paper I**. In the 1980s there was a lot of snow and snow-ice in Southern and Central Finland. Thus the snow-ice thickness had in most cases decreased from the 1980s to the year 2000 in Southern and Central Finland. In Northern Finland, the snow-ice thickness had increased in some places during the twenty-year period.

5.2 Ice phenology as an indicator of climate change in the Northern Hemisphere – extremes and changes in variability (IV, V, VI)

Paper V displayed strong correlations between the River Tornionjoki break-up and spring air temperatures of the region. **Papers IV** and **VI** included Finnish data and also some other rather long time series of ice phenology.

Paper I also discussed extremes of Finnish lake data. Updated extremes of a couple of the longest time series of ice phenology presented in **Paper I** in Finland until the spring 2018 are presented in the discussion chapter.

The occurrence of extremes in the lake ice-on and ice-off dates in the Northern Hemisphere was studied in **Paper IV**. Both changes in the mean condition and in the variability around the mean condition can alter the probability of extreme events. Using long-term ice phenology data covering two periods 1855–1856 to 2004–2005 and 1905–1906 to 2004–2005 for a total of 75 lakes, patterns in long-term trends and variability were examined as well as the incidence of extreme events. Patterns in trends for a 30-year subset (1975–1976 to 2004–2005) of the 100-year data set were also investigated. Trends for ice variables in the recent 30-year period were steeper than those in the 100- and 150-year periods, and trends in the 150-year period were steeper than in the 100-year period. Ranges of rates of change (days per decade) in time periods based on linear regressions were 0.3−1.6 later for freezing, 0.5−1.9 earlier for break-up, and 0.7−4.3 shorter for duration. Mostly, the standard deviation did not change, or it decreased in the 150-year and 100-year periods. During the recent 50-year period, the standard deviation calculated in 10-year windows increased for all ice measures. For the 150-year and 100-year periods, changes in the mean ice dates rather than in variability most strongly influenced increases in the frequency of extreme lake ice events associated with warmer conditions and decreases in the frequency of extreme events associated with cooler conditions. (**Paper IV**)

In **Paper V,** the homogeneity of the River Tornionjoki break-up time series was studied by comparing the ice break-up time series with the air temperature data from the same region. The ice break-up variations were compared with the mean temperatures of the April-May season. The indication of significant changes between the 1880s and 1920s on time scales longer than 64 years suggested significant long-term changes in both series between these dates: the spring temperatures showed a tendency towards a warmer climate while the river ice break-ups had become earlier. A closer look at the temporal points of significant changes in the river ice break-up records and the spring temperature series (Figure 15) indicated that the temporal points of rapid change occurring in 1821, 1845 and 1955 were precisely the same in both time series. In addition, the series showed further similarities in their change points as the years of quick change 1886, 1918 and 1980 in the river ice break-up variability data corresponded to 1889, 1919 and 1974 in the spring temperature series.

In **Paper VI,** changes in extreme events of the River Tornionjoki break-up were investigated. The prevalence of extremely warm years has been increasing over time for the River Tornionjoki (Figure 16). Extremely warm springs were defined as ice break-up dates prior to day 124 (early May), which corresponds to the top 10% of the warmest years. The River Tornionjoki experienced 9 extremely warm years in the 14-year period between 2000–2013 and 10 in the 207-year period between 1693–1899. Similarly, the freeze-up dates of the longest lake ice-on time series in the Northern Hemisphere (Lake Suwa in Japan) had an increasing number of extreme events during the latest 50-year period (Figure 16).

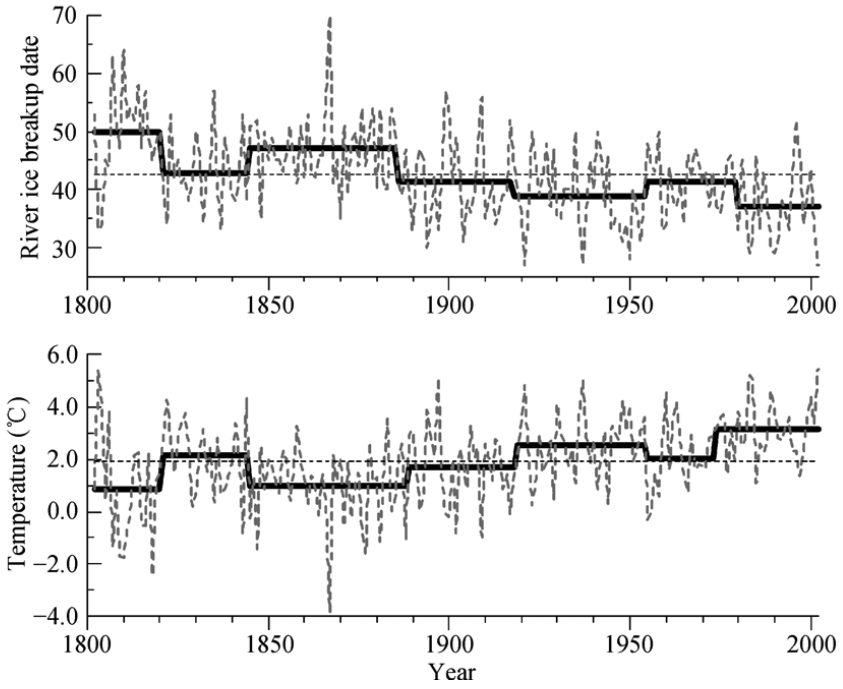


Figure 15. Observed variability in the Tornionjoki river ice break-up dates (number of days since April 1st) and spring temperatures (dashed grey line), their sub-period averages (black line) and the long-term mean (black horizontal dashed line). Figure reprinted from **Paper V** with permission from Springer Nature.

