Department of Civil and Environmental Engineering

Estimation of climate change impacts on hydrology and floods in Finland

Noora Veijalainen

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Estimation of climate change impacts on hydrology and floods in Finland

Noora Veijalainen

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Aalto University
School of Engineering
Department of Civil and Environmental Engineering

Supervisor
Prof. Harri Koivusalo

Instructors
Dr. Docent Bertel Vehviläinen
Dr. Tuomo Karvonen

Preliminary examiners
Dr. Hege Hisdal, Norwegian Water Resources and Energy Directorate, Norway
Dr. Christel Prudhomme, Centre for Ecology and Hydrology, UK

Opponent
Dr. Reader Jonas Olsson, Swedish Meteorological and Hydrological Institute, Sweden

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Abstract

Aalto University, P.O. Box 11000, FI-00076 Aalto www.aalto.fi

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Noora Veijalainen

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Abstract

Climate scenarios project increases in air temperature and precipitation in Finland during the 21st century and these will results in changes in hydrology. In this thesis climate change impacts on hydrology and floods in Finland were estimated with hydrological modelling and several climate scenarios. One of the goals was to understand the influence of different processes and catchment characteristics on the hydrological response to climate change in boreal conditions.

The tool of the climate change impact assessment was the conceptual hydrological model WSFS (Watershed Simulation and Forecasting System). The studies employed and compared two methods of transferring the climate change signal from climate models to the WSFS hydrological model (delta change approach and direct bias corrected Regional Climate Model (RCM) data). Direct RCM data was used to simulate transient hydrological scenarios for 1951-2100 and the simulation results were analysed to detect changes in water balance components and trends in discharge series.

The results revealed that seasonal changes in discharges in Finland were the clearest impacts of climate change. Air temperature increase will affect snow accumulation and melt, increase winter discharge and decrease spring snowmelt discharge. The impacts of climate change on floods in Finland by 2070-2099 varied considerably depending on the location, catchment characteristics, timing of the floods and climate scenario. Floods caused by spring snowmelt decreased or remained unchanged, whereas autumn and winter floods caused by precipitation increased especially in large lakes and their outflow rivers. Since estimation of climate change impacts includes uncertainties in every step of the long modelling process, the accumulated uncertainties by the end of the process become large. The large differences between results from different climate scenarios highlight the need to use several climate scenarios in climate change impact studies.

Possibilities to adapt to climate change impacts through changes in lake regulation were also estimated. Changing the management and permits of many of the regulated lakes in Finland will become necessary during the 21st century in response to climate change induced shifts in hydrological regime.

Keywords Hydrological modelling, climate change, water resources, floods, impact assessment, climate scenarios, adaptation

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Tiivistelmä

Ilmastonmuutoksen myötä ilman lämpötilan ja sadannan ennakoidaan kasvavan Suomessa 2000-luvulla, millä tulee olemaan selviä vaikutuksia hydrologiaan. Tässä väitöskirjassa arvioidaan ilmastonmuutoksen vaikutuksia hydrologiaan ja tulviin Suomessa käyttäen hydrologista mallintamista ja useita ilmastoskenaarioita. Yhtenä tavoitteena on ymmärtää miten eri prosessit ja valuma-alueiden ominaisuudet vaikuttavat ilmastonmuutoksen aiheuttamiin hydrologisiin muutoksiin boreaalisissa olosuhteissa.

Ilmastonmuutoksen vaikutusten arviointiin käytettiin Vesistömallijärjestelmän (WSFS) konseptuaalista hydrologista mallia. Arviointia varten ilmastonmuutossignaali siirrettiin ilmastomallista hydrologiseen malliin käyttäen kahta menetelmää (delta change-menetelmä ja suorat korjatut alueellisen ilmastomallin tulokset) ja menetelmien tuloksia vertailtiin keskenään. Suoria alueellisten ilmastomallien tuloksia käytettiin simuloitaessa jatkuvia hydrologisia skenaarioita jaksolle 1951–2100 ja skenaarioista analysoitiin vesitaseen osatekijöiden muuttumista ja virtaama-aikasarjojen trendejä.

Tutkimusten tulokset osoittavat, että ilmastonmuutoksen selvimmät vaikutukset ovat muutokset eri vuodenaikojen virtaamissa. Ilmastonmuutoksen aiheuttama ilman lämpötilan nousu vaikuttaa lumen kertymiseen ja sulamiseen, mikä kasvattaa talviajan virtaamia sekä pienentää lumen kevätsulannan aiheuttamia virtaamia. Muutokset kerran 100 vuodessa toistuvissa tulvissa jaksolla 2070–2099 vaihtelivat huomattavasti riippuen valuma-alueen sijainnista ja ominaisuuksista sekä tulvien ajoituksesta ja käytetystä ilmastoskenaariosta. Kevään lumen sulamistulvat pienenivät tai pysyivät nykyisen suuruisina, kun taas syksyn ja talven vesisateesta aiheutuvat tulvat kasvoivat etenkin suurissa järvissä ja niiden laskujoissa. Pitkän mallinnusketjun jokaiseen vaiheeseen liittyy epävarmuuksia, joten mallinnusprosessin aikana kertyvät epävarmuudet kasvavat suuriksi. Suuret erot eri ilmastoskenaarioiden tulosten välillä korostavat tarvetta käyttää useita ilmastoskenaarioita arvioitaessa ilmastonmuutoksen vaikutuksia.

Tutkimuksessa arvioitiin myös mahdollisuuksia sopeutua ilmastonmuutoksen vaikutuksiin muuttamalla järvien säännöstelyä. Säännöstelyn uudelleenarviointi tulee tarpeelliseksi 2000-luvun aikana useilla Suomen säännöstelyillä järvillä, kun ilmastonmuutos aiheuttaa muutoksia järvien tulovirtaamissa.

Avainsanat Hydrologinen mallintaminen, ilmastonmuutos, Suomen vesivarat, tulvat, vaikutusten arviointi, ilmastoskenaariot, sopeutuminen

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LIST OF APPENDED PAPERS

This dissertation is based on the following papers:

I. Veijalainen, N., Vehviläinen, B. 2008. The effect of climate change on design floods of high hazard dams in Finland, Hydrology Research 39(5–6), 465–477.

II. Lotsari, E., Veijalainen, N., Alho, P., Käyhkö, J. 2010. Impact of climate change on future discharges and flow characteristics of the Tana River, Sub-Arctic northern Fennoscandia. Geografiska Annalier 92A(2), 263–284.

III. Veijalainen, N., Dubrovin, T., Marttunen, M., Vehviläinen, B. 2010. Climate change impacts on water resources and lake regulation in the Vuoksi watershed in Finland. Water Resources Management 24(13), 3437–3459.

IV. Veijalainen, N., Lotsari, E., Alho, P., Vehviläinen, B., Käyhkö, J. 2010. National scale assessment of climate change impacts on flooding in Finland. Journal of Hydrology 391, 333–350.

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

Papers, I–V, reprinted with permission, are copyright as follows:

Contribution of the author to papers I to V:

I: Noora Veijalainen was responsible for the model application and mainly responsible for the interpretation of results and writing of the paper. Dr. Vehviläinen participated in the development of the methodology and interpretation of the results and provided comments during the writing of the paper.

II: Noora Veijalainen was responsible for the hydrological simulations in the paper and partly (30%) responsible for writing the paper. Lotsari was responsible for the hydraulic and sediment model applications and for the majority of the writing of the paper. Dr. Alho and Prof. Käyhkö participated in the writing of the paper.

III: Noora Veijalainen was responsible for the hydrological simulations in the paper. The impact assessment was performed by Dubrovin, Dr. Marttunen and Veijalainen. Veijalainen wrote the paper and Dubrovin, Dr. Vehviläinen and Dr. Marttunen provided comments on the manuscript.

IV: Noora Veijalainen was responsible for the hydrological modelling and frequency analysis of the paper and was mainly (60%) responsibly for writing the paper. Lotsari was responsible for the hydraulic modelling performed in four study catchments and wrote parts of the paper. Dr. Alho, Prof. Käyhkö and Dr. Vehviläinen provided comments during the writing of the paper.

V: Noora Veijalainen was responsible for the hydrological modelling in the paper and had the main responsibility for writing the paper. Korhonen performed the statistical analysis and participated in the writing of the portions related to the statistical analysis. Prof. Koivusalo and Dr. Vehviläinen provided comments during the analysis of the results and writing of the paper.

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In Helsinki April 9th, 2012

Noora Veijalainen

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1 Introduction

1.1 Background and motivation

Climate change is one of the big challenges of the 21st century. The projected changes in climate will have direct and indirect impacts on natural environment as well as on human societies. Hydrology and water resources will be affected, since they are closely linked to climate. In Finland the current hydrological regime is characterised by temperature-sensitive snow-dominated seasonality. Even relatively modest increases in temperature can result in substantial changes in seasonal runoff patterns in snow-dominated areas (Arnell 1999; Lettenmaier et al. 1999; Payne et al. 2004; Barnett 2005). Therefore climate change may induce major changes in hydrological conditions in Finland. These changes can be studied with the use of climate scenarios and hydrological models.

Research on climate change impacts on nature and society on local and national scale provides the knowledge needed by planners, managers and policy makers to assess adaptation possibilities and to direct adaptation efforts to the most vulnerable geographic regions and societal sectors. Adaptation is important to reduce the negative impacts and to take advantage of possible opportunities of climate change (Marttila et al. 2005). An example of a topical application field for climate change information is the flood directive of the European Union (European commission 2007). It requires that member countries prepare flood risk assessments, and advises that the impacts of climate change on the occurrence of floods should be taken into account when preliminary flood risks are assessed. Lake and reservoir regulation permits and hydraulic structures such as dam spillways are planned to be in use for decades into the future; taking climate change into consideration when new permits or structures are constructed or existing ones are redesigned may save changes and modifications of hydraulic structures and other infrastructure later on.

Global or continental scale studies concerning changes in water resources and floods have been carried out using large scale (global and continental) hydrological models (e.g. Lehner et al. 2006; Nohara et al. 2006; Dankers and Feyen 2008; 2009), but the precision and reliability of these results in catchment-scale (i.e. the scale of most rivers and catchments, usually between 10 and 200 000 km^2) have not been demonstrated. The location of Finland in the transitional zone between maritime and continental climate regions, with varying soil types and diverse hydrology characterised in many parts by large numbers of connected natural lakes results in exceptional climatic and hydrological conditions (Vakkilainen and Karvonen 1980). Climate change impacts can vary between catchments even within relatively small areas due to local climate and catchment characteristics (Arnell and Reynard 1996). Thus reliable estimates of climate change impacts on hydrology in Finland are difficult to infer from large scale results or by analogy from nearby locations. Modelling of climate change impacts on hydrology in local and national scale is therefore needed. Studies in local and national scale can make use of data available in national archives (e.g. the database of water level and discharge observations and locations and areas for the thousands of lakes) and knowledge of local conditions (such as knowledge of lake regulation practices).

1.2 Climate change

Anthropogenic climate change (hereafter “climate change”) is with high confidence caused by intensification of the greenhouse effect due to increase of greenhouse gases in the atmosphere (IPCC 2007a). Greenhouse gas concentrations have increased since pre-industrial times because of fossil fuel use, land use change and agriculture (IPCC 2007a). Atmospheric concentrations of carbon dioxide (CO_2), which is the most important greenhouse gas, have increased from a pre-industrial value of approximately 280 ppm (parts per million, the ratio of the number of carbon dioxide molecules to the total number of molecules of dry air) in 1870 (Etheridge et al. 1996; IPCC 2007a) to 390 ppm in 2010 (NOAA 2011). Increases in greenhouse gas concentrations alter the energy balance of the climate system and drive warming influences on global climate (IPCC 2007a). The latest climate change research is brought together in the regular Assessment reports by the Intergovernmental Panel on Climate Change (IPCC).

Warming of the climate is becoming evident from observations showing increase in global average temperature, melting of snow and ice and rising global average sea level (Holgate and Woodworth 2004; Brohan et al. 2006; IPCC 2007a). The increase in global average temperature from 1850–1899 to 2001–2005 was on average 0.76°C (IPCC 2007a). Most of the observed increase in global average temperature since the mid 20th century cannot be explained by natural forcing such as changes in solar radiation and volcanic activity, but is very likely due to the observed increase in anthropogenic greenhouse gas concentrations (Tett et al. 2002; Stott et al. 2006; IPCC 2007a). The global average change in observed precipitation over land areas shows non-linear behaviour (IPCC 2007a). No significant global trends have hitherto been detected in most of the precipitation datasets, partly because changes in different directions in different regions partly cancel each other out (IPCC 2007a; Zhang et al. 2007). Within latitudinal bands anthropogenic forcing has had a detectable effect on the observed changes in average precipitation (Zhang et al. 2007). The spatial patterns of precipitation change are varied, with increasing trends in most parts of high latitudes including northern Europe and the strongest decreasing trends in western Africa and Sahel (IPCC 2007a).

In Finland the average temperature increased approximately 0.7 °C during the 20th century (Jylhä et al. 2004), with the largest increases taking place during the last decades (Fig. 1). The greatest warming occurred in spring months (March–May) (Tuomenvirta 2004). No significant nationwide trends were observed in precipitation in Finland, although notable interdecadal variability was observed during the 20th century (Tuomenvirta 2004).

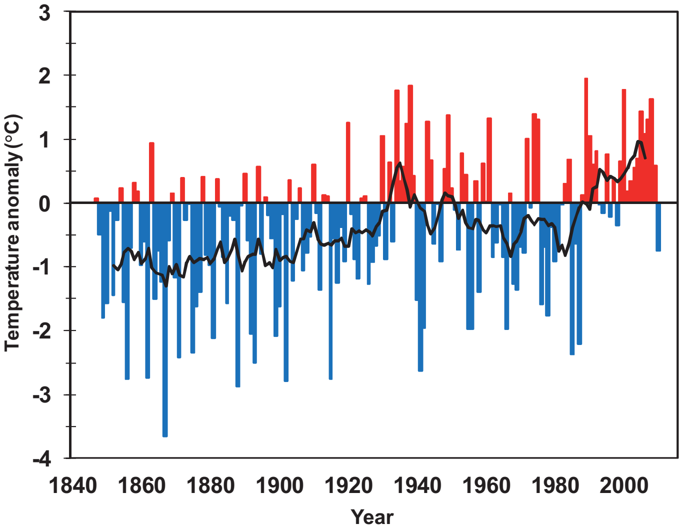

Figure 1. Observed differences of average annual air temperature in 1847–2010 from the average temperature of 1971–2000 at four temperature observation stations in Finland (Helsinki, Kuopio, Oulu and Kajaani) (Finnish Meteorological Institute 2011a). The red bars show the anomaly above the average temperature and blue bars below it. The black line shows the value of the 10 year moving average.

Observed changes in runoff and flood magnitudes have been analysed in many studies throughout the world (e.g. Hodgkins et al. 2003; Pekárová et al. 2003; McCabe and Clark 2005; Huntington 2006; Hisdal et al. 2007; Wilson et al. 2010). In general, observational evidence indicates intensification of the water cycle, although regional variations and spatial and temporal limitation in data remain large (review by Huntington 2006). No conclusive evidence about the increase in frequency of flood occurrence was found (Kundzewicz and Schellnhuber 2004; Huntington 2006). In large western and central European rivers no significant trends in mean annual runoff were found, but cyclic occurrence of dry and wet periods was observed (Pekárová et al. 2003). Multi-decadal variability was also noted in undisturbed catchments in the UK (Hannaford and Marsh 2008). In North America, observations showed statistically significant increases in discharge of rivers in the Great Lakes Basin (McBean and Motiee 2008) and decreases in the magnitude of snowmelt-induced floods in Canada (Cunderlik and Ouarda 2009). Several studies report earlier occurrence of peak discharge caused by spring snowmelt and increase in winter discharge in North America and northern Eurasia (Hodgkins et al. 2003; McCabe and Clark 2005; Hisdal et al. 2007; Korhonen and Kuusisto 2010; Wilson et al. 2010). In the Nordic countries the majority of the long observation series did not show significant trends in annual discharge, but regionally positive trends existed in south-western Norway and northern Sweden (Lindström and Bergström 2004; Hisdal et al. 2007; Wilson et al. 2010). Positive trends were also observed in winter and spring discharge in the Nordic countries (Wilson et al. 2010). In Finland, no statistically significant changes in mean annual discharge or annual maximum discharge were found in general, but there were clear trends in seasonal discharge series with increases in winter and spring mean discharge and earlier timing of the spring peak in many of the observation stations (Korhonen and Kuusisto 2010).

Future global warming will depend on future emissions of greenhouse gases, which are described by different emission scenarios. The most recent set of emission scenarios is the group of SRES (Special Report on Emission Scenarios, IPCC 2000) emission scenarios (Fig. 2), which includes a total of 40 different scenarios from four scenario families based on alternative future pathways and different modelling approaches. Seven groups - the scenario families A2, B1, and B2 and the four groups within the A1 scenario family - and four cumulative emissions categories are recommended as the subset of SRES emission scenarios that captures the range of uncertainties associated with driving forces and emissions (IPCC 2000). The most commonly used SRES emission scenarios in climate models are currently the A2, B1 and A1B scenarios, of which A2 produces the highest CO_2 concentrations by the end of the 21st century, B1 the lowest and A1B intermediate CO_2 concentrations (Fig. 2).