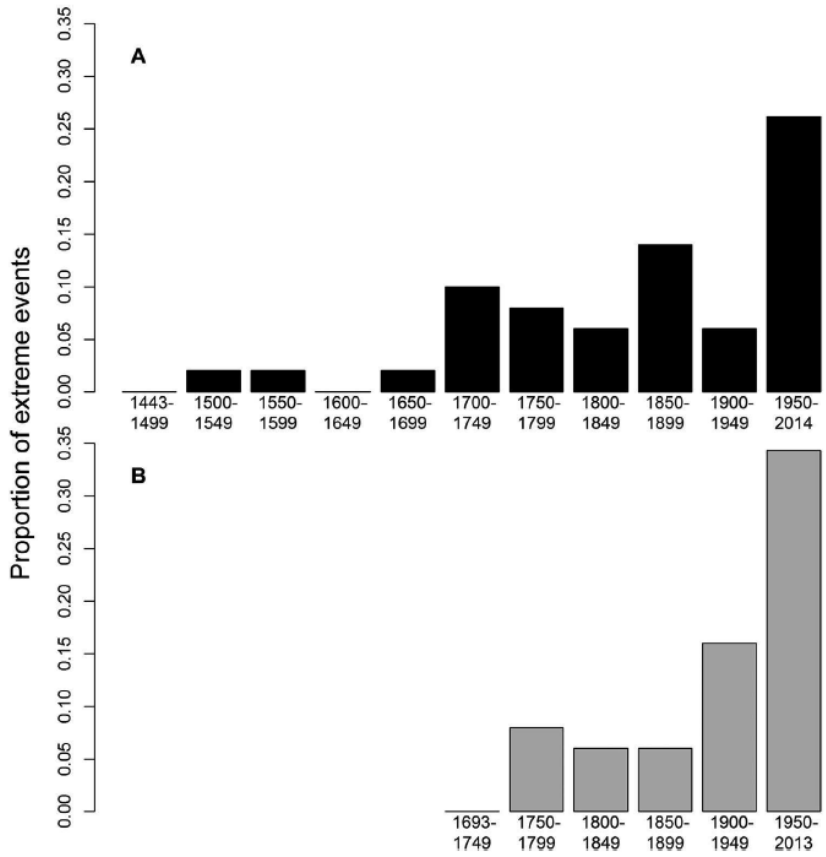


Figure 16. The proportion of extreme warm events over time indicated by the ice dates. In Suwa (A, black), a year was extreme if the lake did not freeze. In Tornionjoki (B, grey), a year was defined as extreme if the ice break-up date was before calendar day 124. Figure reprinted from **Paper VI** with permission from Springer Nature.

5.3 Discharge variability and trends

The river discharge variability and trends in Finland were investigated in **Papers II** and **III**. The analysis of the observation data was done up to year 2004 in both papers. The main findings of the changes in the discharge regime in Finland were presented in **Paper II**. **Paper III** also looked at changes in the future climate conditions simulated for the period until 2099 according to four different regional climate models (RCMs) using A1B emission scenarios.

5.3.1 Total discharge from Finland (II)

The monthly and annual mean discharges from the territory of Finland were determined for the period 1912–2004 in **Paper II** and earlier by Korhonen (2007). The total discharge was calculated by combining many different discharge records from all available drainage basins. Since there were very different periods of records from the observation stations, the discharge was calculated using several combinations of stations (Kuusisto 1992). The mean discharge from the territory of Finland in 1912–2004 was about 3,300 m^3/s. The standard deviation of the mean annual discharge was 18%. The variation percent for the total discharge from Finland was lower than for the individual stations, and this is explained by the fact that the regional differences even out when merged together. The smallest mean annual outflow from Finland was about 1,600 m^3/s in 1941 and the highest mean annual outflow about 4,700 m^3/s in 1981. Thus, the ratio between the highest and lowest mean annual outflow was almost three. The highest monthly discharges have normally been recorded in May, due to spring floods (Figure 17). The highest monthly mean discharge from the territory of Finland was about 10,350 m^3/s in May 1920. The lowest monthly mean discharge was only 640 m^3/s, in March 1942. The ratio between the highest and the lowest monthly discharge is more than 16. Normally the outflow is lowest in the wintertime and peaks in the spring or early summer. The variation in the monthly mean discharge was the lowest in May (22%) and highest in September, 35%.

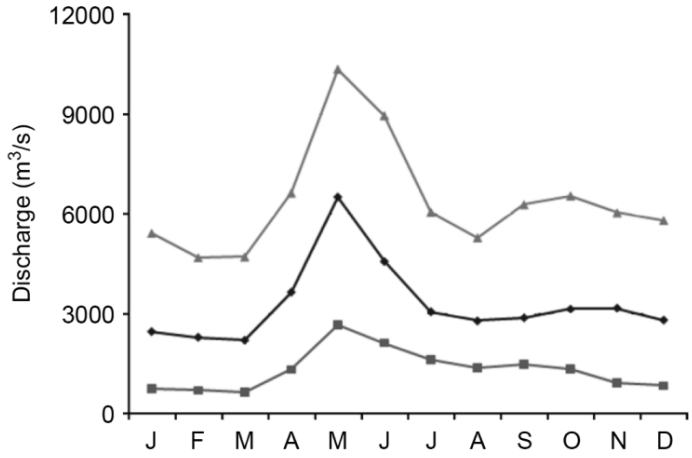


Figure 17. The monthly mean, minimum and maximum discharge from Finland in 1912–2004 as presented in **Paper II.** Reprinted with permission from IWA Publishing.

The discharge regime has changed over the decades on account of both climatic and human impacts (predominantly water regulation). Climate change has affected the annual flow cycle, particularly the seasonal distribution of the flow. The most significant shift occurred in the hydrological regimes of the winter and spring. Winters and springs had already become milder in the 20th century – and as a consequence – the late-winter and the early-spring discharges had increased. However, the magnitudes of the spring high flow had not changed. Regulation has increased the winter and spring mean discharges in some places. There was no statistically significant change in the annual mean outflow from Finland in the 1912–2004 period, but both the winter and the spring mean discharges had increased (Figure 18). Winter and spring monthly mean discharges from the territory of Finland had increased by 100–150 m^3/s per decade during the 1912–2004 period.

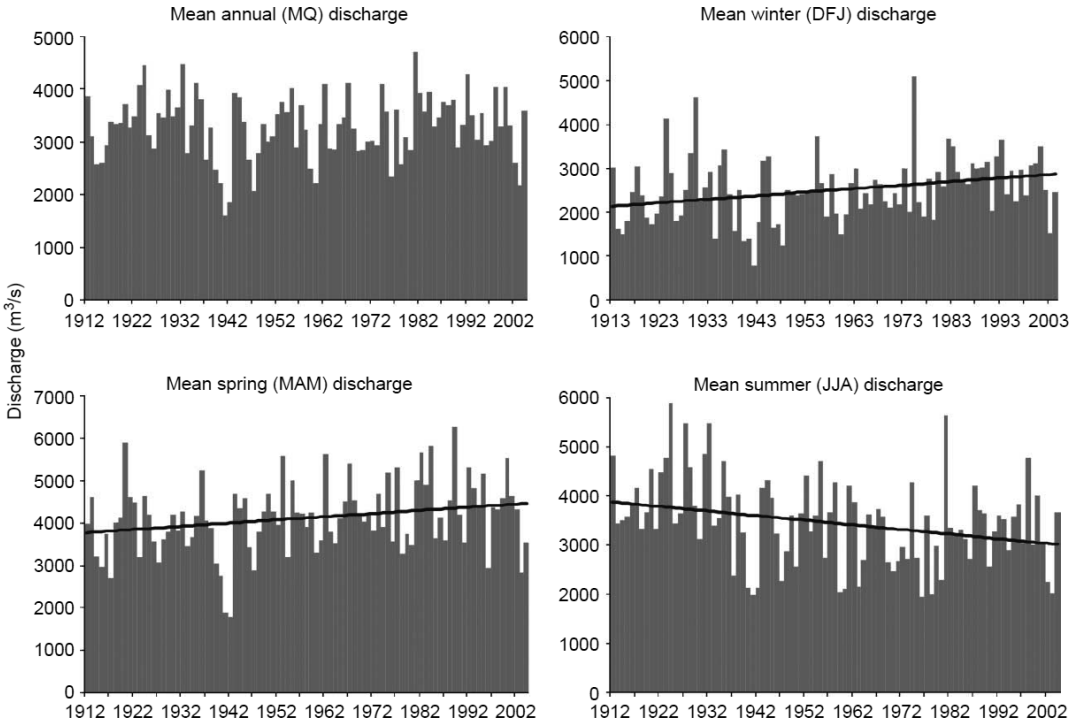


Figure 18. Time series and trends of the mean annual (MQ), winter (DJF), spring (MAM) and summer (JJA) outflow from the territory of Finland in the 1912–2004 period. Only statistically significant trends are shown in the graph. The figure is adopted from **Paper II**. Reprinted with permission from IWA Publishing.

Most drainage basins in Finland are affected by regulation, since the largest rivers of the country are mainly regulated. The only exception is the River Tornionjoki. Thus the trends of monthly outflows from Finland are clearly influenced by regulation, especially in Northern Finland and in Ostrobothnia. Changes in seasonal discharges were different in the different regions. Winter and spring discharges had increased mostly in the north.

5.3.2 Discharge trends from individual observation stations (II)

Long-term changes in the individual discharge series were similar to the changes in the outflow from Finland. This is logical since the total outflow from Finland consists of these separate time series. **Paper II** showed that statistically significant overall changes have not been observed in the mean annual discharges. At most sites, the winter and spring mean discharges had increased (Figure 19). In Northern Lapland it seemed more likely that winter discharges had decreased up to 2004. The increase in the winter discharges focused on the late winter and the increase of the spring discharges was concentrated on the early spring. Therefore, the rise of the winter and spring discharges could be accounted for by the warming in winter and spring and the earlier snowmelt. At some regulated sites, the release of water had been increased in the winter and early spring in order to increase the storage capacity for the snowmelt water. This explained the stronger winter and spring discharge trends at some regulated sites.

The timing of the spring high flow had become earlier at about one third of the observation sites. At unregulated sites, the change was in most cases 1–3 days per decade, while at regulated sites it was somewhat more. The mean annual flow and annual high flow did not show statistically significant trends in general, apart from at a couple of sites. Changes in the mean monthly or seasonal discharges were typically some percent of the period mean flow per decade, in most cases not higher than 10%. Trends at the regulated sites were stronger than at the unregulated ones.

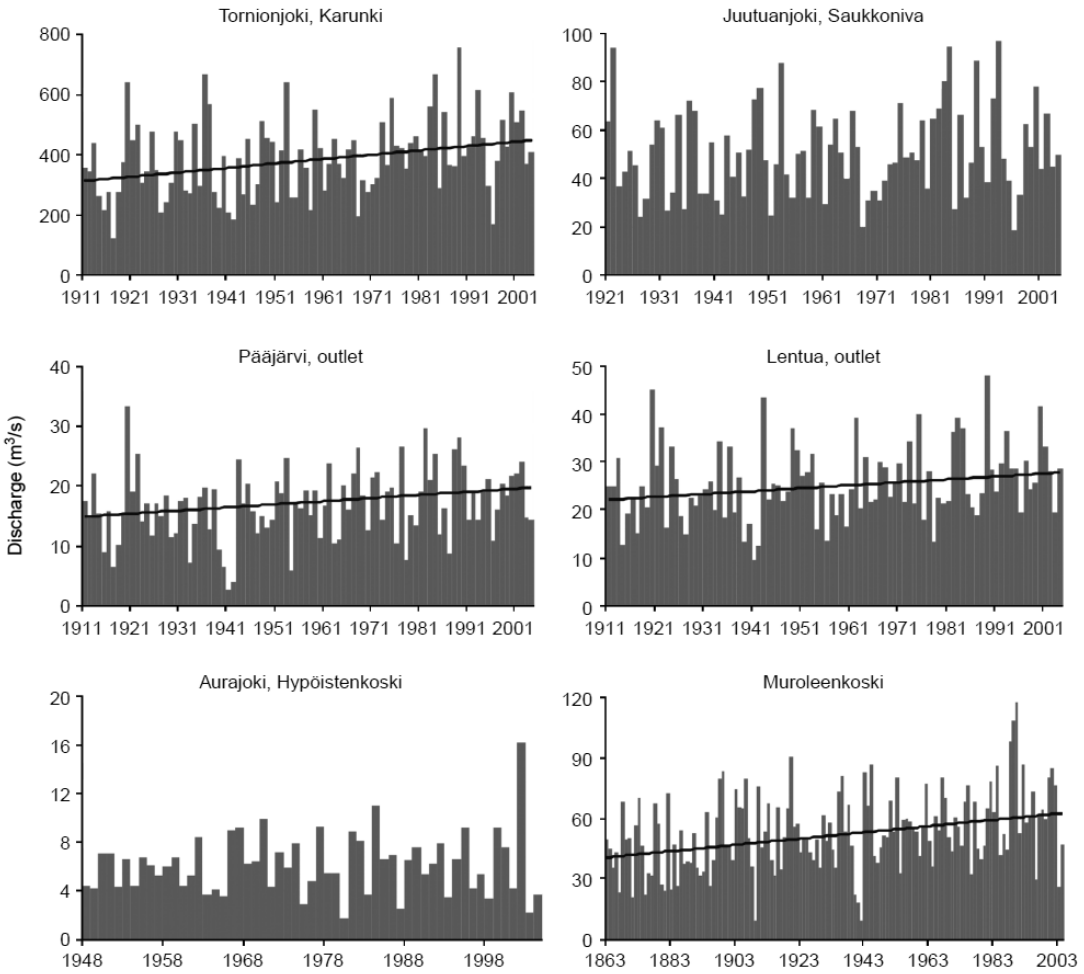


Figure 19. Time series and trends of the mean spring (MAM) discharge at some unregulated observation sites based on **Paper II**. Only statistically significant trends are shown in the graph. Reprinted with permission from IWA Publishing.

5.4 Future climate change effects on river discharges in Finland (III)

The results of **Paper III** showed that climate change has impacts on simulated seasonal hydrology in Finland for the period 1951–2099, but that differences between different climate scenarios remained considerable. The annual mean discharge did not change statistically significantly for most scenarios in the future, except in the northernmost study site at Juutuanjoki in Lapland, where three out of four scenarios showed an increasing trend (Table

2). The most consistent result was the positive trend in the winter discharge, which occurred at all sites in all scenarios. Other seasonal trends, such as an increase in the spring discharge in the more northern sites and a decrease in the southernmost site in the spring discharge, were also found in all four scenarios. The strongest trends were those related to the increase of temperature rather than changes in precipitation. These changes correspond well with the findings of **Paper II**. This outcome is logical as the projected increases in temperature are more consistent among the climate models than changes in precipitation (Barnett et al. 2005), and in relative terms projected precipitation changes are more uncertain than those of air temperature when compared to natural variability (Räisänen & Ruokolainen 2006).

Table 2. Results of the MK trend test for the simulated discharge in 1951–2099, 1951–2050 and 1961–2004. The percentage of climate scenarios for each site and variable that have statistically significant (5% significance level) positive (+) or negative (–) trends. 100% means all scenarios have a significant trend, 0% means that none have a trend (**Paper III**). Reprinted with permission from IWA Publishing.