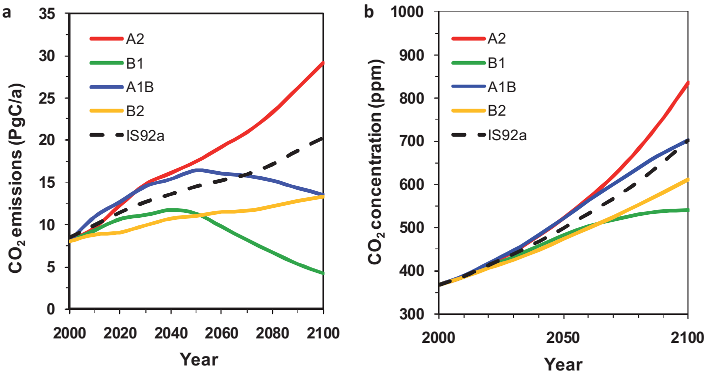

Figure 2. Emission scenarios of a) total anthropogenic CO_2 emissions and b) atmospheric CO_2 concentration (ppm, Bern-CC) until 2100. (IPCC 2000; IPCC 2001)

The current best estimate from the IPCC Fourth Assessment Report for the projected global average temperature change by the end of the 21st century is 1.8–4.0 °C from 1980-1999 with different emission scenarios (IPCC 2007a). The likely range with six emission scenarios and several climate models is 1.1–6.4 °C (IPCC 2007a). Projections of precipitation change during the 21st century indicate increases in the high latitudes, whereas decreases are likely in most sub-tropical land regions (IPCC 2007a).

According to different climate scenarios from several global climate models and SRES emission scenarios the average annual temperature in Finland is expected to increase by 2.0–6.5 °C by the 2080s and average precipitation by 7–26 % (Jylhä et al. 2009; Fig. 3). The largest projected increases in both temperature and precipitation are during winter: projected increases in winter temperatures are 3–9 °C and in precipitation 10–40%, while the corresponding figures for summer are 1–5 °C and 0–20% (Jylhä et al. 2009). This study is motivated by the need to estimate the consequences of these projected changes for the hydrological regime in Finland (papers I–V).

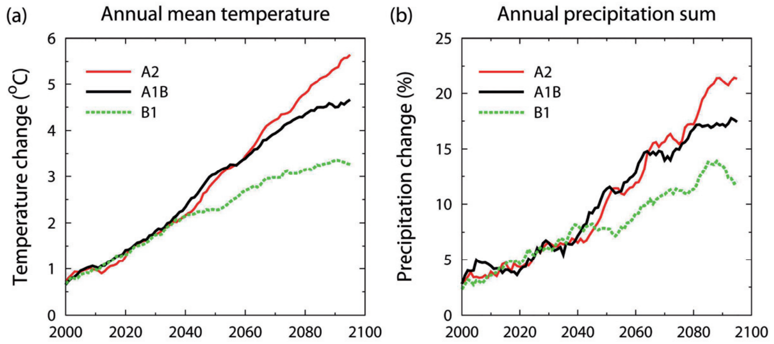

Figure 3. Projected average changes during the 21st century in a) annual mean temperature (°C) and b) annual precipitation sum (%) in Finland with three emission scenarios (Finnish Meteorological Institute 2011b).

1.2.1 Climate models

Effects of the increases in atmospheric greenhouse gas concentrations on climate are studied with climate model simulations. Climate models are a simplified representation of the climate system described through mathematical formulations of physical laws. Today the advanced climate models are coupled atmosphere-ocean general circulation models, which operate on global scale and couple three-dimensional atmospheric circulation models with ocean general circulation models, sea ice models and land-surface process models (Covey et al. 2003; IPCC 2007a). These models are usually referred to as General Circulation Models or Global Climate Models (GCMs) and they produce the best and most comprehensive available projections of climate change impacts on global scale (IPCC 2007a). Most major centres for atmospheric research in the largest countries have developed their own climate models, and the IPCC Fourth Assessment Report (AR4, IPCC 2007a) includes results from 23 GCMs, although not all of them are independent since some are different versions of the same GCM.

Greenhouse gas emission scenarios during the 20th century (IPCC 2000) are used as external forcing of the GCMs. Together the emission scenario and the climate model or combination of climate models form what is here referred to as a climate scenario.

The evolution of climate models has been rapid over the last 20 years. The GCMs in the IPCC First Assessment report (IPCC 1990) mostly included only an atmospheric model, had a grid size of 500 km (~5 degrees) and simulated equilibrium climate resulting from doubling of CO_2 concentration (IPCC 2007a). By comparison the GCMs included in the AR4 (IPCC 2007a) were fully coupled complex atmosphere-ocean general circulation models, sometimes even including interactive chemical or biochemical components, with 110–250 km (~1–2.5 degrees) grid resolution and time-dependent scenarios. The latest set of GCMs includes new processes as well as improvements in resolution, computational methods and parameterisations compared to earlier versions (IPCC 2007a).

In addition to GCMs operating on global scales, Regional Climate Models (RCMs) are used in many parts of the world to dynamically downscale GCM results to smaller scale (~10–50 km) (Kotlarski et al. 2005; IPCC 2007a). RCMs are able to resolve important regional scale processes such as orographic lifting of air masses (Kotlarski et al. 2005). In Europe alone there are up to 15 RCMs, which have been compared in the ENSEMBLES project (Hewitt 2005; van der Linden and Mitchell 2009). Since the RCMs only cover part of the world, they use output from GCMs to provide initial conditions and time-dependent meteorological boundary conditions as well as greenhouse gas and aerosol forcing (Mearns et al. 2003). The results of the RCM therefore depend largely on the driving GCMs, whereas no feedback from the RCM to the driving GCM is used. The advantage of RCMs is their ability to reproduce the spatial patterns of climate in sub-regions of the globe better than the GCMs, and to reproduce precipitation extremes on a scale not simulated by the GCMs (Mearns et al. 2003; Frei et al. 2006; Boberg et al. 2010).

Even though climate models have become much more advanced, the range of model results has not diminished (Covey et al. 2003; IPCC 2007a). The main sources of uncertainties in climate prediction are the climate model uncertainties and errors originating from the fact that some of the physical processes modelled are either not completely understood or cannot yet be adequately represented due to limited computational power (Schnur 2002; Covey et al. 2003; IPCC 2007a). Notable uncertainties are associated in particular with representation of clouds and cloud feedbacks in climate models (Stephens 2005; IPCC 2007a). Many small-scale processes such as cloud formation have to be described in an approximate form to simulate their interaction with large-scale features (IPCC 2007a). A number of different algorithms and a number of parameterisation methods of the small-scale processes have been developed in different climate models, and this is the main reason for the wide range of results produced by the different GCMs (Covey et al. 2003; Prudhomme et al. 2003; IPCC 2007a).

The ability of the GCMs and RCMs to correctly simulate the current observed climatic conditions is a necessary, although not in itself sufficient, condition for a model to produce reliable climate change projections (Mitchell et al. 2011). Evaluations of GCM performance on global scale have demonstrated the ability of the GCMs to reproduce relatively well the general observed features of past and recent climate and changes in climate (e.g. Covey et al. 2003; Collins et al. 2006; IPCC 2007a). Many studies have also evaluated GCM and RCM performance on regional and national scales in Finland, Scandinavia and Europe (Jylhä et al. 2004; IPCC 2007a; Jacob et al. 2007; Lind and Kjellström 2009; Boberg et al. 2010). GCMs included in the AR4 simulated annual precipitation in Finland relatively well, but were often unable to produce the observed seasonal cycle (Jylhä et al. 2004; IPCC 2007a). These GCMs often produced too much precipitation in winter and too little in summer (IPCC 2007a). The annual cycle of air temperature in Finland was simulated qualitatively well by five GCMs studied by Jylhä et al. (2004), but some of the models had a cold bias and too continental climate for Finland.

The RCMs generally reproduce the circulation patterns of the driving GCM, but in many regions the RCM results also differ from GCMs (Mearns et al. 2003; Jacob et al. 2007) and the biases in the driving GCM can even be amplified by the RCM (Kjellström and Lind 2009). Some RCMs were found to have warm winter bias over Scandinavia (Jacob et al. 2007) and the Baltic Sea drainage basin (Lind and Kjellström 2009). A systematic wet bias was reported in several RCMs in Scandinavia or the Baltic Sea drainage basin (Graham et al. 2007b; Jacob et al. 2007; Kjellström and Ruosteenoja 2007; Lind and Kjellström 2009). Inter-annual precipitation variability and simulated precipitation probability density functions of RCMs were found to be in relatively good agreement with observations in the Nordic region (Jacob et al. 2007; Boberg et al. 2010). RCMs were reported to have too high evaporation rates in the Baltic Sea Drainage Basin (Graham et al. 2007b). The limitations of the climate models in simulating current climatic variables are important, especially if these daily values are used in further climate change impact assessments as input to other models, such as the hydrological model in paper (V).

1.3 Hydrological modelling of climate change impacts

Since climate models quantify water balance and simulate its components such as runoff, one may question why there is a need to use separate off-line hydrological models. The use of off-line hydrological modelling as a tool for climate change impact studies originated from necessity in the 1980s, because the scale and quality of the GCMs at that time did not permit the use of their water balance components in a meaningful way (Blyth 2009). The priority in the land surface component of the GCMs was, and still is, to reproduce accurately the evaporation fluxes for the purposes of the atmospheric model, and therefore the emphasis given to accurate runoff simulation was much lower (Blyth 2009).

Both physical content and resolution of the GCMs have evolved rapidly in recent decades and nested RCMs able to dynamically downscale GCM results to a finer scale over selected areas have become more common (Mearns et al. 2003; Kotlarski et al. 2005; IPCC 2007; van der Linden and Mitchell 2009). However, even with the improved spatial resolution and more complex physics, the results of the runoff simulated by GCMs and RCMs are still unreliable and usually do not provide sufficient detail to satisfactorily simulate hydrology at scales necessary for catchment-scale impact assessments (Varis et al. 2004; Graham et al. 2007b). Even with the improved spatial scales, the grid size of the RCMs (~10–50 km) is still larger than in most off-line hydrological models and representation of surface heterogeneities still needs to be improved (Hagemann et al. 2009). For example the RCMs from the ENSEMBLES data archive have a grid size of 25km x 25km=625 km^2 (Hewitt 2005; van der Linden and Mitchell 2009), whereas many hydrological models have a resolution lower than 100 km^2 (Boé et al. 2007).

In addition to runoff (water flow per area in mm/d), which the climate models calculate for each grid cell, discharges (flow in river or stream in m^3/s) are also needed in impact assessments. To derive discharges, runoff needs to be temporally lagged and spatially integrated over a catchment with a river routing scheme (Milly et al. 2005; International Arctic Science Committee 2010). The land-surface components of the latest versions of GCMs usually include only simplified river routing schemes for the largest river catchments (Varis et al. 2004; International Arctic Science Committee 2010). Additional and more comprehensive river routing schemes, which include simulations of horizontal transport of runoff within the catchment, are thus needed (International Arctic Science Committee 2010).

Despite the advances, substantial uncertainties still exist in the GCM- and RCM-simulated land-surface processes including runoff simulation (Xu et al. 2005; Graham et al. 2007b). Comparison of different land surface schemes used in climate models and in weather prediction made in northern Scandinavia (Nijssen et al. 2003) and in France (Boone et al. 2004) showed large differences in snow accumulation and ablation as well as soil moisture, and as a result a wide range of monthly runoff and discharge estimates was produced by the different models. Problems in land surface models remain especially in the simulation of winter snow sublimation and detention of runoff in lakes, wetlands and peatland areas (Nijssen et al. 2003). Hitherto most assessments using GCM- or RCM-simulated runoff and discharge have been limited to very large rivers around the world

(Arora 2001; Milly et al. 2002; Milly et al. 2005) or other large areas such as the Baltic Sea drainage basin with its large number of sub-catchments (Graham et al. 2007b). An older version of Canadian GCM was unable to produce even the mean annual discharge within 20 % of observed estimates in approximately 70 % of the large rivers studied (Arora 2001). Graham et al. (2007b) compared the discharges based on runoff simulated by different RCMs and routed with two river routing schemes in the Baltic Sea drainage basin and found that these produced very different results on timing and magnitude of discharges on a monthly scale. Even when mean annual discharge is reproduced reasonably well, seasonal runoff and discharges based on GCM or RCM results often differ significantly from observations (Lind and Kjellström 2009; International Arctic Science Committee 2010).

The off-line hydrological models lack two-way interaction with the climate models (Xu et al. 2005) and only use part of the outputs of the climate models (Hurkmans et al. 2008). The physics of the hydrological models are usually less advanced than in the land surface models which solve the coupled water and energy balance (Hurkmans et al. 2008). Especially conceptual hydrological models are based on conceptualisations without a solid physical base. However, the advantage of hydrological models is their ability to simulate accurately the river discharges and especially peak discharges based on calibration against observed discharges (Blyth 2009). Off-line hydrological models are also considerably faster to operate than the land surface models of GCMs and RCMs (Hurkmans et al. 2008). Therefore they can be used to simulate large numbers of climate scenarios, and to examine the influence of adaptation strategies and water resources management actions (e.g. lake and reservoir regulation, paper III) on river discharge. Continuing improvement in the resolution and physical content of the climate models may in the future lead to runoff from RCMs being sufficiently reliable to be used in catchment-scale impact assessments (Blyth 2009). Convergence of hydrological and land surface models into a new generation of land surface hydrology models combining the best of both model types is studied e.g. in the EU WATCH project (Blyth 2009). Until this becomes reality, the limitations of GCM- and RCM-simulated runoff mean that off-line hydrological modelling (papers I–V) still remains the main tool for hydrological climate change impact assessments.

1.3.1 Historical perspective

The first mathematical formulations relating rainfall to runoff were developed in the 19th century and these were empirical formulas such as the rational method for flood peak estimation (e.g. Beven 2001; Kokkonen 2003).

More realistic process-based methods to predict flood peaks were developed in the 1930s with the unit hydrograph concept (Sherman 1932), which later became widely used (Ward 1978; Kokkonen 2003). In its current form, hydrological modelling began in the 1960s when emerging computers first enabled the use of simulation models for hydrological analyses (e.g. the Standford watershed model by Linsley and Crawford 1960). These first hydrological models were conceptual models, which developed into numerous variants during the following decades (Beven 2001). Despite the development of more detailed and physically based distributed models (Beven 2001), conceptual models are still commonly used both in studies of hydrological impacts (e.g. Andréasson et al. 2004; van Pelt et al. 2009) and in operational forecasting (e.g. in Sweden, Norway, Finland, Røhr and Husebye 2005; Vehviläinen et al. 2005; Arheimer et al. 2011). Today the number of different hydrological models is considerable and they range from simple lumped conceptual models to complex fully-distributed physically based models (Beven 2001).

Hydrological modelling in Finland began in earnest during the 1970s and 1980s (Kuusisto 1977; Virtanen 1977; Virta 1978; Vakkilainen and Karvonen 1980; Vehviläinen 1982; Karvonen 1988). Currently hydrological modelling is applied e.g. in flood forecasting (Vehviläinen et al. 2005), modelling of hydrological processes (e.g. Koivusalo 2002; Kokkonen 2003; Laine-Kaulio 2011), modelling of nutrient cycles (e.g. Huttunen et al. 2008; Rankinen et al. 2009; Ronkanen and Kløve 2009) and modelling of surface water hydrodynamics and water quality (e.g. Virtanen et al. 1998; Virtanen 2009; Lepistö et al. 2008; Huttula et al. 2010). The nationwide hydrological forecasting system Watershed Simulation and Forecasting System (WSFS, Vehviläinen 1982) is currently developed and operated at the Finnish Environment Institute (SYKE). In addition to forecasting and flood warnings the WSFS is also used for research purposes (Vehviläinen and Huttunen 1997; papers (I–V))

The WSFS hydrological model is of the HBV (Hydrologiska Byråns Vattenbalansavdelning) model type. The HBV model is a conceptual model first developed in Sweden in the 1970s (Bergström 1976). With its several versions it remains a popular model type used most commonly in the Nordic countries (Sweden, Norway, Denmark, Finland and Iceland) (Vehviläinen and Huttunen 1997; Andréasson et al. 2004; Beldring et al. 2008), but also in many other parts of the world (Booij 2005; Akhtar et al. 2008; Steele-Dunne et al. 2008; van Pelt et al. 2009). Its application field ranges from operational flood forecasting (Røhr and Husebye 2005; Vehviläinen et al. 2005; Arheimer et al. 2011) to research including hydrological climate change studies (Vehviläinen and Huttunen 1997; Andréasson et al. 2004; Booij 2005; Akhtar et al. 2008; Beldring et al. 2008; Steele-Dunne et al. 2008; van Pelt et al. 2009).

The benefit of conceptual hydrological models compared to the more physically based models is the need for relatively little input information and fast and easy operation (Uhlenbrook et al. 1999). This is beneficial especially in operational forecasting, where large areas are being simulated in near real time. However, the conceptual hydrological models are often overparameterized with a larger number of parameters than can be determined based on the available observations and with intercorrelation between parameters (Uhlenbrook et al. 1999). This leads to equifinality in the identification of the parameter values, i.e. many different sets of parameter values produce reasonable simulations (Beven 1996; Beven 2001). It has been argued that the physically based models have more physically based parameter values that can be more robustly estimated from catchment characteristics than the parameter values of conceptual models (Beven 1996). However, even the more physically based models are based on aggregation of small scale theories to catchment-scale and suffer from a lack of data in appropriate spatial and temporal scale, and thus have the same problems of having to rely on model calibration and equifinality of the parameters (Beven 1996; Beven 2001).

Studies of climate change impacts on hydrology with hydrological models began in earnest in the 1980s (Němec and Schaake 1982; Gleick 1986; Arnell and Reynard 1989; Kuchment et al. 1989), although assessments of climate-water relationships had been carried out much earlier (e.g. Langbein et al. 1949). From the start, hydrological modelling was the main tool in estimating climate change impacts on hydrology, although temporal and spatial analogies and regression relationships between climate and hydrology were also used in the 1980s (IPCC 1990). The first studies were limited by the lack of reliable climate scenarios on an appropriate scale (IPCC 1990) and used either hypothetical scenarios based on expert judgement, sensitivity analysis (Němec and Schaake 1982) or the few GCM scenarios for doubling carbon dioxide (CO_2) concentrations available from the 1980s onwards (IPCC 1990; Bultot et al. 1992; Varis et al. 2004).