	1 Juutuanjoki	2 Nilakka	3 Kitusjärvi	4 Hypöistenkoski
1951–2099				
Mean annual discharge (%)	+75	+25	+25	+25/− 25
Mean seasonal discharge				
Winter (%)	+100	+100	+100	+100
Spring (%)	+100	+100	+25	−100
Summer (%)	−100	−75	−75	−75/+ 25
Autumn (%)	+100	−75/+ 25	+25/− 25	+25/− 25
1951–2050				
Mean annual discharge (%)	+50	+50	+50	+25
Mean seasonal discharge				
Winter (%)	+100	+75	+100	+100
Spring (%)	+100	+100	0	−100
Summer (%)	−50	−25	−25	0
Autumn (%)	+25	0	+25	+25
1961–2004				
Mean annual discharge (%)	0	0	+50	+25
Mean seasonal discharge				
Winter (%)	0	0	+25	+25
Spring (%)	0	+50	+25	0
Summer (%)	0	0	0	0
Autumn (%)	0	0	0	+25

5.5 Atmospheric circulation patterns and periodicity (II, VI)

5.5.1 ACPs and hydrological regime

Korhonen (2005) presented a connection between the NAO index and ice conditions and later between the NAO index and discharge conditions (Korhonen 2007 and **Paper II**). In **Paper II**, the relation between the NAO index and the total outflow from Finland, and also between the NAO index and discharge stations were examined. Both the 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 investigated. There was a large variation in the correlation coefficient; it was around 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 and was 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 1961–2002 period were studied, the correlation coefficients for the annual values varied between 0.03 and 0.42, and for the winter from 0.05 to 0.58. The highest correlation was found for the winter flow at the Aurajoki, and Hypöistenkoski, in the south. 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.

5.5.2 Periodicity

In **Paper VI,** quasi-periodic dynamics of the ice cover time series of the River Tornionjoki were studied. Before the Industrial Revolution, the ice records for the River Tornionjoki displayed inter-annual and multi-decadal quasi-cycles with significant periods between 8 and 64 years. The River Tornionjoki also revealed significant inter-annual quasi-cycles with shorter periods of 2 to 8 years. Following the start of the Industrial Revolution, for Tornionjoki only quasi-cycles with shorter periods in the range of 4–16 years persisted. The longer periods present at the beginning of the ice record and before the start of the Industrial Revolution were not apparent in the recent time period. Mudelsee (2012) found also 2 and 5 year peaks related to the data on the Lake Näsijärvi ice phenology.

Periodicity for the longest river discharge and lake water level time series in Finland were investigated in **Paper II**, since it had been detected for other rivers (Pekárová et al. 2003) and from the sea level in Europe (Jevrejeva et al. 2005). The two longest unregulated discharge time series were analysed (Muroleenkoski and Nilakka Äyskoski), as well as two water level time series (Saimaa and Tornionjoki). The analysis revealed that there was 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.

6. Discussion

In this chapter, the results of this dissertation are discussed and compared to other relevant studies. Also, some of the time series presented in **Papers I** and **II** are updated to the present situation and trends are compared with those presented in **Papers I** and **II**.

6.1 Ice cover analysis

Paper I included an extensive analysis of ice time series (freeze-up, break-up, ice cover duration, ice thickness) until the year 2002. After these analyses, Finland has experienced very mild winters and new records have been set for the longest observation series during the 2000s. Data up to the 2017–2018 winter was updated and compared to the results of **Papers I** and **VI**. **Paper VI** already confirmed an increased number of early break-up events for the River Tornionjoki during the recent decades until 2013, and **Paper IV** showed increased numbers of extreme events for lakes.

According to the updated data, break-ups in the spring of 2014 set a new record for the earliest break-up ever observed for the River Tornionjoki, Lake Kallavesi, and Lake Näsijärvi (Table 3). For the freeze-up, the 2007–2008 winter set a new record as latest freeze-up so far for Lake Näsijärvi. Lake Oulujärvi reached a new record for its break-up in the spring of 2015 and latest freeze-up in the history in the 2011–2012 winter. Lake Näsijärvi tied in the spring of 2015 with the break-up record of 2014. For the duration of the ice season, Lakes Kallavesi and Oulujärvi had new records after 2002 (the shortest ever), in the winters of 2013–2014 and 2011–2012, respectively. When comparing the break-ups and freeze-ups of the 2001–2018 winters to the averages of those from 1961–2000 of these longest time series, the winters of the 21st century have been extremely mild. The results of the updated data until the 2017–2018 winter, prove that 16–17 out of 18 (89–94%) break-ups have been earlier and 14–16 out of 17 (82–94%) freeze-ups have been later than the 1961–2000 average for each time series.

The updated data shows that the trends of the longest time series of break-ups and freeze-ups in Finland have continued in the same direction since 2002, when the data of **Paper I** ended. Also, the trends have even become stronger. For the River Tornionjoki the trend towards earlier break-ups in 1693–2018 was +4.65 days per 100 years (Figure 20) as for the 1693–2002 period it was +4.3 days per 100 years. For Lake Kallavesi the freeze-up date trend for the period of 1833–2017 was +10.2 per century (Figure 21) and the break-up trend –7.1 days per century, as until 2002 (**Paper I**) they were +6.7 days per

century for the freeze-up and –6.0 days per century for the break-up. For all the longest time series, the trends have become steeper during the last decades.

Table 3. The extreme dates of freeze-ups, break-ups and the duration of ice cover of the longest ice phenology time series in Finland until the winter 2017–2018, modified based on the table in **Paper I.**

Site	Freeze-up date		Break-up date		Ice cover duration (d)	
	Min	Max	Min	Max	Min	Max
Tornionjoki	-	-	Apr 26 2014	Jun 9 1867	-	-
Oulujärvi	Oct 22 1894	Jan 1 2012	Apr 30 2015	Jun 23 1867	132 (2011-12)	229 (1880-81)
Kallavesi	Nov 3 1864	Jan 27 1930	Apr 19 2014	Jun 17 1867	95 (2013-14)	207 (1866-67)
Näsijärvi	Oct 25 1891	Jan 31 2008	Apr 13 2014, 2015	Jun 17 1867	79 (1929-30)	208 (1891-92)

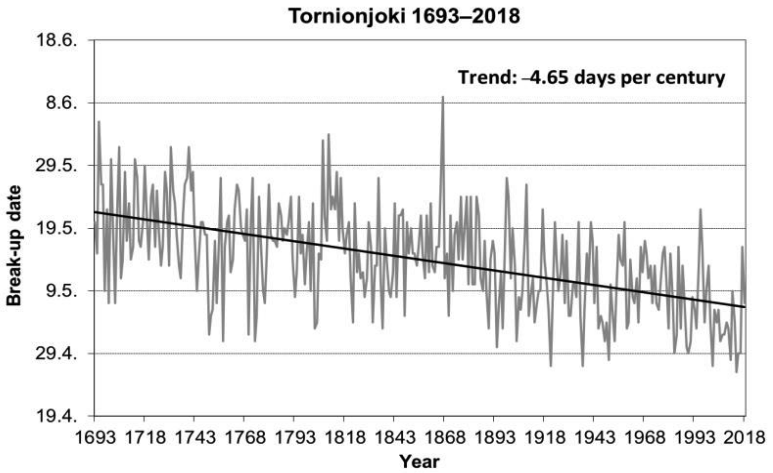


Figure 20. The River Tornionjoki break-up time series updated until the spring 2018.