During the 1990s the level of confidence in the climate change estimates improved with increasing scientific understanding about the drivers and feedbacks of climate change and better climate models (IPCC 2001; IPCC 2007a). As a consequence climate change impact studies in hydrology became increasingly common (e.g. Arnell and Reynard 1996; Wood et al. 1997; Vehviläinen and Huttunen 1997; Arnell 1999). With the increase in available climate scenarios for time periods in the future (e.g. for 2070–2099), the use of several climate scenarios became the most common way of estimating climate change impacts on hydrology during the 1990s (Varis et al. 2004). During the past 20 years the number of studies has increased and the methods used in hydrological impact assessments have become more and more sophisticated (see next section 1.3.2).

In Finland the first studies modelling climate change impacts on hydrology were carried out in the 1980s and 1990s (Vehviläinen and Lohvansuu 1991; Huttula et al. 1992; Vehviläinen and Huttunen 1997; Sælthun et al. 1997). In the 21st century research on hydrological modelling of climate change impacts in Finland has expanded; several studies on climate change and water resources have been carried out (e.g. Beldring et al. 2006; Schneiderman et al. 2009; Perrels et al. 2010; papers (I–V)). The research contributions in Finland have focused mainly on practical applications, such as changes in hydropower production (Fenger 2007) and design values of dams (paper I).

1.3.2 Climate change impacts on hydrology

The most important climatic drivers of hydrology and water availability are temperature, precipitation and evaporation (IPCC 2007b). In the dry regions in mid latitudes where decreases in precipitation are projected, mean annual runoff is expected to decrease (Milly et al. 2005; IPCC 2007b). On the other hand, increases in mean annual runoff are estimated for the areas with increasing precipitation at the high latitudes and in some wet tropical areas (Milly et al. 2005; IPCC 2007b). Changes in air temperature may cause significant shifts in seasonality in areas with snow-dominated hydrology (e.g. Lettenmaier et al. 1999; Bates et al. 2008; Kundzewicz et al. 2008).

Climate change impacts on hydrology have been quantified in numerous studies using hydrological models (Arnell 1999, 2003; Lettenmaier et al. 1999; Prudhomme et al. 2003; Bates et al. 2008; Dankers and Feyen 2008; Wilby et al. 2008). The traditional approach to studying climate change impacts on hydrology is comparison of hydrological model results for future time periods against the results for a past control period (e.g. Arnell 1999; Prudhomme et al. 2003; Schneiderman et al. 2009). The most common method in climate change impact studies in the past has been the delta change approach (section 3.2.1), in which observed meteorological variables for the control period are perturbed according to the projected changes in these variables from climate scenarios, usually as monthly average changes (e.g. Arnell 1999; Hay et al. 2000; Prudhomme et al. 2003).

The spatial resolution of GCMs (currently 110–250 km) is considered to be too coarse for the direct outputs to be used in hydrological impact assessments on catchment-scale (Hay et al. 2002; Diaz-Nieto and Wilby 2005; Fowler et al. 2007; Leander and Buishand 2007). Therefore different methods to downscale the results to appropriate scales have been developed. The methods can be classified into two groups: dynamical downscaling and statistical downscaling (Fowler et al. 2007). In dynamical downscaling, a Regional Climate Model (RCM) or Limited Area Model (LAM) of higher spatial resolution is set up for a region (Hay et al. 2002). RCMs use boundary conditions from the GCMs, but capture geographical details more precisely than GCMs (Hay et al. 2002). Methods of statistical downscaling establish relationships between large-scale climate variables and local surface climate variables and range from simple statistical methods to complex weather generators and weather typing schemes (review by Fowler et al. 2007).

Until a few years ago poor availability of dynamically downscaled climate scenarios and biases in these scenarios led to the delta change approach (section 3.2.1) being the preferred option in most impact studies (Mearns 2003; Fronzek and Carter 2008). In this approach future (e.g. 2070–2099) and control period time slices, which are both assumed to be stationary within the periods, are compared with each other. In recent years the availability of RCM results with different driving GCMs has improved. Consequently a number of studies have appeared describing methods to correct the RCM bias and to use RCM data directly as input to the hydrological model (Hay et al. 2002; Déqué 2007; Leander and Buishand 2007; Piani et al. 2010; Yang et al. 2010). In Europe the ENSEMBLES project (Hewitt 2005; van der Linden and Mitchell 2009) and its data archive is vital in making ensembles of transient RCM scenarios available to scientists. With the available RCM data, long transient hydrological simulations up to the end of the 21st century can now be carried out (e.g. Minville et al. 2010). Thus far only few studies (Minville et al. 2010; Kay and Jones 2012) have examined long continuous transient hydrological scenarios. In paper (V), RCM daily results of temperature and precipitation are bias corrected and used as input to the hydrological model in order to simulate and analyse transient hydrological scenarios for the first time in Finland.

The reasons behind the changes in runoff can be better understood by examining the changes in water balance components. Changes in precipitation, potential evapotranspiration, evapotranspiration, snow accumulation and melt as well as soil moisture all contribute to runoff changes. The importance of each process for the runoff formation and its the projected future changes can be studied with climate models and hydrological modelling (paper V). Kjellström and Lind (2009) reported that the hydrological cycle in the Swedish RCM RCAO was intensified and resulted in 15–20 %

increases in precipitation, evaporation and runoff for the Baltic Sea drainage basin by the end of the century.

Besides the direct need for information about future changes in hydrology and floods, hydrological scenarios are needed in further analysis of possible impacts caused by climate change on flood inundation areas (paper IV; Lane et al. 2007); sediment transport (paper II; Lane et al. 2007), nutrient transport and water quality (Wilby et al. 2006; Tu 2009) and ecology (Murray-Hudson et al. 2006). The indirect impacts of climate change on water quality and subsequent impacts on ecology can be substantial (European Environment Agency 2007) and may be even greater and more important than changes in quantity.

Adaptation to climate change is another issue that has recently gained momentum, since it has become more evident that, despite attempts to mitigate the impacts through planned reductions of greenhouse gas emissions, some further warming will inevitably take place (European Environment Agency 2007). Lake and reservoir regulation is one field in which adaptation measures can be implemented. Hydrological climate change simulations and impact assessment in regulated lakes or reservoirs have been performed especially in heavily modified catchments, where either water supply or hydropower has a major role (Lettenmaier 1999; Christensen and Lettenmaier 2007; Hingray et al. 2007; Fowler et al. 2007; Minville et al. 2009; Pulido-Velazquez et al. 2011). Studies of natural lakes with hydrometeorological conditions relatively similar to those in Finland have been carried out in the large lakes of Sweden (Bergström et al. 2006) and in the Great Lakes in North America (Hartmann 1990; Lee et al. 1997). However, Finland’s hydrological conditions with its large number of lakes, many of them connected through complex systems of waterways, and the lake regulation permits and rules in Finland produce a special situation which has not previously been adequately studied. Detailed studies on the impact of climate change on lake regulation are therefore very much needed in Finland (paper III).

1.3.3 Climate change impacts on floods

Floods cause large economical losses worldwide, and although Finland is among the least vulnerable areas for flooding in Europe (Schmidt-Thomé et al. 2006), the economical damages of extreme flooding in Finland can still be considerable (Ollila et al. 2000). The average flood damages in Finland are rather small, less than one million Euros per year, but in 2004 the damages from fluvial floods were eight million Euros and in 2005 five million Euros (Tulvariskityöryhmä 2009). It is estimated that an extreme flood with a return period of 250 years would cause damages of 662 million Euros (changed to 2011 value), although this flood would not occur throughout the country at the same time (Ollila et al. 2000). Timonen et al. (2003) listed 69 flood risk areas in Finland where considerable damages have occurred and 30 flood areas where frazil ice and ice dams frequently cause flood damages.

Climate change can potentially lead to either increase or decrease in floods in Finland. Floods can increase due to expected increases in both mean precipitation and its extreme intensities in northern Europe (Beniston et al. 2007; IPCC 2007a), whereas decreasing snow depths can lead to decreasing flood magnitudes in regions dominated by snowmelt floods (Booij 2005; Dankers et al. 2007). The catchment response to climate change can substantially vary depending on current climate and catchment physical characteristics (Arnell and Reynard 1996).

Climate change impacts on floods have been studied in many regions (Simonovic and Li 2004; Akhtar et al. 2008; Bates et al. 2008; Kiem et al. 2008), with the largest proportion of studies published in Europe and North America (Andréasson et el. 2004; Graham et al. 2007a; Lenderink et al. 2007; Minville et al. 2008; Kay et al. 2009). Most studies have focussed on individual case study catchments or a few catchments with sizes varying from small streams (~10 km^2 catchment area, e.g. Cameron et al. 2000) to regionally important catchment areas of major rivers such as the River Rhine (185 000 km^2, Lenderink et al. 2007) or the Colorado River (630 000 km^2, Christensen and Lettenmaier 2007). Studies carried out during the last decade have projected increases in flood frequency e.g. in the UK (Reynard et al. 2001; Prudhomme et al. 2003; Fowler and Kilsby 2007), in British Columbia in Canada (Loukas et al. 2002) and in Denmark (Thodsen 2007). However, studies in other regions such as Ireland (Steele-Dunne et al. 2008) and the rivers Rhine and Meuse (Menzel et al. 2006; Leander et al. 2008) reported varying results depending on climate scenario and catchment. Both increasing and decreasing floods during the next century have been projected in the Nordic countries (Andréasson et al. 2004; Graham et al. 2007a; Beldring et al. 2008).

Continental scale studies on climate change impacts on floods have been carried out to produce a general overview in Europe (Lehner et al. 2006; Dankers and Feyen 2008; 2009). Dankers and Feyen (2008, 2009) found mostly decreases in floods in Finland and surrounding areas by the end of the century, whereas Lehner et al. (2006) estimated an increase in flood risk in Scandinavia and Finland. The contradicting results for Finland show that large scale results are not necessarily reliable in smaller scale. Large scale modelling includes simplifications of processes and catchment properties and often has less data available than studies on smaller scale. The unreliability of large scale estimations and the differences between hydrological conditions in Finland compared to other regions provide a strong motivation to estimate climate change impacts on floods on national and local scale in Finland (papers I, II, IV). Thus far nationwide estimations have only been carried out in a few countries (e.g. in Norway by Lawrence and Hisdal 2011).

Special methods to model flood magnitudes and climate change induced changes in very extreme floods have been developed, since these extreme floods are important for the safety of dams and other infrastructure. The most common methods for flood estimation are statistical methods, especially flood frequency analysis (Ward 1978, Harlin 1992). Flood frequency analysis is simple to apply, but it includes large uncertainties in the choice of the frequency distribution especially when extrapolating to extreme floods (Harlin 1992). Furthermore it cannot produce the flood hydrographs necessary for dams with reservoirs, and it is dependent on the availability of good quality observations (Harlin 1992). Another method for estimation of extreme floods is continuous simulation (Cameron et al. 2000; Blazkova and Beven 2004), in which long sequences of precipitation and air temperature up to thousands of years are generated with a weather generator and the corresponding discharge sequence is simulated. A commonly used method is the deterministic approach, in which flood generating factors are maximized and a unit hydrograph or hydrological model is used to simulate the resulting flood (Harlin 1992). One of the most common methods is to estimate the Probable Maximum Precipitation (PMP) and convert PMP together with other critical catchment conditions such as snowmelt and saturated soils to a flood hydrograph, i.e. the Probable Maximum Flood (PMF) (Ward et al. 1978; Harlin 1992). A deterministic approach, somewhat similar to the PMF procedure and based on critical combination of design precipitation event and other flood generating factors, is also used in dam design in Sweden (Flödeskommittén 1990; Andréasson et al. 2007; Swedenergy et al. 2007). This methodology is also appropriate for Finnish conditions and therefore a similar methodology was used in Finland to estimate impacts of climate change on design floods of high hazard dams (paper I).

Estimation climate change induced changes in hydrology and especially in floods includes large uncertainties from several sources. These uncertainties and their relative magnitudes can be quantified by using probabilistic approaches (Minville et al. 2008; Kay et al. 2009; Prudhomme and Davies 2009), but in many studies these uncertainties are not quantified at all. At least some of the most important uncertainties should be considered in assessing the confidence attached to the hydrological projections and the possible variability in the climate change impacts (papers IV and V, section 4.6).

1.4 Objectives

In this thesis a hydrological model is used to estimate climate change impacts on hydrology and floods in Finland. The goal is to assess the processes, catchment characteristics and methods that impact the hydrological response to climate change, and to gain understanding and perspective on projected national and regional scale changes in Finland.

The specific objectives are:

1) To quantify projected changes caused by climate change in hydrological processes and water balance in a boreal environment, including catchments with lake routes, and to understand the drivers and the importance of different processes (III, IV, V)
2) To estimate changes in floods of different return periods caused by climate change (I, II, IV) with different methods
3) To develop and compare methods used to transfer the climate signal from the climate model to the hydrological model (I, IV,V)
4) To evaluate the possibilities to adapt to climate change through changes in lake regulation (III)
5) To evaluate and partly quantify uncertainties involved in hydrological climate change impact studies (IV,V)

The thesis offers a national perspective on hydrological climate change impacts in Finland with the latest methods and climate scenarios. An offline conceptual hydrological model is used for these evaluations. Climatic and hydrological conditions in Finland are rather unique due to the location of Finland in the transitional zone between maritime and continental climate regions, varying soil types and thousands of connected natural lakes (Vakkilainen and Karvonen 1980). Thus the climate change impacts on hydrology and floods in Finland warrant specific studies that can be compared against earlier similar studies from other countries (e.g. Andréasson et el. 2004; Beldring et al. 2008; Minville et al. 2009).

The thesis and the papers (I–V) include several subjects which have not previously been studied in Finland, such as estimation of climate change induced changes in flood magnitudes (papers I, II and IV) and the use and analysis of transient hydrological scenarios produced from direct bias corrected RCM data (paper V). To date transient climate scenarios and the bias correction necessary to reproduce the observed hydrology in the control period have not been widely studied in boreal conditions. National scale evaluation of climate change impacts on extreme floods used as dam design floods (paper I) is also a subject about which only limited studies have been published thus far.

The results increase our knowledge of regional issues concerning boreal and sub-arctic conditions such as catchment response to climate change with regard to catchment characteristics and flood producing mechanisms. The comparison of the results of changes in floods (paper IV) during the next century with continental scale estimates for changes in floods (Lehner et al. 2006; Dankers and Feyen 2008; 2009) can be used to provide insight into the reliability of large scale estimates on smaller scale. Different methods of taking climate change into account are used and compared and their advantages and limitations are discussed.

Only fluvial floods caused by snowmelt, rainfall or their combination are studied in this thesis. Impacts of climate change on floods caused by sea level rise, urban floods in small scale and ice jam and frazil ice floods are beyond the scope of this thesis, even though the changes in these floods due to climate change may be important. Although the thesis includes some estimation of uncertainties especially from climate models, the systematic quantification of the major uncertainties involved in hydrological climate change impact assessment that would require entire studies with e.g. resampling and Monte-Carlo analysis (Minville et al. 2008; Steele-Dunne et al. 2008; Prudhomme and Davies 2009), is outside the scope of this thesis.

2 Materials and study catchments

2.1 Climate and Hydrology in Finland

The Köppen-Geiger climate classification places Finland in the class of cold climate with no dry season (Df) and most of the country to the sub-class with cold summers (Dfc), whereas the coastal area in southern Finland falls within the warm summers (Dfb) sub-class (e.g. Peel et al. 2007). In 1971–2000 the average annual air temperature varied from 5 °C in the south-western coast and Åland to -2 °C in northern Lapland (Drebs et al. 2002; Fig. 4a). The temperature gradient from northern to southern Finland, or from 70 to 60 degrees latitude, can be strong especially in winter. The thermal winter lasts on average for 100 days in south-western Finland, while in northern Finland it lasts for 200 days (Vehviläinen and Huttunen 1997; Drebs et al. 2002).

The observed (uncorrected) average annual precipitation sum in 1971–2000 varied from 350 mm in northern Lapland to around 700 mm in southern and central Finland (Fig. 4b, Drebs et al. 2002). Average annual maximum snow water equivalent ranges from less than 100 mm in the southern coast to more than 220 mm in southern Lapland (Fig. 5a). Evaporation is larger in southern Finland due to the longer growing season (Fig. 5b), and thus average runoff (Fig. 5c) varies less than average precipitation, from 200 to 450 mm per year (Mustonen 1986; Korhonen and Kuusisto 2010). The latitudinal gradient, the maritime climate from the Atlantic Ocean and the continental climate from Eurasia, the Scandinavian mountain range and the Baltic Sea all impact the climate in Finland (Atlas of Finland 1987; Käyhkö 2004).

The main land use types in Finland are forest (68 %), lakes (10 %), open areas such as peatland (10 %), agricultural land (8 %) and constructed land and roads (4 %) (Tilastokeskus 2002). Finland has plentiful water resources with the fifth largest amount of water available per capita in Europe, approximately 19 000 m^3/capita/year in 2001 (European Environment Agency 2005). Finland can be divided into three hydrological regions: catchments in the lake area in central Finland, small and medium size coastal rivers and large and medium size rivers of northern Finland (Fig.

6a) (Mustonen 1986; Korhonen and Kuusisto 2010). The same division is broadly followed by topography, soil types and land use, with forested, hilly till-covered areas in the north, flat clay areas with a high proportion of agricultural land near the coast and forested till areas with lakes in central Finland. The catchments in the lake area are characterized by numerous lakes. Finland has 187 888 lakes with an area of at least 0.05 ha and 2606 lakes with an area over 1.0 km².