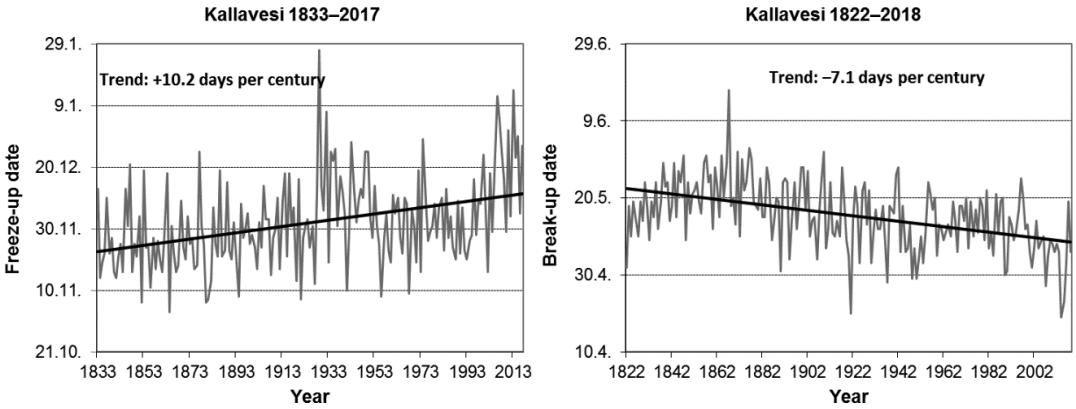


Figure 21. Lake Kallavesi freeze-up and break-up time series updated until the winter 2017–2018.

These findings are in line with observed air temperature trends in Finland, which have increased especially in the winter and spring months (Mikkonen et al. 2015). Šmejkalová et al. (2016) showed that Arctic lakes have stronger trends towards earlier break-up in the 21st century than earlier. This study included Finnish lake data as well. Additionally, Arctic rivers show trends towards earlier break-ups in the 21st century (Cooley & Pavelsky 2016). Additionally, Lei et al. (2012) found a trend towards shorter ice cover periods and later freeze-ups for Lake Kilpisjärvi in the 1964–2008 period. Likewise the Lake Ladoga (Russian Karelia) time series indicates milder winters since 1990 (Karetnikov et al. 2017) and other Karelian lakes show later freeze-up and earlier break-up dates (Efremova et al. 2013). In Estonia, air temperatures have increased, and the large Lakes Peipsi and Võrtsjärv revealed nonlinear delays in their freeze-up and displayed earlier break-ups (Nõges & Nõges 2014). In Sweden's largest lakes, Vänern and Vättern, the break-up of the ice has occurred considerably earlier since 1979 and ice-free winters have become more frequent (Weyhenmeyer et al. 2008). Additionally, the break-ups show a nonlinear response to the air temperature (Weyhenmeyer et al. 2004). These findings are also in line with climate change scenarios and models implicating shorter ice cover periods due to climate change in Finland and elsewhere in the NH (e.g. Huttula et al. 1992; Stefan & Fang 1997; Walsh et al. 1998; Elo et al. 1998; Livingstone & Adrian 2009; George 2010; Dibike et al. 2011; Brown & Duguay 2011; Gebre et al. 2014).

The maximum ice thickness time series was updated until the 2017–2018 winter for some of the selected sites that were presented in the figures of **Paper I**. Some of the observation sites used in **Paper I** are not in operation

anymore, so data could not be updated for all sites. In general, trends showing a decreasing maximum ice thickness have continued in the south (Figure 22).

For example at Lake Päijänne – Tehi, a decreasing trend has continued since 2002. Actually both sides of extremes have been observed during 2003–2018. The largest maximum ice thickness (83 cm) in history was measured in the winter 2003. In contrast, during the 2017–2018 winter the ice was too weak to go to the observation site by car (as it is usually done). Therefore, the winter 2018 maximum is estimated (Figure 22) as 20 cm. In the winter of 2008 there was also very weak ice cover at Tehi, which was only 25 cm at maximum. Actually, the five smallest winter maxima have been observed in the 21st century (2018, 2008, 2014, 2007 and 2015). Similarly, many of the smallest winter maxima ever observed have been in the 21st century for other sites as well. Also, decreasing trends in the south have continued e.g. Lake Kuivajärvi, Lake Näsijärvi and Lake Saimaa, as well as Lake Oulujärvi in the north have shown decreasing trends.

Some of the Northern and Central Finland observation sites had increasing maximum ice thickness trends until 2002 and 2000. When the data was updated until 2018, no more increasing trends were present, due to recent mild recurring winters. For example Lake Inari, Lake Muurasjärvi, and Lake Pielavesi did not show increasing trends for the longest observation period available until 2018. Korhonen and Koskela (2017) included a trend analysis of the maximum ice thickness of Northern Finland stations up to 2016. This analysis showed statistically significant decreasing trends in the maximum ice thickness for Lapland stations for shorter time periods, and these changes were not present in **Paper I**. A sensitivity analysis of the change in the ice thickness measurement method did not have a remarkable effect on the study results. Previous analysis (**Paper I**) until 2002 did not show trends in Northern Finland, and this shows that the recent years in the 2000s have been very mild compared to the 20th century also in Northern Finland. These results are in line with the results of **Paper III** in simulations for the climate change scenarios until 2099, showing warmer winters also in Northern Finland.

Until 2002, the increasing maximum ice thickness trends in Northern and Central Finland were probably at least partly due to increased snow-ice portion as winters had become warmer and wetter. A recent study showed increased winter precipitation in Finland for the 1911–2011 period (Irannezhad, Marttila & Kløve 2014) but also a decrease in the SWE peak (Irannezhad, Ronkanen & Kløve 2015). Winters with less snow cover during

the recent decades might explain changes in the trends of the maximum ice thicknesses in Central and Northern Finland between **Paper I** and the updated data extending up to 2018.

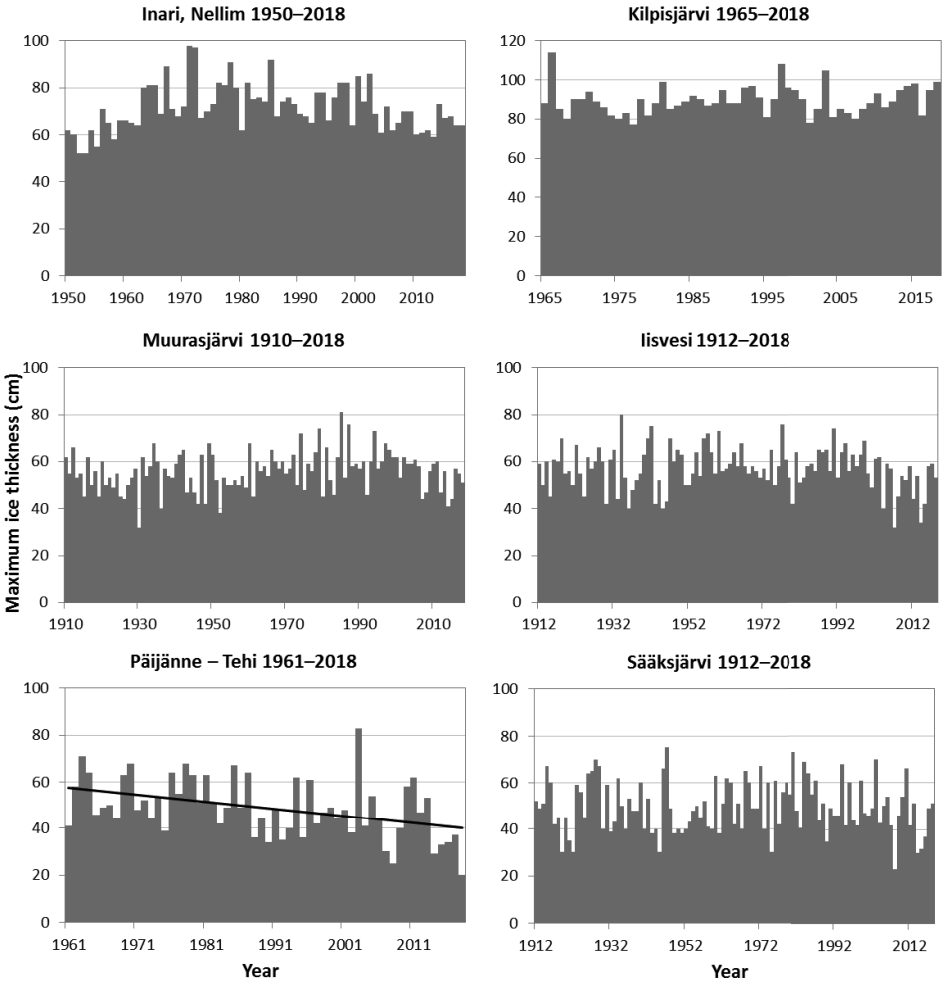


Figure 22. Updated time series of maximum ice thickness until the winter 2017–2018 for the same sites as a figure in **Paper I**. Only statistically significant trends are drawn in the graph.

6.2 Discharge analysis

In **Paper II**, the discharge from Finnish territory in 1912–2004 and several individual time series of discharge data were analysed to detect long-term changes in the discharge regime. Here, some of the individual time series are updated and their trends investigated until the year 2017. Unfortunately, there

has been data lacking and also delays in data quality control for the hydrological stations in the recent years. Updating the nationwide annual or monthly outflow from Finland to the present day is not straightforward, as some of the stations used in **Paper II** have been closed after 2004 and there are gaps in the data. In this respect, new calculation rules should have been created for stations. However, some of the individual time series of **Paper II** that had quality-controlled data available until 2017 are updated here. Changes in winter and spring regime were analysed for the following stations of **Paper II**: Pääjärvi, Vantaanjoki, Muroleenkoski, Lentua, and Tornionjoki. The analysis of these selected sites until 2017 shows that the trends that were present in **Paper II** and Korhonen (2007) still existed and they have become even stronger. None of the trends had disappeared. Some new trends, especially at a monthly level were found as well. For example, Vantaanjoki – Oulunkylä in the south showed a decreasing MAM trend for 1961–2017 that was not present in the 1961–2004 data. This is more likely related to the warmer springs and less snow in the south. Lake Pääjärvi showed an increasing mean annual discharge trend for 1911–2017 that was not present in the 1911–2004 data. Trends in the winter and spring discharges and mean annual discharges updated until 2017 are presented in Table 4, and spring season (MAM) time series in Figure 23.

Table 4. Winter and spring season and annual mean flow trends of selected discharge stations until the year 2017. The station numbering refers to **Paper II** (Table 1) and Figure 5a in this thesis. + refers to an increasing trend and – to a decreasing trend. + (–) refers to 5% significance, ++ (– –) to 1% significance and +++ (– – –) to 0.1% significance.

Site	Season and time period	Trend and significance
2. Pääjärvi – lake outlet	DJF 1911–2017	+++
	DJF 1961–2017	++
	MAM 1911–2017	+
	MQ 1911–2017	+
4. Vantaanjoki – Oulunkylä	DJF 1937–2017	++
	MAM 1961–2017	–
7. Muroleenkoski – lake outlet	DJF 1863–2017	+++
	MAM 1863–2017	+++
	MAM 1911–2017	+
9. Lentua – lake outlet	DJF 1911–2017	++
	DJF 1961–2017	+++
	MAM 1911–2017	++
11. Tornionjoki – Karunki	DJF 1911–2017	+++
	MAM 1911–2017	+++
	MAM 1961–2017	+++
	MQ 1911–2017	+++
	MQ 1961–2017	+