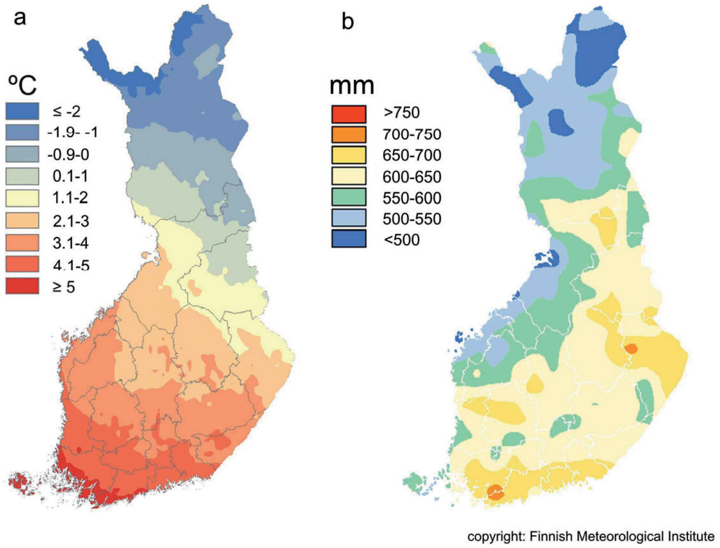

Figure 4. a) Average annual air temperature (°C) and b) average annual uncorrected precipitation sum (mm) in 1971–2000. (Finnish Meteorological Institute 2011c)

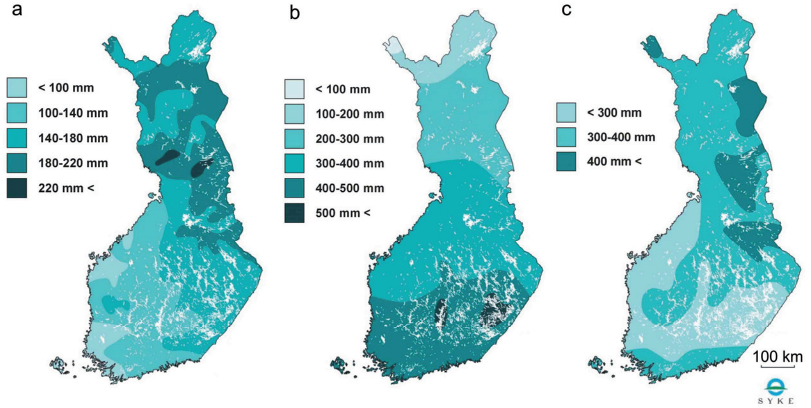

Figure 5. a) Average annual maximum snow water equivalent, b) average annual evaporation sum and c) average annual runoff sum in Finland (Mustonen 1986).

The seasonal cycle in hydrology in Finland is generally strong (Fig. 6b–d); snow accumulates during winter and melts in spring, causing an increase in runoff. Autumn rains cause another increase in runoff, which is usually substantially lower than the spring peak. This seasonal cycle is especially strong in northern Finland (Fig. 6b), but also in the small upstream lakes and rivers in the northern lake area and in the northernmost coastal rivers. In these areas most, if not all, of the annual maximum floods are caused by spring snowmelt. Further south in the coastal rivers major floods can be caused by either snowmelt or heavy rain events (Fig. 6d). In southern and south-western Finland air temperature in winter is quite frequently above 0 °C and thus snowmelt and flooding during winter are not uncommon (Fig. 6d). Since the catchments in the coastal area are small with low lake percentage, the discharge variations are large and rapid, and both droughts and floods are common (Fig. 6d, Korhonen and Kuusisto 2010). In the lake area, the large storage capacity of the numerous lakes smoothes the seasonal discharge variations (Fig. 6c). In the large central lakes and their outflow rivers floods are long-lasting high flows caused by either prolonged heavy rain or melting of deep snowpack, or both (Mustonen 1986). Due to the large storage capacities these floods are generated slowly by large amounts of excess water in contrast to short-term flood peaks in areas with minor surface water storage volume (Mustonen 1986).

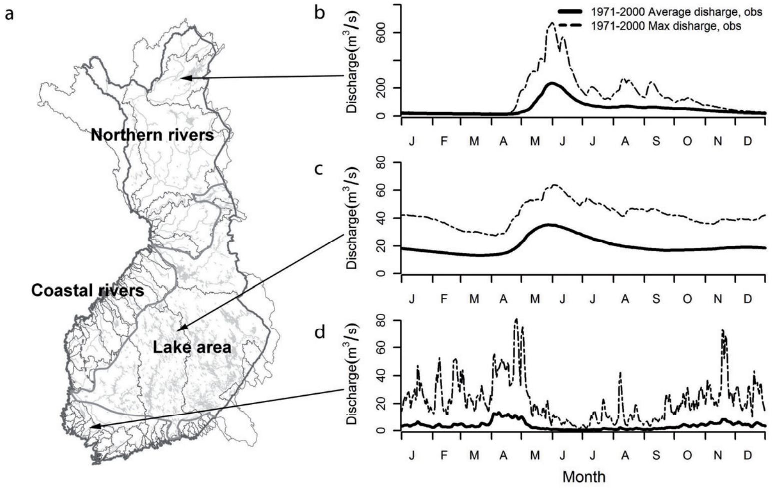

Figure 6. a) Hydrological regions and major catchments in Finland and b–d) example hydrographs from the hydrological regions at Juutuanjoki (b, norhern rivers), Nilakka (c, lake area) and Hypöistenkoski (d, coastal rivers). Graphs show the average (solid line) and maximum (dashed line) observed daily discharge during 1971–2000.

2.2 Observations

The air temperature and precipitation observations from the Finnish Meteorological Institute were used as input to the hydrological model WSFS (section 3.1). This included in 2010 approximately 190 stations with daily temperature observations at 2 m height and 250 stations with precipitation observations. Additional observations from 11 temperature and 16 precipitation observation stations in Norway, Sweden and Russia were provided by the Norwegian Meteorological Institute, the Swedish Meteorological and Hydrological Institute and the Hydrometeorological Centre of Russia and were used as model input in the cross-boundary catchments. Daily air temperature and precipitation observations were used as input of the simulations for 1961–2000 or 1971–2000 (papers I–IV) and in the calibration of the model for 1986–2009 or 1981–2008.

Other data used in this study were the discharge and water level observations, observations of snow water equivalent from snow courses, Class A pan evaporation measurements, and satellite data about the extent of the snow covered area. These data were used in the calibration of the hydrological model WSFS. In 2010 there were 295 discharge observation stations and 410 water level observation stations in Finland with continuous data on a daily scale. The number of snow courses, where snow depth and snow water equivalent were measured, was 150 and the number of Class A pan measurement sites was 10.

The measurement networks are denser in southern and central Finland than in the north. Precipitation gauging errors, which are especially large for solid precipitation (e.g. Førland et al. 1996), were taken into account by separate correction factors for solid and liquid precipitation in the hydrological model WSFS (Vehviläinen et al. 2005). Sources of uncertainty in the observations include e.g. the gauging error of precipitation, modifications to the observation network and change of the precipitation gauge type over the years (Mustonen 1986), the shortcomings of the spatial coverage of the precipitation observation network, the extrapolation of rating curves to high water levels and discharges, possible increases in water levels due to ice dams and the impact of ice on winter water levels, which are adjusted with an ice reduction (Korhonen 2007).

2.3 Study catchments

The hydrological modelling was carried out at catchment-scale with the majority of the study catchments having areas between 80 and 25 000 km^2.

The smallest catchment area was 0.7 km² in paper (I), whereas the second smallest catchment area was 66 km² and the largest 61 000 km². Discharge was simulated at rivers or lake outlets altogether for 98 different catchments, although the discharge series were not all independent because some catchments are located within the drainage areas of others.

Two approaches were used: case studies using one to four study catchments (papers II, III and V) and modelling large numbers of study catchments for producing an overview over the whole of Finland (papers I and IV).

2.3.1 High hazard dams (I)

High hazard dams (called category 1-dams, previously P-dams) are dams that cause risk to human life or health or considerable and obvious risk to property and environment in the case of dam failure (Ministry of Agriculture and Forestry 1997; Maijala 2010). Climate change impacts on design floods of high hazard dams were studied in paper (I), which included 34 high hazard dams located in different parts of Finland (Fig. 7a). This includes all those high hazard dams in Finland in 2006 for which design flood is a relevant design criterion for the safety of the dam. Waste dams, where rivers do not interact with the reservoirs, were excluded. The largest catchment area of a high hazard dam is 61 071 km² at Imatrankoski dam. Imatrankoski is located in the river Vuoksi and the catchment area is the Vuoksi watershed, the largest catchment in Finland (Fig. 7a). The smallest catchment is around a small water supply reservoir with a catchment area of 0.74 km². Most of the dams (22 out of 34) are in connection with a reservoir or lake that can be regulated by the dam, but 35 % of the dams (12 out of 34) are run-off-river type dams with negligible storage capacities. Lake percentage of the catchment areas varies from 0 % to 52 %. The 52 % lake percentage is for the smallest catchment, whereas the second largest lake percentage is 22%.

2.3.2 Flood study catchments (IV)

In 67 catchments in Finland, changes in 100-year floods due to climate change were estimated in order to produce a general overview for the country (paper IV) (Fig. 7b). The catchments were chosen to cover many types and sizes of catchments with relatively long and good-quality discharge observations. The catchments had an average of 67 years of daily discharge observations with a minimum of 29 years. The catchment areas vary from 86 km² to 61 000 km² and the lake percentage from zero to 22 %. Some smaller catchments are located nested within the larger catchments, and therefore the discharge series are not totally independent of each other.

Unregulated catchments were preferred in the selection. However, in order to include all types of catchments and to represent the whole of Finland and all the important flood risk areas, 15 catchments affected by regulation were included. In nine of the 15 catchments the impact of regulation is negligible, but at six locations (Kallavesi, Vuoksi, Kymijoki, Peltokoski, Harjavalta and Isohaara, marked with squares in Fig. 7b) the effect of regulation on daily discharge is notable (the daily discharges differ on average by more than 5 % from the natural situation).

Five of the flood study catchments are also locations for high hazard dams (Isohaara in the river Kemijoki, Raasakka in the river Iijoki, Harjavalta in the river Kokemäenjoki, Imatrankoski in the river Vuoksi, Kaltimo in the river Pielisjoki in the Vuoksi watershed, marked with crosses in Fig. 7b) and were therefore included in both papers (I) and (IV). These are all dams in large rivers with large catchment areas.

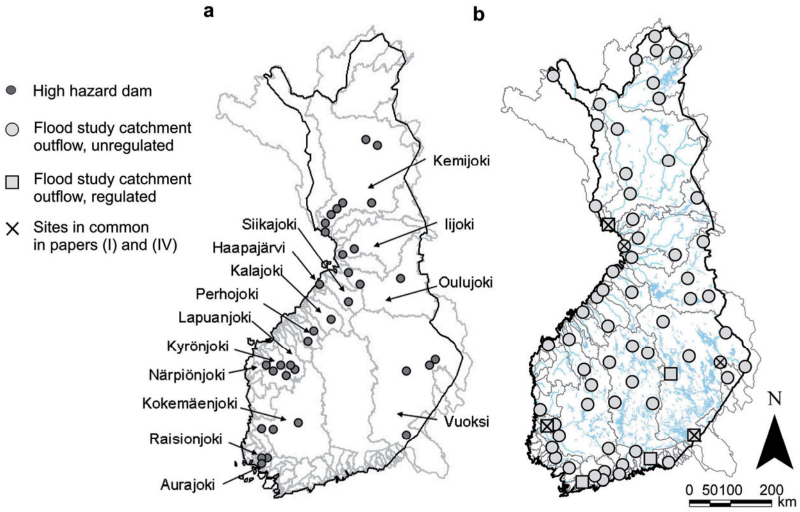

Figure 7. Study catchments. a) Locations of high hazard dams (dots) studied in paper (I) and the names of the major catchments in which they are located. b) Locations of the discharge observation stations of the cathcments studied in paper (IV).

2.3.3 Case study catchments (II, III, V)

Tana River catchment (Finnish Tenojoki, Fig. 8a) was the case study site for estimation of changes in floods, which was extended to a further analysis of climate change impacts on sediment transport (paper II). The Tana River catchment is located in the border area between Finland and Norway in sub-arctic northern Fennoscandia (Fig. 8a). The catchment area is 16 000 km^2 with two thirds on the Norwegian side of the border (Mansikkaniemi 1970).

The impact of climate change on lake regulation (paper III) was studied in the Vuoksi watershed in eastern Finland. With a catchment area of 61 000 km^2 at Imatrankoski, including 9 100 km^2 in Russia, it is the largest catchment in Finland (Fig. 8b). The catchment is within the lake area of Finland and has a lake percentage of 20 % with most of the largest lakes being regulated for benefits in hydropower, flood protection and recreational use. Three lakes, Lakes Saimaa, Pielinen and Syväri (Fig. 8b), were examined in this study. Lake Saimaa is the largest lake in Finland with a lake area of 4 380 km^2 and catchment area of 61 000 km^2. Lake Pielinen has a lake area of 890 km^2 and catchment area of 20 820 km^2 and Lake Syväri a lake area of 81 km^2 and catchment area of 2 430 km^2. These lakes represent different types of lakes in the Vuoksi watershed: a medium sized upstream regulated lake (Lake Syväri) and large and important central lakes (Lakes Saimaa and Pielinen).

Lake Syväri has been regulated since 1959 and the current regulation permits granted in 1988 define upper and lower limits for water levels. In Lakes Pielinen and Saimaa the outflow mostly follows the natural rating curve, where the outflow at a certain water level is always the same. Thus the outflow from the lake is usually the same as the natural, unregulated outflow. However, a dam exists in the outlets of both lakes, providing the technical possibility to change the outflow, and this option is used during both flood and drought conditions (Höytämö and Leiviskä 2009).

Discharge and water balance components of 1951–2100 were simulated in four catchments (Fig. 8a) in different hydrological regions (Fig. 6a) of Finland using transient climate scenarios (paper V). From north to south these catchments are Juutuanjoki (in the hydrological region northern rivers, Fig. 6a), Nilakka and Kitusjärvi (lake area), and Hypöistenkoski (coastal rivers) (Fig. 8a). The catchment areas of Juutuanjoki, Nilakka, Kitusjärvi and Hypöistenkoski are 5 160 km^2, 2 160 km^2, 550 km^2 and 350 km^2, respectively, and the lake percentages are 5%, 18%, 10% and 0%, respectively. These catchments were selected to represent different types of catchments in different hydrological regions in Finland. The other demands for the catchments were that they are unregulated and have long discharge observations from at least 1951 onwards. All the catchments were included in a study by Korhonen and Kuusisto (2010) and in paper (IV) to enable comparisons against their results.

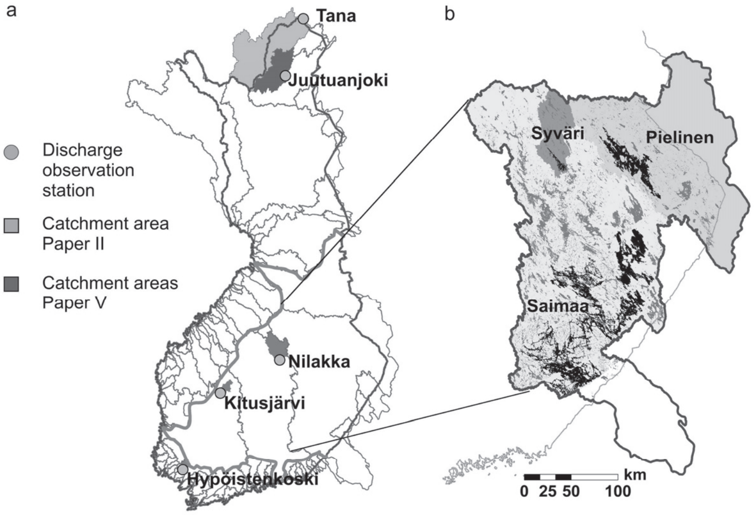

Figure 8. Case study areas a) in Finland in papers (II) and (V) and b) in the Vuoksi watershed in paper (III).

2.4 Climate scenarios

In each paper a slightly different set of climate scenarios (Table 1) was used, in part due to the continuous development of the climate scenarios with new and improved versions of climate models becoming available. Partly the different goals and methods of the studies stipulated different scenario needs. Three sets of scenarios can be identified (Table 1);

- the earliest scenarios from the model versions prior to 2006 from the Finnish Meteorological Institute (FMI) (Ruosteenoja et al. 2000) and Swedish Meteorological and Hydrological Institute (SMHI) (Fenger 2007) used in paper (I) (Table 1, scenarios number 23–27)
- the scenarios from GCMs in IPCC AR4 (1–15 in Table 1; IPCC 2007a) provided by FMI (Ruosteenoja et al. 2007; Jylhä et al. 2009) in 2007 and used in papers (II–IV) and
- the RCM scenarios (16–22 in Table 1) from the ENSEMBLES-project (van der Linden and Mitchell 2009) data archive available in 2009–2010 and used in papers (II–V)

The scenarios for each study were chosen based on the following criteria: availability, model performance in northern Europe (based on e.g. IPCC 2007a and Boberg et al. 2010), past experiences of the models, and their use in other studies in the northern hemisphere. Gridded data with 2.5 degree grid (~250 km) for GCMs (Table 1, 1–15) and 0.25 degree (~25 km)

(Table 1, 16–21) or 0.5 degree (~50 km) (Table 1, 22–26) grid for RCMs was used, except for scenario 27, which was used as an average value for the whole of Finland. From the gridded data, the values (in paper V) or changes (in papers I–IV) of the meteorological variables for each sub-catchment of the WSFS hydrological model were calculated based on four closest grid points and the distance of the center point of the sub-catchment from them.

Table 1. Climate scenarios used in papers (I–V)

No.	**GCM**	**RCM**	**Emission scenario**	**Abbreviation**	**Used in paper**
1	19 GCM mean	-	A2	Mean-A2	III, IV
2	19 GCM mean	-	A1B	Mean-A1B	III, IV
3	19 GCM mean	-	B1	Mean-B1	III, IV
4	ECHAM5/MPI-OM	-	A2	Echam5-A2	II, III, IV
5	ECHAM5/MPI-OM	-	A1B	Echam5-A1B	II, III, IV
6	ECHAM5/MPI-OM	-	B1	Echam5-B1	II, III, IV
7	UKMO-HadCM3-Q0[a]	-	A2	HadCM3-A2	II, III, IV
8	UKMO-HadCM3-Q0[a]	-	A1B	HadCM3-A1B	II, III, IV
9	UKMO-HadCM3-Q0[a]	-	B1	HadCM3-B1	II, III, IV
10	CCSM3	-	A2	CCSM3-A2	III, IV
11	CCSM3	-	A1B	CCSM3-A1B	III, IV
12	CCSM3	-	B1	CCSM3-B1	III, IV
13	CNMR-CM3	-	A2	CNMR-A2	IV
14	CNMR-CM3	-	A1B	CNMR-A1B	IV
15	CNMR-CM3	-	B1	CNMR-B1	IV
16	ECHAM5/MPI-OM	RCA3	A1B	RCA3-E-A1B	IV
17	ECHAM5/MPI-OM	REMO	A1B	REMO-E-A1B	IV, V
18	UKMO-HadCM3-Q3[b]	RCA3	A1B	RCA3-H-A1B	IV, V
19	UKMO-HadCM3-Q0[a]	HadRM	A1B	HadRM-H-A1B	IV, V
20	ARPEGE/CNMR-CM3	HIRHAM	A1B	HIRH-A-A1B	IV, V
21	UKMO-HadCM3-Q16[c]	RCA3 (C4I[d])	A1B	C4I Had a1b	II, III
22	ECHAM5/MPI-OM	RCA3 (50km)	A1B	SMHI Ec5 a1b	II, III
23	HadAM3H	RCAO	A2	RH A2	I
24	HadAM3H	RCAO	B2	RH B2	I
25	ECHAM4/OPYC3	RCAO	A2	RE A2	I
26	ECHAM4/OPYC3	RCAO	B2	RE B2	I
27	HadCM2	-	IS92a	HadCM2	I

[a] mean sensitivity version (Collins et al. 2005)
[b] low sensitivity version (Collins et al. 2005)
[c] high sensitivity version (Collins et al. 2005)
[d] different version of the RCA3 model run by Community Climate Change Consortium for Ireland (C4I)

The climate scenarios listed in Table 1 are from different versions of four GCMs and use three SRES (IPCC 2000) emission scenarios (A2, B1 and A1B) and one IS92a emission scenario from a previous set of climate scenarios published in 1992 (IPCC 1992). In addition five RCMs (some with several versions) were used. The RCM scenarios used different versions of three GCMs as boundary conditions. In addition a mean scenario, which was calculated by FMI as the mean of 19 GCMs from IPCC AR4 (IPCC 2007a; Jylhä et al. 2009) for three emission scenarios, was used in papers (III and IV). Altogether, 27 climate scenarios were used and the number of scenarios in individual studies varied from four (paper V) to twenty (paper IV).

The time periods in the studies were 2010–2039 (papers III, IV), 2040–2069 (paper III) and 2070–2099 (papers I–IV), whereas transient simulations of 1951–2099 were carried out in paper (V). The control period was 1971–2000, except in paper (V) 1961–2000. The climate model results used were the daily average air temperature at 2 m height and the daily average areal precipitation of each grid cell. The increase in annual temperature from the control period to 2070–2099 projected by the 27 climate scenarios in Finland varied from 1.8 to 5.4 ºC, and the increase in annual precipitation was between 8 and 34 %.

By using both GCM and RCM results in hydrological modelling in papers (I, II, III and IV) the advantages of both model types can be combined (Fronzek and Carter 2007). The advantage for GCMs is the existence of several models with different emission scenarios, while the RCMs include a more accurate representation of spatial variation especially in precipitation in scales smaller than the GCM grid size (110–250 km) (Wood et al. 2004; Christensen and Christensen 2007).

2.5 Design precipitation

The design precipitation is a precipitation of certain intensity, duration and frequency (e.g. mm per hour, day, week or month with a certain return period) used for the design of a structure (Durrans and Kirby 2004). The design precipitation in paper (I) was a two week precipitation sequence similar to that used in the Swedish guidelines for design flood evaluation (Flödeskommittén 1990; Harlin 1992) and with values defined in mm/d for each day of the 14-day period. The design precipitation was used in paper (I) to create a design flood of required return period, in this case 5 000 to 10 000 years, which is the design criteria for high hazard dams in Finland (Ministry of Agriculture and Forestry 1997). The design precipitations for Finland were estimated based on precipitation observations from 1959–1998 and results of frequency analysis in a report by FMI (Solantie and Uusitalo 2000). The design precipitation used should have a return period of approximately 1 000 years. The magnitude and the distribution of the 14 day design precipitation (example in Fig. 9) for each one of the 34 dams was estimated as an areal value for the entire upstream catchment area based on Solantie and Uusitalo (2000). Solantie and Uusitalo (2000) presented maps and tables for the estimation of the design precipitation depending on the time of year, the size of the area in question and the location in Finland.

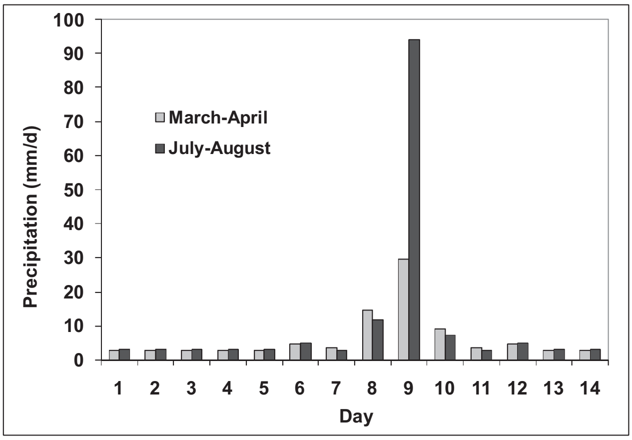

Figure 9. Example of design precipitation in March–April and July–August at Pahkakoski dam in the river Iijoki catchment (paper I, based on Solantie and Uusitalo 2000)

2.5.1 Change in design precipitation due to climate change

Since extreme precipitation is usually estimated to change differently than the average precipitation (Palmer and Räisänen 2002; Beniston et al. 2007), the change in the design precipitation due to climate change was evaluated separately. Tuomenvirta et al. (2000) estimated the changes in design precipitation by 2070–2099 with the results from HadCM2 global climate model and emission scenario IS92a. The estimation of changes in design floods by 2070–2099 (paper I) was carried out using two different scenarios for the design precipitation change based on Tuomenvirta et al. (2000) in order to produce a range of possible results. In the smaller case the change in design precipitation was from 12 to 40 % depending on the month in question and in the larger case from 35 to 60 % in large catchment areas and from 35 to 85 % in small catchment areas (paper I, Fig. 5, Tuomenvirta et al. 2000).

3 Methods

3.1 Hydrological model

The hydrological model used in this thesis and papers (I–V) was the Watershed Simulation and Forecasting System (WSFS), which was developed in the National Board of Waters (Vehviläinen 1982) and later at SYKE (Vehviläinen et al. 2005). WSFS is operated at SYKE and is used as the national hydrological forecasting and flood warning system (Finnish Environment Institute 2011). WSFS is also used for regulation planning and research purposes e.g. in climate change and nutrient transport studies (Vehviläinen and Huttunen 1997; Huttunen et al. 2008). The main part of WSFS is a conceptual rainfall-runoff model based on the HBV model developed at SMHI (Swedish Meteorological and Hydrological Institute) (Bergström 1976). The basic structure of WSFS is HBV model structure, but since the models have been developed separately since the 1980s there are many differences, e.g. in the river routing, catchment description and in some process models such as the snow model (Vehviläinen 1992; Vehviläinen et al. 2005).

The WSFS hydrological model consists of small lumped sub-catchments, with an average size of 60 km^2 (20–500 km^2) and numbering over 6 000 in Finland (Vehviläinen et al. 2005). Water balance simulations are conducted for each sub-catchment, and sub-catchments are connected to produce the water balance and simulate water storage in the river and lake network within the entire catchment. The sub-models in WSFS include a precipitation model calculating areal value and form for precipitation, a snow model based on the temperature-index (degree-day) approach, a rainfall-runoff model with three storages, and models for lake and river routing (Fig. 10). WSFS includes approximately 2 600 lakes, which means that all lakes in Finland with an area over 1 km^2 are included. The data of the lakes is obtained from the national data base compiled by SYKE.

The input data to the hydrological model in all papers was daily precipitation and air temperature, either observed and in climate change simulations perturbed (papers I–IV), or simulated by RCM (paper V). Potential evapotranspiration (PET) was calculated in WSFS with an empirical equation that uses air temperature, precipitation and time of year (an index for available net radiation) (Vehviläinen and Huttunen 1997). This PET routine has been calibrated and verified against observations of Class A pan evaporation values (Vehviläinen and Huttunen 1997). The actual evapotranspiration was calculated as a function of PET and soil moisture deficit produced by the rainfall-runoff routine.

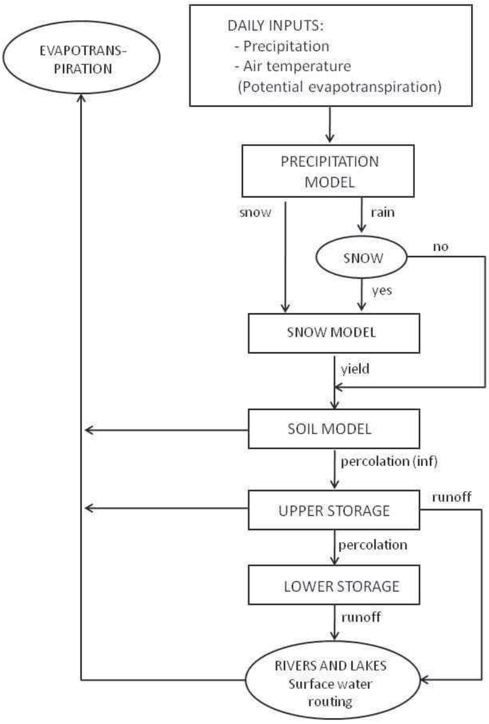

Figure 10. The basic structure of the WSFS model (Vehviläinen et al. 2005).

WSFS was calibrated against observations of snow water equivalent, extent of snow covered area, lake water level and discharge. The data used in calibration were from the national archive operated by SYKE. Since the studies (papers I–V) included in this thesis were completed over a period of seven years, different papers use slightly different versions of the WSFS, which have different parameter sets from different calibrations. The model was also constantly developed during the time period from 2004 to 2010.

The most recent set of parameters used in paper (V) was calibrated against the data from the period 1986–2009. The calibration was performed by optimization of the sum of the square of the difference between the observed and simulated water equivalent of snow, discharge, water level and the difference between simulated extent of snow-covered area and observed snow cover from satellite pictures. The weights for calibration variables were selected based on estimated relative reliabilities of the observed values and on experience of model performance with different weights. A modification of the direct search Hooke-Jeeves optimization algorithm (Hooke and Jeeves 1961) was used in the automatic calibration (Vehviläinen et al. 2005). Parameters were calibrated for the sub-models of areal air temperature and precipitation, snow accumulation and melt, evapotranspiration, runoff generation, storages and river and lake routing. Each study used only one optimal parameter set, although these were different in different studies due to new calibrations. Validation of the hydrological model results is presented in the results in section 4.1.

Since many of Finland's numerous lakes are regulated, regulation must be included in the models for most of the large catchments. Lake regulation, which was relevant in catchments studied in papers (I, III, IV), was described with model operating rules, where a certain water level for each day corresponds to a certain outflow.

In paper (I) the operating rule was tailored for each design flood event based on dam outflow capacity, regulation permits and observed outflows. In papers (III, IV) the same operating rule was used for the entire 30 year simulation period. In the latter case the results in the control period corresponded on average to the actual regulation, but the regulation was not necessarily optimal in all individual years. Modifications were made to the operation rules in papers (III, IV) in simulation of future time periods in order to improve the functioning of the operating rules in the changing climate with different timing and magnitude of spring floods. In paper (III) an operating rule suggested by Verta et al. (2007) was used as the modified regulation for Lake Pielinen (paper III, Fig. 2).

3.2 Modelling climate change impacts on hydrology

When using a hydrological model to evaluate climate change impacts, the way in which the climate change signal is transferred from the climate model to the hydrological model is one of the key issues. When using GCM results the downscaling to appropriate scale for the hydrological model is important and this is usually conducted with one of the two main methodologies, statistical and dynamical downscaling (Fowler et al. 2007).

Two methods were used in this study for the transfer of the climate signal to the hydrological model; the delta change approach (II–IV) (Fig. 11a) and the direct RCM data, where the daily bias corrected results from RCM are used as input to the hydrological model (V) (Fig. 11b). The delta change approach can be classified as the simplest method of statistical downscaling

(Fowler et al. 2007), whereas the direct RCM data relies on data dynamically downscaled by the RCM with an additional bias correction step. Changes in design floods of high hazard dams (paper I) were estimated with a separate method described in section 3.3.

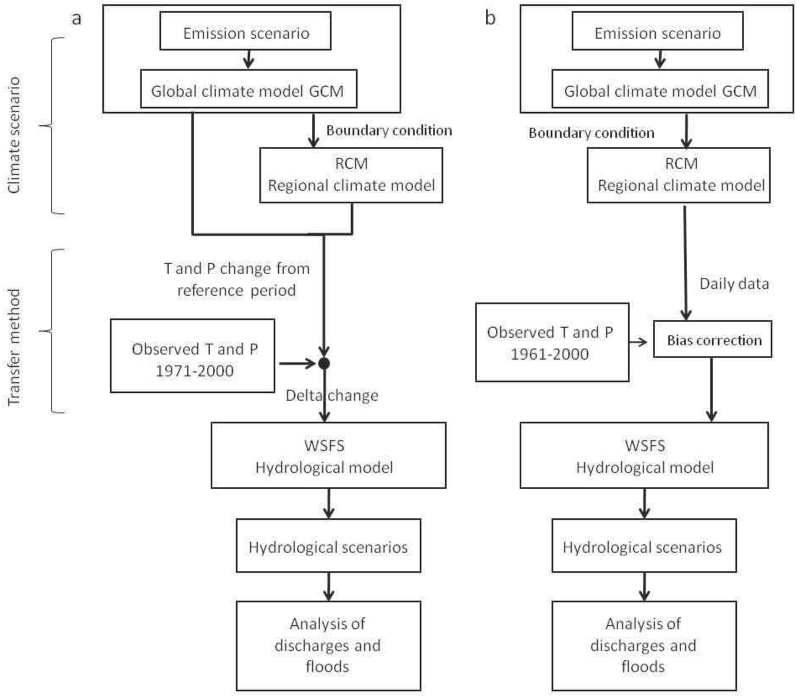

Figure 11. The study methodologies used in papers (II–V). a) The delta change approach used in papers (II–IV) and b) the direct RCM data approach used in paper (V). T is air temperature and P is precipitation.

3.2.1 Delta change approach

Probably the most common method used thus far in impact studies to transfer the climate change signal from the climate model to the hydrological model is the delta change approach (also called the perturbation or change factor approach) (Arnell 1999; Hay et al. 2000; Minville et al. 2008). In this approach the observed meteorological data from a past control period is used as the reference for past climate, and projected changes of the meteorological variables due to climate change from climate scenarios are added to the observed values (Fig. 11a). The hydrological model is then run with the perturbed variables as inputs and the simulated hydrology is compared to corresponding values simulated with the observed input.

In these studies the monthly changes in air temperature (in °C) and precipitation (in %) projected by the climate scenarios are added to (for temperature) to or multiplied by (for precipitation) the observed values of temperature and precipitation, respectively, from the control period. Results from either GCMs or RCMs can be used to provide the monthly change factors for temperature an precipitation. The control period was 1971–2000 in papers (II– IV).

In papers (I, II and IV) air temperature change was calculated with a modification of the standard delta change method, proposed by Andréasson et al. (2004) (Eq. 1). According to RCM results, cold days in Finland especially in winter will warm more than the average monthly temperature (Räisänen et al. 2004; IPCC 2007a) and therefore the distribution, not only average values, of temperature will also change. The delta change approach therefore included a temperature-dependent component to relate the temperature change to the original control period temperature with seasonal linear transfer functions (Andréasson et al. 2004). In papers (II and IV) the temperature changes in the 30 year period were scaled to match the average monthly temperature change to the monthly change in the climate scenario (Eq. 1).

$$T_{mod} = T_{obs} + \Delta T = T_{obs} + s_m(a_s T_{obs} + b_s) \qquad (1)$$

where T_{mod} is the modified daily air temperature, T_{obs} is the observed daily air temperature in the control period, ΔT is the temperature change, s_m is the monthly scaling factor scaling the monthly changes to the monthly changes of the climate scenario, and a_s and b_s are the coefficients of the seasonal linear transfer functions estimated from the daily air temperatures of the RCMs. The coefficients for seasonal transfer functions were estimated for five regions (north, north-central, west, central, and east) in Finland and for each RCM scenario. In paper (III) the delta change approach with only monthly changes in temperature was used, because the daily RCM data used to estimate the coefficients of Equation (1) were not yet available at the time of the study. The study region in paper (III) is also less affected by the daily variability of temperature than other catchments in Finland due to the long lake routes.

When compared with the standard delta change approach, the main influence of the temperature-dependent temperature change is in snow accumulation when temperature is close to zero. The method (Eq. 1) has very little influence on mean annual discharge values, but affects seasonal values and produces lower winter discharge and higher spring snowmelt discharge than the seasonal values obtained with the standard delta change approach.

In southern Finland, the largest influence of the temperature-dependent delta change approach is during the early part of the 21st century, since by the end of the century the permanent snow cover has become rare. In northern Finland the influence is larger during the end of the century. In more temperate climates with no permanent snow cover the effect of the temperature-dependent temperature change would presumably be small.

3.2.2 Direct bias corrected RCM data

In the second method, used in paper (V), the daily air temperature and precipitation simulated by RCMs was used as input to the hydrological model after a bias correction (Fig. 11b). The bias correction method was the quantile-quantile mapping (Wood et al. 2004; Boé et al. 2007; Déqué 2007; Seguí et al. 2010) and the control period was 1961–2000.