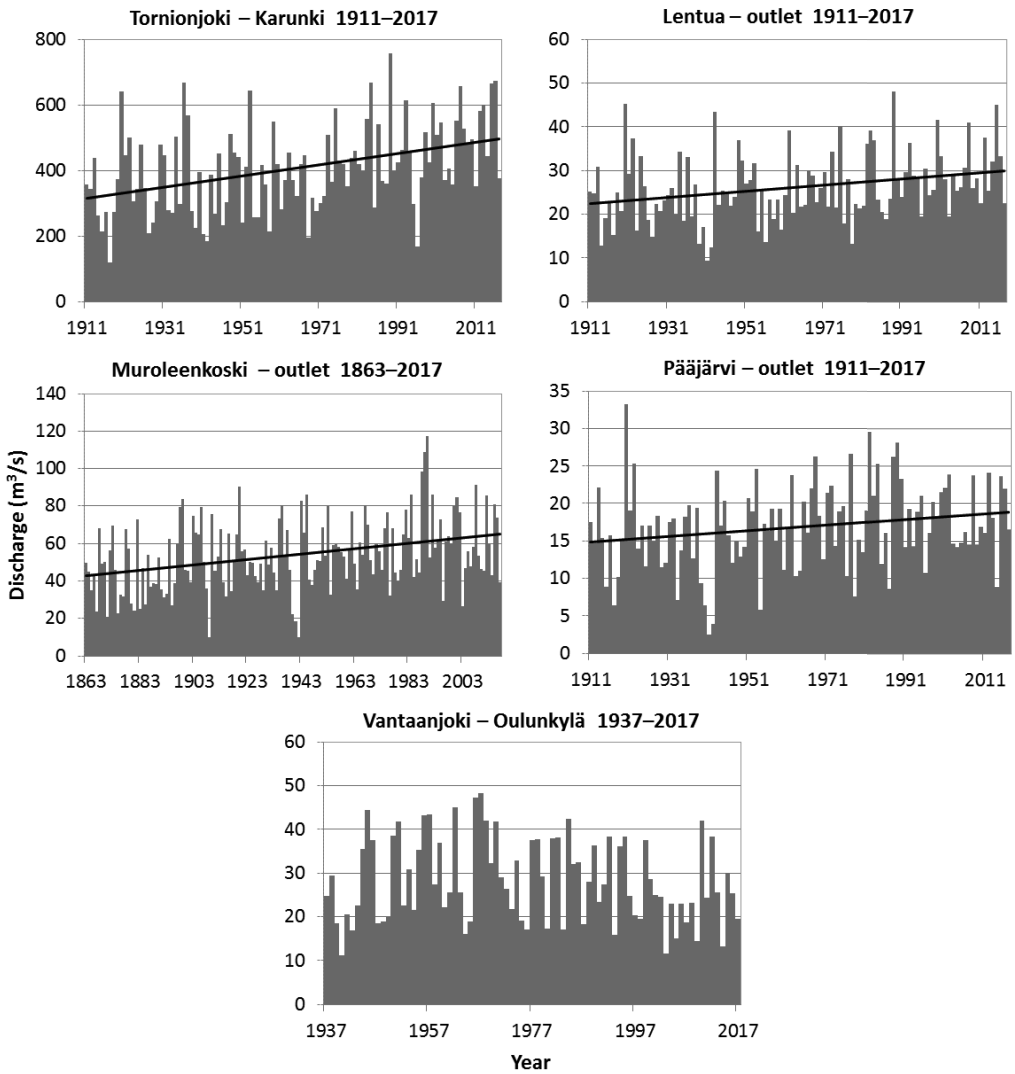


Figure 22. Updated spring season time series (MAM) and their trends for selected five discharge time series. Only statistically significant trends are drawn in the graph.

The mean air temperatures have increased on an annual level, as well as the winter and spring temperatures (Irannezhad et al. 2014; Mikkonen et al. 2015). Irannezhad, Marttila and Kløve (2014) showed an increase in the annual precipitation and for certain winter and spring months for the 1911–2011 period in Finland. For the period of 1962–2014 decreases in the annual, winter, and summer temperature variability were discovered across Finland, in Southern Finland, and in Northern Finland, respectively. The precipitation

variability decreased in the winter and spring in northern and central parts of Finland (Lindgren 2016; Lindgren et al. 2017). These changes in climatic conditions are in line with changes found in observed discharge time series, as well changes projected for the future (**Paper III**; Olsson et al. 2015; Räty et al. 2017). The runoff variability increased in the winter in most parts of Finland, but decreased in the spring in Southern Finland (Lindgren 2016; Lindgren et al. 2017).

In other Nordic countries (Sweden, Norway, Denmark, Iceland), an increase in the runoff has been observed up to the early 21st century (Hisdal et al. 2003; 2004; Lindström & Bergström 2004; Jónsdottir et al. 2006; 2008; Wilson et al. 2010). In Karelia, in Northwest Russia, the precipitation increased during the 20th century (Filatov et al. 2005). In the Baltic countries, especially the winter precipitation and winter discharge have increased (Jaagus 2006; Reihan et al. 2007; Klavins & Rodinov 2008) and the spring discharge has decreased (Apsīte et al. 2012; Reihan et al. 2012; Meilutytė-Lukauskienė et al. 2017). Similar changes have been found in the discharge time series as in Southern Finland. In the Baltic Sea river basin, changes reflect similar patterns as in the studies mentioned above (Käyhkö et al. 2015). In large Eurasian rivers an increase in discharges has been observed (Rawlins et al. 2009) as well in the discharge into the Arctic sea (Peterson et al. 2002).

In the introduction, Finnish and Nordic discharge studies prior to **Papers II** and **III** were familiarized. There have not been thorough research papers concentrating only on Finnish data after **Paper II**, but a number of studies including European or world-wide data have included Finnish time series in their analysis. Madsen et al. (2014) have presented a comprehensive review of studies related to European flood and extreme precipitation trends and climate change projections. A vast analysis of observed and simulated discharges in Europe showed generally negative trends in Southern and Eastern Europe and positive trends elsewhere. There was an indication of positive trends in rain-dominated regimes, and inconsistent or decreasing trends in snow-dominated regimes (Stahl et al. 2012). Recently, Mangini et al. (2018) found both decreasing and increasing trends in 1965–2005 annual maximum floods (AMFs) for the Nordic countries. In central Europe and Britain, AMFs have been increasing, but in more southern Europe these have been decreasing. A large European study showed that the timing of floods has shifted across much of Europe, and this has occurred dramatically in some areas (Blöschl et al. 2017). This research is in line with findings of this thesis as presented by **Papers II** and **III** showing earlier spring peaks in Finland. Hodgkins et al. (2017) showed that large-scale multidecadal

ocean/atmosphere variability, as represented by the AMO index, is related to the generation of major floods. There were more than three times as many significant relationships between major-flood occurrence and the AMO for 1961–2010 and 1931–2010 than significant trends over time for these periods. The influence of the AMO on major floods is consistent with the influence of the AMO on the general dryness in North America and wetness in Europe.

Trend analyses of long time series of large Western and Central European rivers revealed a cyclic occurrence of dry and wet periods (Pekárová et al. 2003). In Germany, flood series trends were linked with ACPs (Petrow & Merz 2009; Petrow et al. 2009). Grötzner et al. (1999) found an approximately 30-year periodicity in the North Atlantic Circulation. Jevrejeva and Moore (2001), as well as Jevrejeva et al. (2005), found both high frequency (roughly 2–8 years) and low frequency (13–30 years) signals in the Arctic Oscillation and the North Atlantic Oscillation. Accordingly, the roughly 3–7 year and 30-year cycles in discharges and water levels in Finland can very likely be explained by the atmospheric circulation periodicity pattern. Kuusisto (1975) previously found a 7-year periodicity in the Finnish runoff time series.

6.3 Uncertainties

It should be borne in mind that time periods in the separate papers differ from each other. Also the length of different time series varies within and between articles included in this dissertation. In trend analyses, study periods are usually selected to represent a trade-off between the record length and network density (Burn et al. 2012). Trends are naturally dependent on the chosen time period and time period dependence in the Finnish data is discussed by Korhonen and Kuusisto (2009; 2010). Several authors (e.g. Svensson et al. 2006; Chen & Grasby 2009; Hannaford et al. 2013) have pointed out a difficulty in detecting trends and that several signals can overlap. Decadal and interdecadal variability are difficult to quantify if the series is too short (e.g. a few decades). Long historical series provide the basis for detecting trends with higher confidence. The longer the time series the less variation in trend slopes and that can be seen from the updated time series in Chapters 6.1 and 6.2; the differences in the trend slopes between the recent data and **Papers I** and **II** are rather small for a time series of at least 100 years. Hannaford et al. (2013) showed that the magnitude and even direction of short-term trends in Central Europe and parts of Scandinavia are heavily influenced by interdecadal variability. Chen and Grasby (2009) stated that trend analyses of time series records less than 60 years should be done

with caution, since the estimated trend may have limited power in providing appropriate future trend estimates.