A bias correction aims at removing the systematic bias in RCM data in the control period compared to the observed values of the same period. Bias correction is necessary since RCM biases not only affect the absolute values, but can also influence the relative changes (Leander et al. 2008). Since the tails of the distribution often play the most important role in hydrological applications, the methods having variable bias correction in different parts of the distribution are usually most suitable (Déqué 2007). The method chosen in paper (V) was the quantile-quantile mapping that was recently used in several studies (Wood et al. 2004; Boé et al. 2007; Déqué 2007; Seguí et al. 2010). In this method the simulated distributions (in practice the cumulative density functions, CDFs) of air temperature and precipitation during the control period are corrected to match their observed distributions. The differences between the simulated and observed CDFs are calculated for 99 percentiles and a linear interpolation is performed between the percentiles. The value of the closest quantile was used outside the 99 percent tail of the distribution. Through the adjustments made in the precipitation distribution, the method corrects the wet-day number of the RCM simulated precipitation to correspond to the observed wet-day number.

The bias corrections were estimated for each RCM grid point (0.25 degree grid) and for each month as a three month moving average. The same corrections estimated for 1961–2000 were applied to the entire period 1951–2099 with the assumption of a constant correction function (Seguí et al. 2010).

3.3 Modelling extreme floods

In paper (I) changes in design floods of high hazard dams in Finland were evaluated. According to the Finnish dam safety law and code of practice (Ministry of Agriculture and Forestry 1997), the design floods of high hazard dams should have a return period of between 5 000 and 10 000 years in the current conditions. To estimate such extreme floods a different methodology based on combining an extreme precipitation event with other critical hydrological conditions was used for these dams.

The method used to calculate the design floods is based on the Swedish design flood calculation method described in the Swedish guidelines for design flood evaluation for large dams (Flödeskommittén 1990) with some modifications. In the method used, the design flood was estimated by combining an extreme precipitation episode with other critical hydrological conditions in a hydrological model in a way that generates an extreme flood (Harlin 1992). A design precipitation period with a length of 14 days and an approximate return period of 1 000 years was moved day by day through the 40-year control period 1961–2000 with the design precipitation replacing the observed precipitation for the 14-day time period (Fig. 12). The timing of the design precipitation period which together with the other critical flood generating factors produced the most severe flood, was identified and this flood was considered to be the design flood of the dam. The most severe flood was the flood that caused the highest outflow demand and water level on the dam.

This procedure for estimating the design flood was first performed in the control period with the observed weather data from 1961–2000 and a design precipitation estimated from observations (Solantie and Uusitalo 2000, section 2.5). Then the same process was carried out for the future time period 2070–2100 (paper I, Fig. 4). The control period air temperature and precipitation series based on observations of 1961–2000 were changed with the delta change approach (Section 3.2.1) including a temperature-dependent temperature change based on results provided by Rummukainen et al. (2000). In addition, the change in design precipitation caused by climate change, which was estimated by FMI (Tuomenvirta et al. 2000, section 2.5.1), was carried out separately. The simulations for 2070–2100 were carried out with five climate scenarios from GCMs and RCMs (Table 1, 23–27) and two changes in design precipitation, which altogether lead to ten scenarios for the change in design floods.

Since the design floods were based on the combination of rare events, it is difficult to evaluate the joint probability and the exact return period of the simulated design floods. The design floods calculated with the adopted method are assumed, on average, to be rare enough to be suitable for the design of high hazard dams, i.e. their return period is at least 5 000 years (see section 4.1.2 for verification of this assumption).

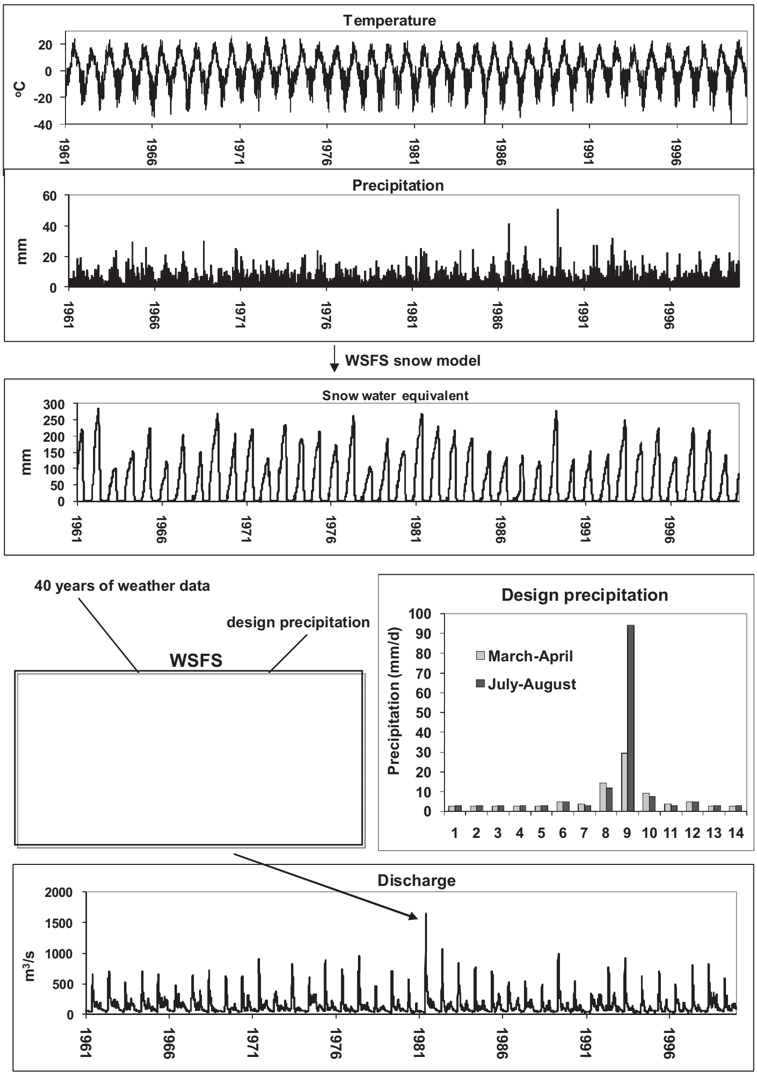

Figure 12. Presentation of the method used to simulate design floods for high hazard dams (paper I).

The method used was chosen because it can simulate floods with high return periods and it is versatile enough to be used in catchments with different physical properties and for both rainfall and snowmelt floods (Harlin 1992). With this method, the shape of the design flood can change when the timing of the flood event changes. The 14-day design precipitation has a shape that can produce short term floods when the largest one day design precipitation is most important factor in the flood generation process. Long lasting floods are generated when the 14-day sequence is combined with observed heavy precipitation just before and /or after the design precipitation period. An additional advantage is that the method does not necessarily require discharge observations from the dam site as long as the hydrological model is set up for the catchments with the dam. The disadvantages include certain subjectivity, especially in the choice of the regulation strategy during the design flood, and uncertainty of the capability of the hydrological model to simulate accurately extreme floods larger than the events in the calibration and validation data (Seibert 2003). However, evaluation of extreme floods always contains uncertainty, regardless of the method used. The main goal of the study was to evaluate the relative changes in design floods caused by climate change, not the absolute values of the design floods.

3.4 Statistical and frequency analysis

Magnitudes of floods with certain return period based on the simulated or observed discharges were estimated with frequency analysis in papers (I, II, and IV). In paper (II) floods with return periods of 2 and 250 years were estimated and in paper (IV) the 100-year floods were estimated. In paper (I) 5 000- and 10 000-year floods were calculated from observations for comparison and validation of the simulated design floods. The annual maximum discharges were first identified and then the frequency distribution was fitted to the unhomogenised annual maximum values of 30 years of simulated discharges (in papers II and IV) or observed discharges (in paper I).

The distribution used in papers (I, II and IV) was the Gumbel (Extreme Value type I) distribution, since it is the most common and officially recommended distribution applied in flood analyses in Finland (Ministry of Agriculture and Forestry 1997). With a relatively short length of the series analysed (30 years) a two parameter distribution, such as the Gumbel distribution, with a prescribed shape parameter, provides more stable results than three parameter distributions when extrapolating to rare floods (Ward 1978).

In paper (I) three frequency distributions were used in order to estimate the uncertainty involved in the choice of the frequency distribution when estimating floods with extremely long return periods. In addition to the Gumbel distribution Pearson 3 and log-Pearson 3 distributions were also tested. The parameters of the frequency distributions were estimated with the method of moments presented by Kite (1977).

In paper (IV) the hydrological year from September to August was used to identify the annual maximum values in order to avoid picking the same flood event twice during long lasting winter floods, which are expected to become common in the large catchments in the future. When using the hydrological year instead of the calendar year in Finland the same problem does not usually occur, since summer floods occur only in small catchments where floods are short-lasting. In papers (I, II) calendar year was used since winter floods do not occur as far north as the Tana River (II) and are rare during the observation period (I).

Statistical analysis of trends in the transient hydrological scenarios was performed in paper (V). The significances of the trends in mean annual discharges (calendar year), seasonal mean discharges for winter (December, January, February), spring (March, April, May), summer (June, July, August), and autumn (September, October, November), as well as annual maximum and minimum discharge were tested with a non-parametric Mann-Kendall trend test. The risk level used was 5 %. A non-parametric linear Sen's slope estimator (Sen 1968) was used to calculate the trend magnitude. If the data had statistically significant ($p<0.05$) autocorrelation, serial autocorrelation was removed from the time series with the pre-whitening method of Wang and Swail (2001) and the significance of the trend was tested from the pre-whitened time series.

In paper (IV) the influence of catchment properties and climatological characteristics on the climate change impact on floods was estimated by calculating correlations between the results (the simulated average change in 100-year floods from 20 climate scenarios in the study catchments) and the explanatory variables. The coefficient of multiple correlation R was used as an estimate of the combined influence of multiple variables on the dependent variable. The linear relationship between the results and multiple variables was calculated by optimising Eq. (2) by the least squares approach to yield the highest coefficient of multiple correlation R.

$$[y]=a_1[x_1]+a_2[x_2]+...+a_n[x_n]+b \qquad (2)$$

Where $[y]$ is the vector of dependent variables (results for each study catchments), a_1–a_n are the parameters, b is the constant intercept and $[x_i]$ are the vectors of the explanatory variables (properties of the study catchments, Table 4).

4 Results and Discussion

The results and discussion presented in this section are mostly based on material presented in papers (I–V) with the following additions. The results in Tables 2, 3, 5 and 6 as well as in Figures 13, 15 and 18 are from studies described in papers (IV) and (V), but are not presented in the papers in this form. From paper (IV), in which 67 study catchments and 20 climate scenarios were studied, the results from four catchments and climate scenarios in common with paper (V) are shown here in more detail to enable comparisons between the results of the two papers. Sections (4.2.1 and 4.3.2) also include comparisons between the results of papers (I), (IV) and (V) and a discussion on the differences in methods, which are not presented in the papers.

4.1 Model validation (I–V)

The performance of the hydrological model with the observed air temperature and precipitation as input was assessed with the Nash-Sutcliffe efficiency criterion R^2 (Nash and Sutcliffe 1970). It was used to compare the daily simulated discharge or water level values to the corresponding observed values. A value of 1 represents a perfect fit between observed and modelled data, whereas a value of 0 indicates that the model predictions are as accurate as the mean of the observed data.

In paper (II) R^2 for the control period discharge was 0.86 at Polmak in Tana River. In paper (III) R^2 for water levels was 0.93 for Lake Pielinen, 0.86 for Lake Syväri and 0.93 for Lake Saimaa in the calibration period 1981–2006 and 0.88, 0.72 and 0.82, respectively, for the validation period of 1971–1980 and 2007–2008.

In the 67 study catchments in paper (IV), R^2 for discharges was on average 0.87 (range 0.67–0.94) for the control period 1971–2000. For the calibration period 1981–2008 R^2 was on average 0.86 (0.60–0.94) and for the validation period 1971–1980 0.86 (0.66–0.95). For the four catchments in paper (V) R^2 was on average 0.83 (0.61–0.92) for the calibration period

1986–2009 and 0.81 (0.71–0.89) for the validation period 1961–1985. The model performance was similar in the calibration and validation periods.

The differences between the modelled and observed discharges are caused mainly by:

- model structure and parameter errors
- errors in discharge and water level observations caused e.g. by rating curve extrapolation and ice jams
- errors in areal precipitation and to a lesser extent temperature estimates that arise from deficiencies in the observation network
- differences between modelled and observed lake regulation in catchments affected by regulation.

4.1.1 Comparison of present design floods (I)

The simulated control period design floods in paper (I) should have a return period of 5 000 to 10 000 years in order to match the design criteria of high hazard dams in Finland (Ministry of Agriculture and Forestry 1997). To establish this, the simulated floods of the control period 1961–2000 were compared with 5 000- and 10 000-year flood estimates calculated with three frequency distributions for six dams, where there were long discharge observation series (on average 74 years) and the assumptions of independent and random observations were met. Even with the relatively long time series, the extrapolation of frequency distributions to such extreme return periods as 5 000–10 000 years contains large uncertainties and must be viewed with extreme caution (Ward 1978).

The simulated design floods were of the same magnitude or smaller than the estimated flood magnitudes from Gumbel distribution and of the same magnitude or larger than estimated from Pearson 3 and log-Pearson 3 distributions (paper I, Table 3). There were large differences between the results from the different distributions, mainly because the estimated coefficient of skewness in Pearson 3 and log-Pearson 3 distributions was considerably smaller than the predetermined coefficient of skewness in the Gumbel distribution. When extrapolating to long return periods this led to considerably larger flood estimates with the Gumbel distribution than with the other two distributions. Based on these results, the model simulated floods should have approximately correct return periods for use as design floods for high hazard dams in the estimation of climate change impacts on design floods.

4.1.2 Bias corrected RCM data (V)

In paper (V) the daily air temperature and precipitation values from four RCMs were bias corrected with quantile-quantile mapping method (section 3.2.2) and the resulting time series were compared against observations during 1961–2000 in the four study catchments. The bias correction removed most of the bias in temperature and precipitation data. The average bias in temperature decreased from -2.2–+0.9 ºC in the uncorrected values to less than 0.1 ºC with the bias correction and the precipitation bias decreased from +14–+30 % to approximately -3 % compared to observed values (paper V, Table 3).

When the uncorrected air temperature and precipitation values from the RCMs were used as input to the hydrological model, the average discharges of the four study catchments were overestimated by 15–63% with different scenarios in 1961–2000 (paper V, Table 4). This was of similar magnitude to the overestimation discharge by +6–+72 % when using RCM precipitation and temperature as inputs to a hydrological model in the Baltic Sea drainage basin reported by Graham et al. (2007b). With the bias correction the simulated average discharge was 2–3 % smaller than the reference discharge simulated with observed temperature and precipitation input. The reference average discharge in turn was approximately 5 % smaller than the observed average discharge. The differences between simulated and observed mean annual discharge values were not statistically significant when tested with the student’s t-test at 5 % confidence level. However, there were significant differences in the simulated and observed seasonal mean discharges on average in 6 % of scenarios and seasons, which is close to the expected non-acceptance rate with 5 % confidence level. The mean annual maximum discharge simulated with the bias corrected RCM data was on average 8 % lower (-27–+14 %) than the corresponding observed values (paper V, Table 4).

These differences in simulated and observed discharges were caused by the structural and parameter uncertainty of the hydrological model, by the remaining biases in the RCM temperature and precipitation series, and by natural variability between different realisations of the control period climate in RCM and in observations. As noted by Wood et al. (2004), the monthly temporal scale and separate correction of temperature and precipitation fails to correct subtle differences between climate model simulations and observed temperature and precipitation.

4.2 Hydrology and climate change (III, IV, V)

Papers (III–V) all project similar changes in hydrology by the end of the century; large changes in seasonal discharge dynamics and on average a moderate increase in mean annual discharge. The projected average change from 20 climate scenarios in mean annual discharge by 2070–99 compared to the control period (paper IV) was a 10 % increase (Table 2). The variability in mean annual discharge between 20 climate scenarios (paper IV) was however large, from a 2 % decrease to a 29 % increase (Table 2). In individual catchments there were even larger differences, from 20 % decrease to 42 % increase in mean annual discharge. Generally the increases in mean annual discharge projected to south-western Finland were slightly smaller than the increases in eastern and northern Finland, which was mainly caused by larger increases in precipitation further north and east in most climate scenarios.

Table 2. Changes (%) in annual and seasonal mean discharge from 1971–2000 to 2070–2099 in Finland and its different hydrological regions (Fig. 6a). The average, maximum (max) and minimum (min) changes from 20 scenarios (based on 67 study catchments in paper (IV), Fig. 7b). Results are from the delta change approach.

	Annual (%)	Winter (%)	Spring (%)	Summer (%)	Autumn (%)
Finland					
Average	9.9	120	5.4	-31	16
Max	29	170	11	-5.1	49
Min	-1.9	61	-9.8	-47	-3.1
Northern rivers					
Average	10	120	30	-31	30
Max	19	220	43	-16	46
Min	2.3	50	12	-44	13
Coastal rivers					
Average	9.2	130	-30	-25	18
Max	34	170	-15	28	65
Min	-9.0	73	-49	-49	-14
Lake area					
Average	11	100	17	-36	3
Max	33	130	33	-13	39
Min	-3.7	61	2.5	-52	-19

The seasonal changes by 2070–99 were large, with increases in winter discharges and water levels and decreasing and earlier snowmelt discharge peaks (Table 2; Fig. 13). Winter discharges increased considerably (on average 120 %, Table 2) everywhere, whereas changes in spring discharge varied in different parts of the country. In coastal and southern parts of Finland the spring discharge values decreased (15–49 %), because the decrease in snow accumulation caused the spring snowmelt peaks almost to disappear (Table 2, Fig. 13 g, h). By the end of the century permanent winter with prolonged air temperature below freezing became rare in southern Finland. In the more northern parts of the country and in the lake areas with discharge retention due to lake storage capacity, the period of spring snowmelt currently lasts until the summer months (typically until June, Fig. 13 a, b). Earlier timing of spring snowmelt caused by warmer temperatures lead to an increase in spring (March–May) discharge (on average by 3 to 43 %), while summer discharge decreased by 13 to 52 % (Table 2). In coastal rivers the summer discharge on average decreased (25 %), but the scenarios with largest increases in summer precipitation produced increases in summer discharge. Autumn discharge on average increased due to increases in autumn precipitation, but differences between climate scenarios were considerable. In the lake area the increase in autumn discharge was smaller and with some scenarios the autumn discharge even decreased. This was mostly caused by increases in lake evaporation and by the smaller summer runoff affecting the autumn discharges due to retention in the lake routes.

In the lakes in the Vuoksi watershed studied in paper (III), the changes in mean annual water levels were rather small in most climate scenarios in Lake Pielinen and Lake Saimaa, but the seasonal changes were significant. The average seasonal (winter, spring, summer, autumn) changes in water levels in 2040–2069 and 2070–2099 from 14 climate scenarios were statistically significant (students t-test at 5% significance level), except in Lake Syväri during autumn. The water levels increased during winter and decreased during summer months. Already during 2010–39 the seasonal changes in water levels from the control period were on average statistically significant during most seasons. The variation between the results from 14 climate scenarios was however large (paper III, Table 2).

Statistical analysis of transient hydrological scenarios in 1951–2099 based on direct bias corrected RCM data revealed significant trends especially in seasonal mean discharge, but also large differences between the four catchments and four climate scenarios (paper V, Table 5). There were statistically significant trends in mean annual discharge in 1951–2099 in seven out of 16 cases (four climate scenarios and four catchments). In the northernmost catchment Juutuanjoki, there were increases in mean annual discharge with three out of four scenarios, whereas the other catchments only had increases with one scenario (the wettest scenario RCA3-H) (paper V, Fig. 7). In addition in the southernmost catchment Hypöistenkoski one scenario produced significantly decreasing mean annual discharge.

The increasing trend in winter discharge was statistically significant in all the catchments and all the scenarios in 1951–2099 (paper V, Table 5, Fig. 8). Trends in summer discharge were mostly decreasing, with one exception of increasing trend in the southernmost catchment Hypöistenkoski. In Juutuanjoki (northern river) and in Nilakka (large lake) spring discharge showed an increasing trend with all climate scenarios due to shift to earlier snowmelt peak during spring moths, whereas in the south in Hypöistenkoski spring discharge decreased as a result of less snow accumulated during the winter. During autumn the scenarios produced both increased and decreased discharges in all other catchments except in Juutuanjoki, where all scenarios produced increases.

The clearest and most consistent trends and changes in simulated discharges were related to increase of air temperature rather than the changes in precipitation. This is because the projected temperature increases are more consistent among the climate scenarios (Barnett et al. 2005) and are in relative terms more certain than the projected precipitation changes (Räisänen and Ruokolainen 2006). Thus far observed changes in discharge are also the ones related to shift in air temperature (Hisdal et al. 2007; Korhonen and Kuusisto 2010; Wilson et al. 2010). Some consistent trends related to precipitation changes were however found, such as increases in mean annual and autumn discharges in northern Finland, where the projected precipitation changes were larger than further south.

The results in papers (III–V) on changes in hydrology were in agreement with results from previous studies in Finland (Vehviläinen and Huttunen, 1997; Silander et al. 2006) and other Nordic countries (Andréasson et al. 2004; Beldring et al. 2006; Beldring et al. 2008; Graham et al. 2007a; Schneiderman et al. 2009). Mean annual runoff was projected to increase in northern and central Sweden and in most of Norway (Beldring et al. 2006), whereas different scenarios produced both increases and decreases in southern Sweden (Andréasson et al. 2004). Winter discharge was projected to increase in all studies and spring snowmelt discharge peaks occurred earlier (e.g. Andréasson et al. 2004; Beldring et al. 2008). Compared to previous studies in Finland this thesis and papers (III–V) produce more comprehensive results of projected changes in hydrology in Finland both in terms of spatial coverage and representation of climate change uncertainties with the use of several climate scenarios. The trend analysis of the transient hydrological scenarios produced with bias corrected RCM data as input of the hydrological model (paper V) is to the author's knowledge the first of its kind to be published in the Nordic countries to date. One of the few studies that use transient RCM scenarios as input to the hydrological model and analyse the resulting continuous time series was carried out in

Canada by Minville et al. (2010). They reported positive trends by 2099 in hydropower production, which is closely correlated to discharge. Another recent study by Kay and Jones (2012) estimated transient changes in flood frequency in the UK based on transient climate projections, and revealed increasing flood risk and non-linear trends with varying statistical significance.

4.2.1 Comparison of transfer methods (IV, V)

The effect of the method used to transfer the climate signal from the climate model to the hydrological model was also studied. The delta change approach (papers II–IV), and the direct bias corrected RCM data (V) were compared at four study catchments (Fig. 8a) with four RCM scenarios used in paper (V) (Fig. 13 and Table 3). The results from the delta change approach were a sub-set from the larger group of catchments and scenarios in paper (IV).

The comparison shows that the projected increases in mean annual discharge were similar, but slightly smaller (on average 2.5 percentage points) in the delta change approach than in the approach using direct RCM data (Table 3). Winter discharge was larger in the delta change approach than with the direct RCM data, except in Hypöistenkoski, while spring discharge was smaller except in Nilakka. Summer discharge was smaller in all catchments in the delta change approach than with the direct RCM data. Autumn discharge showed only small differences, with slightly smaller discharge in the delta change approach, except in Kitusjärvi.

Hydrographs of average daily discharge produced with the two methods are mostly similar (Fig. 13). The largest differences include earlier and smaller spring snowmelt discharge in Juutuanjoki in the delta change approach (Fig. 13a, b) and smaller summer discharge in all the catchments. It should be noted that the control period discharges were also different in the two approaches. In the delta change approach the observed temperature and precipitation are used as input to the hydrological model in the control period and simulated discharge is close to observed values (e.g. the average Nash-Sutcliffe efficiency criterion R^2 for the four catchments in the validation period was 0.81). On the other hand the direct RCM data approach uses the bias corrected RCM temperature and precipitation for the control period and differs more from observations. Year to year comparisons with observations are not possible, since the RCM simulated data is one realisation of the control period climate not related to the observed climate on a daily basis, and only the average statistical properties should be similar between the series (see section 4.1.2 for validation).

The comparison between discharge simulated with the delta change approach and with direct bias corrected RCM data is the first of its kind in Finland, and the first in catchments with a high lake percentage (Nilakka). In other countries several researchers have carried out similar comparisons (Graham et al. 2007a; Lenderink et al. 2007; Beldring et al. 2008; Yang et al. 2010). The authors of these studies found mostly relatively small differences in the future mean annual discharges produced by the different methods, but found differences in seasonal and extreme values. Especially the accumulation and melt of snow is sensitive to the methods used (Beldring et al. 2008), with the delta change approach usually producing larger decreases in snow accumulation than the direct RCM data. See also section 4.4 for more discussion on transfer methods.

Table 3. Changes (%) in annual and seasonal mean discharge from 1971–2000 to 2070–2099 with two methods of transferring the climate signal to the hydrological model. Average of four scenarios (scenarios in paper V) in four catchments (for locations see Fig. 8a).

	Juutuanjoki (%)	**Nilakka (%)**	**Kitusjärvi (%)**	**Hypöisten-koski (%)**
Delta change				
Annual	14.9	8.3	8.6	5.8
Spring	70.2	45.2	-4.1	-46.4
Summer	-35.3	-37.8	-51.6	7.4
Autumn	33.8	-14.0	4.4	12.5
Winter	89.4	56.8	119.5	77.0
Direct bias corrected RCM data				
Annual	18.2	10.5	10.2	8.3
Spring	79.7	42.3	6.2	-42.9
Summer	-28.6	-27.6	-40.1	10.0
Autumn	35.9	-9.7	3.6	14.2
Winter	70.3	46.8	87.1	84.6

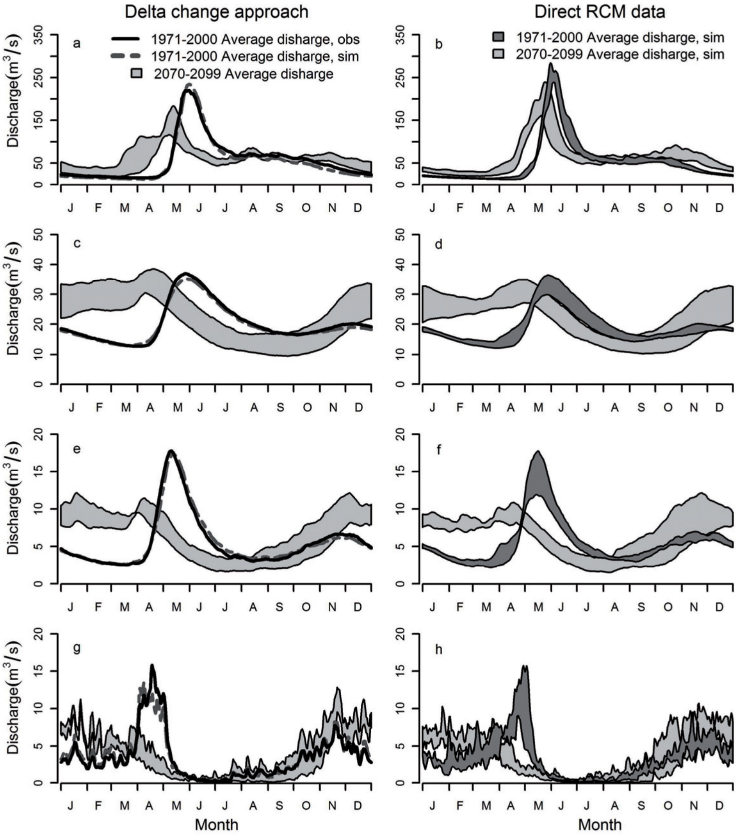

Figure 13. Daily average simulated (sim) discharges in 1971–2000 and 2070–2099 with the delta change approach (left) and direct bias corrected RCM data (right) from four RCM scenarios (paper V) and observed (obs) discharges in 1971–2000. a–b) Juutuanjoki, c–d) Nilakka, e–f) Kitusjärvi and g–h) Hypöistenkoski.

4.2.2 Water balance

Annual changes (in mm) in the water balance components in four study catchments with the direct RCM data for the 21st century (paper V) and with the delta change approach for 2070–2099 are shown in Figure 14. Increases in precipitation occurred in all catchments and scenarios except for one scenario (HIRH-A-A1B) in Hypöistenkoski in southern Finland (Fig. 14m). Potential evapotranspiration (PET, Fig. 14b,f,j,n) and actual evapotranspiration (ET, Fig. 14c,g,k,o) increased with all the scenarios. ET increased less than PET, because decreasing soil moisture during summer (Fig. 15c) limited the increase of ET. Increases in lake evaporation (Fig. 15b) were not limited by lack of water and were larger than increases in ET. Increases in ET cancelled out some of the increases in precipitation and therefore changes in runoff (Fig. 14d,h,l,p) were smaller than the changes in precipitation.

The average increase in runoff by 2070–2099 compared to the control period was larger (50–62 mm/a, 15–18 %) in Juutuanjoki in northern Finland than in the three catchments in southern and central Finland (19–41 mm/a, 6–12 %). The four climate scenarios produced a wide range of results for precipitation and runoff change. Change in runoff by 2070–2099 varied from -21 % to +46 % with the widest range in Hypöistenkoski in southern Finland, where the range of precipitation change was also widest. The changes in runoff during the 21st century were not linear but contained periods of faster and slower changes (Fig. 14d,h,l,p). The projected changes in water balance components were similar in magnitude to those reported by Vehviläinen and Huttunen (1997) and Schneiderman et al. (2009) for case study catchments in Finland.

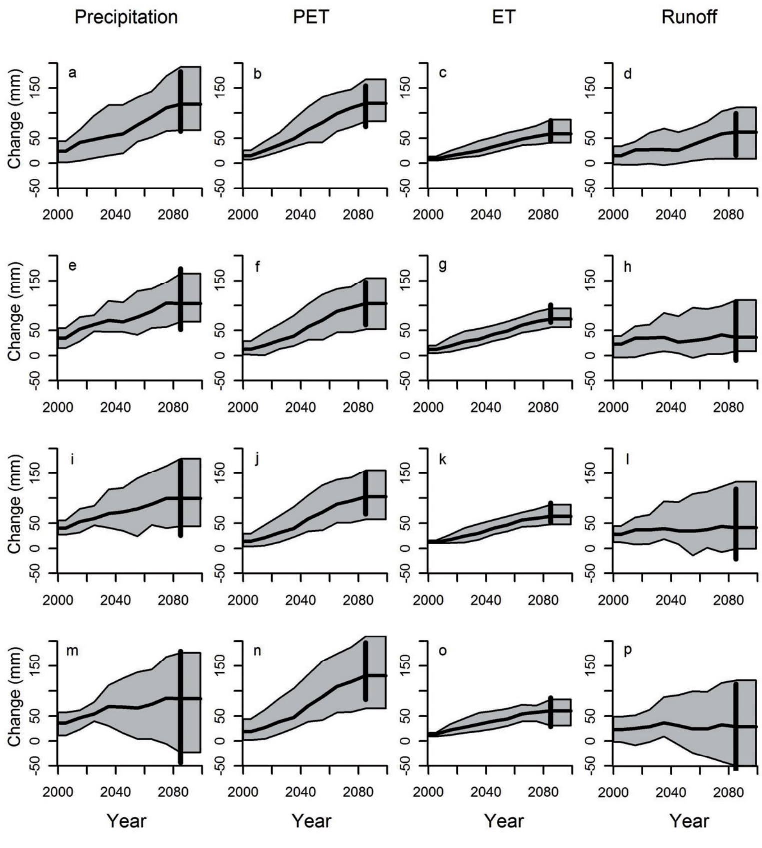

Figure 14. Change (in mm) from the control period in mean annual water balance components (precipitation (a,e,i,m), potential evapotranspiration (b,f,j,n), evapotranspiration (c,g,k,o) and runoff (d,h,l,p)) as 30 year moving averages in 2001–2099. Results are from Juutuanjoki (a–d), Nilakka (e–h), Kitusjärvi (i–l) and Hypöistenkoski (m–p). The grey area is the range from four climate scenarios and the black line is the mean value. Vertical lines show the corresponding range of change in 2070–2099 with the delta change approach.

Results from the delta change approach for 2070–2099 (vertical lines in Fig. 14) were rather similar to the direct RCM data results (Fig. 14 gray area). The main difference was that direct RCM data produced on average 2–3 percentage points larger increases in mean annual runoff (Fig. 14, Table 3) by 2070–2099 and smaller ranges of precipitation (Fig. 14a,e,i,m) and runoff (Fig. 14d,h,l,p) change than the delta change approach in all catchments except Juutuanjoki. Evapotranspiration was higher in the delta change approach than with the direct RCM data in Nilakka (Fig. 14g), but not in the other catchments (Fig. 14c,k,o).

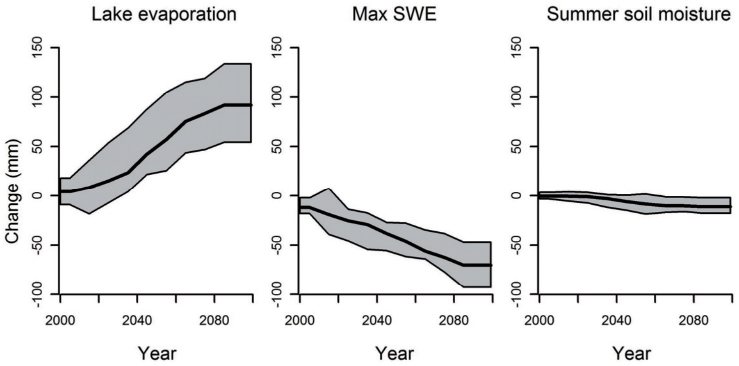

Figure 15. Change (in mm) from the control period in a) mean annual lake evaporation, b) mean annual maximum snow water equivalent (SWE) and c) mean summer (June–August) soil moisture as 30 year moving averages in 2001–2099 in Nilakka. The grey area is the range from four scenarios and the black line is the mean value.

4.3 Floods and climate change (I, II, IV)

Climate change induced changes in floods are different than changes in mean discharge and therefore future floods must be studied separately (Boorman and Sefton 1997). The 100-year floods in Finland estimated with the delta change approach in 67 catchments (Fig. 7b) (paper IV) decreased on average by 16 % (8–24 % in 20 climate scenarios) in 2070–2099 compared to the control period 1971–2000. The results however varied widely between different catchments and regions (Fig. 16). There was a clear shift in flood seasonality with increasing autumn and winter floods and decreasing spring floods especially in southern and central Finland. When 100-year floods were estimated separately for the extended spring season (March–June) and the rest of the year, the floods decreased in spring on average 15–40 % by 2070–2099, and increased 12–40 % in other seasons. In areas in northern and central Finland, where snowmelt floods are currently the largest floods, the annual floods decreased or remained unchanged. Decreases in floods, which were largest in central and north-central Finland, were caused by decreasing snow accumulation due to warmer winters. In northern Finland the decreases were smaller and some scenarios projected no change in floods. The colder temperatures in northern Finland meant that more snow and larger snowmelt floods still remained in 2070–2099 and in some scenarios increasing precipitation was able to compensate for the warmer and shorter winter. Similar results were found in paper (II) in the river Tana in northern Lapland.