Korhonen and Koskela (2017) discussed inconsistencies in hydrological observations in Finland and also a trend analysis for different time periods was done. The results of the maximum discharge trend analysis (although limited selection of sites) showed that the discussed inconsistencies did not have an effect on the trend analysis results but obviously had an effect on the return period analysis (which is not the focus of this thesis). **Papers II** and **III** concentrated more on changes in monthly and seasonal discharges and in these areas the inconsistencies fade out. Uncertainties related to under-ice winter discharges (corrected values) are considerable. Even though there are some uncertainties in estimating winter discharges, increases in winter flows can be considered real based on the fact that the ice cover period has statistically significantly diminished, and that the winter air temperatures have risen, and the winter precipitation has increased.

6.4 The importance of hydrological data

This study was based on Finnish in situ observations and showed their importance also on a global scale. Even though models and remote sensing methods develop all the time, in situ observations are a crucial source of present-state information and are needed for validation and calibration of the new technologies. A recent tendency worldwide has been the declining number of hydrological stations, e.g. in the circumpolar regions (Shiklomanov et al. 2002). As indicated by other researchers earlier (e.g. Silberstein 2006; Woo et al. 2008), this thesis also emphasizes the importance of ground truth (in situ) data – especially in order to detect variations and long-term changes in the northern boreal region which is prone to temperature changes close to zero °C. Lately, interest in citizen observations has also risen remarkably. It should be borne in mind that the longest cryophenology time series have actually been made by citizen observers – and that this is not a novel thing in northern hydrology.

7. Summary and conclusions

Ice cover and river discharge regime, their variability and long-term changes of Finnish lakes and rivers until the early 21st century were investigated in this dissertation. The following results were obtained in **Papers I-VI**.

Ice cover:

- **Paper I** showed that there is a significant change towards earlier ice break-up, later freeze-up, and shorter ice cover duration for the longest time series of lake and river data in Finland up to the year 2002. Break-up and freeze-up trends varied by around 4–10 days per century for the longest time series in Finland. Trends towards a shorter ice cover duration were mainly 11–17 days per century. The updated data to the present in this dissertation and **Papers IV** and **VI** showed that the tendency has continued until the present day and has become even stronger.
- The maximum ice thickness seemed to have increased over the last 40 years until 2002 in some parts of Central and Northern Finland, although a significant decrease in the maximum ice thickness was found in Southern Finland. The changing rate in the maximum ice thickness was mostly 1–3 cm per decade. The increased ice thickness was most likely due to heavy snow on the ice and the production of snow-ice. Updated data until the present did not show increasing trends anymore, but decreasing tendencies still remained in the south.
- The latest study of the dissertation (**Paper VI**) showed that the trend towards earlier break-ups has become even stronger in the 21st century, since most of the earliest break-ups in the River Tornionjoki have occurred during the 2000s.
- During the 2002–2018 period new records have been set for latest freeze-ups, earliest break-ups, shortest ice cover duration and thinnest ice thickness of the year. Actually, in the period of 2001–2017/2018 as high a fraction as 89–94% of the years demonstrated earlier break-ups and 82–94% later freeze-ups than the average of the 1961–2000 period based on data of the longest ice cover time series in Finland.
- In **Paper IV** changes in the occurrence of extremes in the timing of the lake freeze-up and break-up in the Northern Hemisphere using long-term ice phenology data were examined until winter 2004–2005. Trends in the ice variables in the recent 30-year period were steeper than those in the 100- and 150-year periods, and trends in the 150-year period were steeper than in the 100-year period. Mostly, the standard deviation did not change,

or it decreased in the 150-year and 100-year periods. During the recent 50-year period, the standard deviation calculated in 10-year windows increased for all ice measures. For the 150-year and 100-year periods changes in the mean ice dates rather than changes in variability most strongly influenced the significant increases in the frequency of extreme lake ice events associated with warmer conditions and decreases in the frequency of extreme events associated with cooler conditions.

- In **Paper V** records of river ice break-up dates and air temperatures and their interrelations since 1802 in Northern Fennoscandia were examined by using the break-up data for the River Tornionjoki. The temperature history of the April-May season was used as a climatic equivalent for the break-up timings. Both records (temperature and break-up) showed seven sub-periods during which their local means were distinctly different relative to the preceding and subsequent sub-periods. The starting and ending years of these sub-periods occurred in temporal agreement, suggesting no major inhomogeneity issues often linked to historical time series. The most recent sub-period demonstrated the highest spring temperatures with parallel earliest river ice break-ups, showing the relative warmth of the current springtime climate in the study region in the context of the past two centuries.
- **Paper VI** concluded that lake and river ice seasonality (dates of ice freeze-up and break-up) responds sensitively to climatic change and variability. The study showed an earlier spring melt for the River Tornionjoki, increasing frequencies of years with warm extremes, changing inter-annual variability, waning of dominant interdecadal quasi-periodic dynamics, and stronger correlations of ice seasonality with atmospheric CO_2 concentrations and air temperatures since the start of the Industrial Revolution. The study highlighted that global processes including climate change and variability are driving the long-term changes in ice seasonality. Similar findings were presented for Lake Suwa, Japan: with a shift towards later freezing.
- **Papers V and VI** emphasized the importance of multi-centurial (i.e. historical) cryophenological information for highly interesting perspectives on climate and environmental history.

River discharge in winter and spring:

- The river flow trend analysis in **Paper II** revealed no changes in the mean annual flow in general until 2004, but the seasonal distribution of the streamflow had changed. Winter and spring mean monthly discharges had increased at most of the observation sites. Changes in discharges were

mainly 2–10% per decade. The spring peak had moved to an earlier date at over one-third of the sites. The change was mainly 1–3 days per decade at unregulated sites. However, the magnitudes of the spring high flow had not changed. Updated data until the present showed that the same tendencies had continued after 2004. The number of seasonal winter and spring trends had even increased and become stronger than in **Paper II**.

- In **Paper III**, the future changes in discharges on annual and seasonal scales were simulated with a WSFS hydrological model for four catchments in different parts of Finland based on transient climate scenarios until 2099. The results showed that seasonal changes, most importantly the increase in winter runoff, were clearly visible and consistent in different climate scenarios and catchments. The projected changes reflect changes already present in in situ observations.

In general:

- Both ice cover and river discharge are related to large scale atmospheric circulation patterns and show different periodicities in the time series in addition to the long-term changes. The effect of atmospheric circulation patterns should be taken into account while analysing shorter time series. (**Papers II, VI**)
- The influence of the North Atlantic Oscillation (NAO) can be seen in Finnish ice and discharge time series. The strong positive winter NAO index is associated with later freeze-ups, earlier break-ups of ice and higher winter discharges. The influence of the large negative winter NAO index is vice versa. **(Papers II, VI)**
- Nevertheless some papers of this dissertation are a decade old, similar tendencies - warmer winters and earlier springs have recently become more frequent as seen from the updated graphs presented in this dissertation with the most recent data.
- This dissertation shows that long-term hydrological time series are very important research material in the changing climate and changing world we live in. The Finnish time series are unique in length and are highly valuable data sources as climatic indicators on the global level as shown in **Papers IV, V** and **VI**.
- Even though models and remote sensing methods are improving all the time, in situ observations are crucial data sources of present state validation and will be needed for calibration of the new technologies in the future.

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