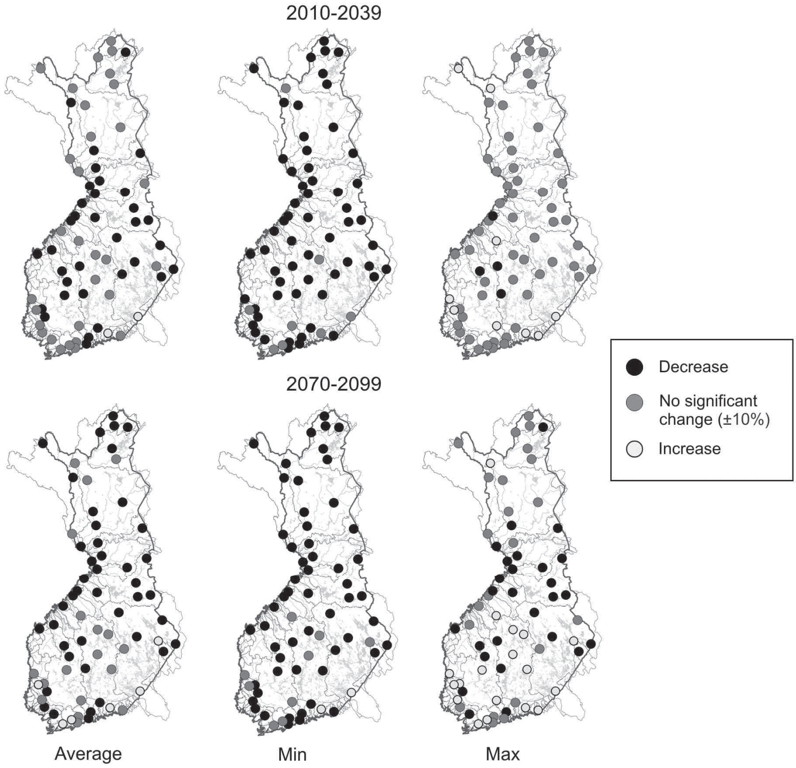

Figure 16. Average (left), minimum (middle) and maximum (right) change in 100-year floods from 20 climate scenarios in 2010–2039 (above) and 2070–2099 (below) from the control period (paper IV).

Increases in the 100-year floods by 2070–2099 took place especially in large central lakes and their outflow rivers in the lake area. Floods in these catchments are long-lasting and can be caused by prolonged heavy rainfall in autumn as well as by spring snowmelt (Fig. 18). The floods in central lakes increased due to increased precipitation, milder winters with more rain, more frequent snowmelt, and low winter evaporation rates. In some small rivers on the southern coast floods also increased with some climate scenarios, because of projected increase of autumn and winter precipitation and floods. In many regions in coastal areas and central Finland there was no consistent climate change signal in flood magnitudes, and both increases and decreases were produced depending on the climate scenario. In 2010–2039 the results were less clear than in 2070–99; there were less increases in floods, the projected changes in floods were smaller in magnitude than in 2070–2099, and there were more catchments with no significant change (Fig. 16).

The extreme precipitation in the delta change approach changes by the same percentage as average precipitation and therefore the larger increases in extreme precipitation projected in many studies (Frei et al. 2006; Beniston 2007; IPCC 2007a) are not taken into account. However, in most study catchments in paper (IV) the largest floods were caused by snowmelt or the floods were long lasting due to large catchment areas and high lake percentage. Therefore the effect of extreme precipitation was more limited and the applicability of the delta change approach may be adequate in most catchments. However, in the coastal area with small catchments, especially in southern Finland, short term heavy precipitation may cause extreme floods, although these have not been very common in the past (Fig. 6d). In these catchments the future floods could be larger (increase more or decrease less) than in the results presented here (Fig. 16), if changes in extreme precipitation increase more than average precipitation. However, results by Jylhä et al. (2007) indicated that the differences between seasonal average and 5 day maximum values of precipitation from several RCMs in Finland were not very large; the increases in average summer precipitation were 5–22 % while the 5 day annual maximum summer precipitation increased by 8–24 %.

The 20 climate scenarios used to estimate the changes in 100-year floods (paper IV) produced a wide range of results by 2070–2099, with average changes ranging from -8 % to -24 % (paper IV, Fig. 5). The largest differences were between climate scenarios from different GCMs (difference between climate scenarios in average change in floods by 2070–99 for the 67 catchments was 5.1 percentage points), whereas the differences between scenarios from RCMs and corresponding GCMs were less important (3.3 percentage points). The smallest differences were between scenarios with different emission scenarios (1.7 percentage points). This indicates that the GCMs are a greater source of uncertainty than the choice of the emission scenario or RCM. Previous studies by e.g. Steele-Dunne et al. (2008) in Ireland and Prudhomme and Davies (2009) in the UK have also reported GCMs as the largest source of uncertainty in the estimation of hydrological impacts of climate change.

The results of changes in 100-year floods in Finland (paper IV) demonstrate that even within a relatively small country like Finland the impacts of climate change on floods can vary substantially due to regional differences in climatic conditions and catchment characteristics. The correlations between the catchment and climate characteristics and the average changes from 20 scenarios in 100-year floods by 2010–2039 and 2070–2099 were calculated (section 3.4) in order to better understand the factors affecting the results. Important explanatory variables in the changes of floods included many present day characteristics such as timing of the floods, importance of snowmelt floods, latitude, lake percentage, average maximum snow water equivalent (SWE), winter temperature and catchment size (Table 4). These can explain most of the average changes in floods in different catchments, and their explanatory power improves when applied separately to different hydrological regions. When all the different variables (Table 4) were combined, the coefficient of multiple correlation R (section 3.4) was 0.88 in 2070–2099 and 0.77 in 2010–2039 for the entire area of Finland. When the same analysis was applied separately to the three hydrological regions (Fig. 6a) the coefficient of multiple correlation was 0.96 for the lake area, 0.95 for the coastal rivers and 0.95 for the northern rivers for 2070–2099.

Table 4. Correlation between the average changes of 100-year floods from the 20 scenarios and the properties of the study catchments during the control period. Statistically significant correlations ($P<0.05$, $N=67$) are marked with an asterisk. (paper IV)

Catchment and climate characteristics	Correlation r	
	2010–2039 average change	2070–2099 average change
Percentage of spring floods	-0.52*	-0.70*
Ratio of spring 100 y floods to floods in other seasons	-0.48*	-0.73*
Latitude	-0.10	-0.35*
$(\text{Latitude})^2$	-0.09	-0.34*
Longitude	-0.15	0.26*
Winter temperature	0.06	0.32*
Annual maximum SWE	-0.19	-0.45*
Size of the catchment (km^2)	0.37*	0.34*
Lake percentage	0.19	0.41*

*Statistically significant correlation

The change in seasonality of floods is another variable that can be correlated to catchment meteorological and physical properties. The most important explanatory variables explaining the projected change in seasonality by 2070–99 were latitude, winter temperature and average maximum SWE in the control period. The change in seasonality was smallest in the coldest and snowiest regions in northern Finland. The catchment physical properties such as size and lake percentage had only a small influence on the projected change in seasonality. However, not all of the physical properties such as vegetation cover, soil type and topography were included in the analysis.

Regionalization of the results for changes in floods within Finland by using these variables is possible, although it should only be used as a very preliminary estimate. While the influence of local climate and catchment characteristics on climate change impacts on hydrology have been addressed earlier (e.g. Arnell and Reynard 1996), the quantification has thus far been carried out in only a few studies (e.g. Lawrence and Hisdal 2011).

Paper (IV) is the first study in Finland producing national scale estimates of changes in floods for the entire country. Other Nordic studies have produced rather similar results on changes of floods (Andréasson et al. 2004; Beldring et al. 2008; Lawrence and Hisdal 2011). Increases were projected in regions where floods are predominately caused by rainfall, such as western Norway (Lawrence and Hisdal 2011). Spring snowmelt floods were projected to occur earlier and to decrease (Andréasson et al. 2004; Lawrence and Hisdal 2011), with the exception of a study catchment in the mountains in northern Sweden, where spring floods remained unchanged in magnitude (Andréasson et al. 2004). Increases in floods in the large central lakes in the lake areas were also previously reported by Vehviläinen and Huttunen (1997) and Bergström et al. (2006). Climate change influences on floods often differ depending on the flood producing mechanism (e.g. snowmelt vs. rainfall), since the processes which generate the floods are different for each type (Loukas et al. 2002).

Comparison with recent continental scale studies on flood risk in Europe (Lehner et al. 2006; Dankers and Feyen 2008; 2009) show that the results presented here differ from both of these studies in some parts of Finland. Lehner et al. (2006), who used monthly GCM data redistributed to daily values, found an increase in flood risk in Finland. The results appear to ignore the decreases in snow, which could be caused by the oversimplified snow model together with the disaggregation of GCM simulated monthly mean values to daily data. Dankers and Feyen (2008; 2009) on the other hand used high-resolution RCM daily data without bias correction and therefore the RCM biases influenced their results. They found mostly decreases in floods in Finland, except with some scenarios in northern Finland (Dankers and Feyen 2009). In most parts of Finland the direction of change in floods in paper (IV) was the same as in the results by Dankers and Feyen (2008; 2009). However, the results differed especially in the lake area, where this study found increasing trends in floods of the large lakes and their outflow rivers, whereas Dankers and Feyen (2008; 2009) projected decreases in this area. The model used by Dankers and Feyen did not include lakes because of time restrictions and unavailability of lake data. The model was therefore unable to reproduce the flood regime of the lake area, which is profoundly affected by the storage volume of lakes. By comparison the WSFS model has the advantage of access to national databases and accounts for retention in approximately 2 600 lakes, all lakes larger than 1.0 km^2, and is therefore more reliable in the lake area.

The results here highlight the importance of comprehensive climatological and hydrological knowledge and the use of several climate scenarios in estimation of climate change impacts on flooding. Generalisations based on only a few case studies or large scale flood assessments using only a few climate scenarios or limited data should be avoided in countries with variable hydrological conditions. The reliability of large scale assessment on smaller scale should be carefully assessed before the generalisations can be utilized for planning purposes. In Finland the results of paper (IV) project decreasing floods in most catchments with most scenarios. Unfortunately in some of the most important flood risk areas with high potential damages, future floods are projected to stay unchanged or to increase. Therefore total flood risk does not necessarily decrease due to climate change.

4.3.1 Design floods for high hazard dams

The changes in design floods by 2070–2100 were estimated using a method based on maximising the flood generating factors with the use of design precipitation (section 2.5) and hydrological modelling in 34 dam sites (Fig. 7a) (paper I). Five climate scenarios (Table 1, 23–27) and two projected changes of the design precipitation (section 2.5.1) were used to produce a range of possible future extreme conditions.

The effect of climate change on design floods depended on the main flood producing mechanism. At the dams in northern Finland, where the design flood was caused by a combination of snowmelt and rainfall both in the control period and in 2070–2100, the floods remained on average at about the same magnitude as at present (Fig. 17). The decrease in snow due to warmer and shorter winters was compensated by the increases in precipitation and design precipitation. In contrast, at the dams in western and southern Finland, where the design floods were mostly caused by heavy summer precipitation events, the design floods increased (Fig. 17). This timing of the design floods in western and southern Finland was partly due to the storage and regulation of the dam reservoirs. At these dam sites the timing of the design floods remained the same in both control and future time periods, but the increase in design precipitation (20–85 % in July–

August) caused the design floods of 2070–2100 to increase considerably. At those dams in eastern Finland, where the timing of the design flood changed from spring in the control period to summer or autumn flood in 2070–2100, the direction of change in design flood magnitude varied from decrease to increase. The change depended on the scenario used and on how dominant the spring flood at present was at the site in question.

The range of projected changes was large at most of the dams due to the considerable differences in the scenarios used for 2070–2100 (Fig. 17). In spite of the wide range of changes, there were consistent increases (by 6–74%) at the dams in western and southern Finland, where design floods occurred during summer. The main cause of the changes in the summer and autumn design floods was the increase in design precipitation. In northern and eastern Finland, the range of change varied from decrease to increase. The decreases were caused by smaller accumulation of snow, while the increases can mostly be attributed to the increase in design precipitation. The spring floods were sensitive to air temperature during winter and spring and the climate scenario used had a large effect on the results.

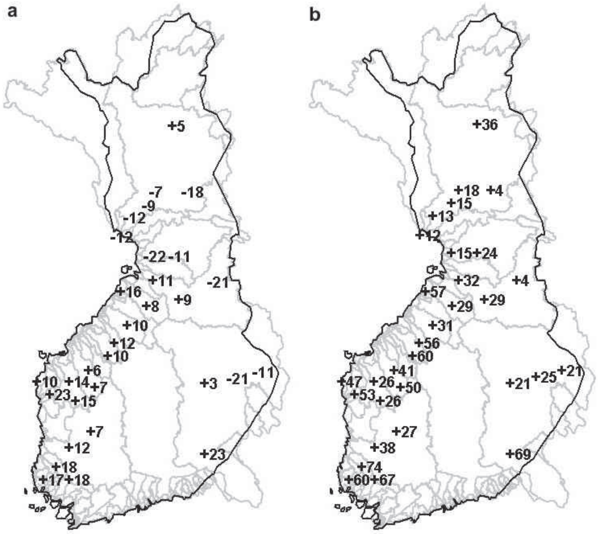

Figure 17. a) The smallest and b) the largest changes (in %) in design floods of high hazard dams from the control period to 2070–2100. The smallest and largest changes are out of the floods in 2070–2100 simulated with ten scenarios. (Paper I)

The results can be used to identify the dams where climate change potentially causes the largest risks to dam safety in the future through changes in design floods and where the clearest adaptation needs exist. At dams where the design floods are likely to increase, the likelihood of dam failure due to inadequate design will also increase. However, at many of the dams the spillway capacities are large enough to handle even the increased design floods. The study (paper I) identified five dams where projected climate change effects are likely to cause the present spillway capacity to be inadequate in the future. All these dams were in southern or western Finland. The results of this study are being used as part of the regular dam safety inspections in Finland.

Studies on climate change impacts on dam design floods (e.g. Cameron et al. 2000; Andréasson et al. 2007; Bergström et al. 2012) have mostly been carried out in case study catchments. A nationwide study as presented in paper (I) has not been previously carried out in the Nordic countries and according to the author's knowledge this study was among the first of its kind in the world. Andréasson et al. (2007) carried out sensitivity analysis of the Swedish dam safety guidelines in changing climate at a few dam sites and concluded that uncertainty between different climate scenarios and dams was great and that the most important factor determining the changes due to climate change was whether the design floods are generated by rain or snowmelt. Comparison of the different dam safety estimation methods in Sweden, Norway and Finland revealed rather similar results with both small increases and decreases in design floods in the four study catchments (Bergström et al. 2012). The different methods, models, and climate scenarios all contributed to the differences between the results from different countries.

The method to estimate changes in design floods could be further improved by changing the shape and the spatial variability of the 14-day design precipitation period along with its magnitude and timing as the climate changes. Currently the same change factors are used for the entire precipitation period and entire country, since the data available at the time of the estimation was deemed insufficient for a more rigorous definition of the changes in the design precipitation period (Tuomenvirta et al. 2000). However, with the improved availability and resolution of RCM data separate changes e.g. for the 1, 5, 14 day precipitation (Andréasson et al. 2007) and for the different parts of the country could be estimated. The timing and also the shape of the design flood can already change from the control period to the future period, when the control period temperature and precipitation are changed according to climate scenarios. However, the use of more detailed definition of changes in design precipitation period would allow for more changes in the temporal properties of the design floods.

4.3.2 Comparison of flood results

Comparison of the results of the two national scale flood studies of papers (I) and (IV) (Fig. 16, Fig. 17) shows that the largest difference in the results occurs in the west coast. The dam design floods in the west coast in paper (I) increased more by 2070–2099 than the 100-year floods in the same region. This is mostly explained by the differences in study catchments: the high hazard dams in the western coastal region (Ostrobothnia) have artificial reservoirs with relatively large storage capacity during spring and often possibilities to divert part of the discharges past the dam. Therefore the simulated present-day design floods of the dams were summer floods caused by short-time heavy precipitation events, whereas the largest floods in current climate in the other parts of coastal rivers are usually spring snowmelt floods. The responses of these two types of floods to climate change are quite different, since snow accumulation is expected to decrease and extreme precipitation to increase.

Comparison of results of changes in floods by 2070–2099 in the five common catchments in papers (I) and (IV) (Table 5, locations shown in Fig. 7b) shows similar results especially in the outflow rivers of large lakes (Harjavalta, Vuoksi, Kaltimo). In the two large northern rivers (Isohaara and Raasakka, Table 5) there were decreases in the 100-year floods in paper (IV), whereas the design floods varied from moderate increase to moderate decrease in paper (I). The differences between the results were mostly due to the differences in methodologies. In the estimation of the design floods in the northern rivers a large increase in design precipitation and a single year with remaining large snow accumulation were used as a basis of the analysis, whereas the delta change approach relied on 30 years of simulation and frequency analysis from the annual maximums of this period to estimate the 100-year floods. The changes in extreme precipitation are different between the two methods, as are the return periods of the floods. Extreme floods may indeed change differently than more frequent ones. The two studies also employed different climate scenarios.

Table 5. Comparison of the changes in 100-year floods and in design floods of high hazard dams in the common catchments in papers (I) and (IV) (locations in Fig. 7b)

Study catchments	**Change in 100- year floods (%) in 2070–2099**		**Change in design floods of high hazard dams (%) in 2070–2099**	
	Min	**Max**	**Min**	**Max**
Isohaara	-43	-11	-12	+12
Raasakka	-59	-31	-22	+15
Harjavalta	+8	+39	+12	+38
Kaltimo, Pielisjoki	-7	+23	-21	+25
Imatra, Vuoksi	+22	+41	+23	+69

Results from the Tana river at Polmak in paper (II) (change in 250-year floods -40–+5 % by 2070–2099, paper II, Table 4) were similar to the results at Onnelansuvanto situated further upstream of the Tana river (change in 100-year flood -37–+1% by 2070–2099) and included in paper (IV). Both showed changes in floods that varied from very small increase (1–5 %) to large decrease (up to 37–40 %). Similarities of the results are not surprising considering the same hydrological model and similar methods and climate scenarios were used in both studies.

In order to estimate how the method used to transfer the climate signal to the hydrological model influences the flood results, 100-year floods based on the delta change approach and the direct bias corrected RCM data were compared (Table 6). In both cases the 100-year floods were calculated with the Gumbel distribution from the annual maximum discharges simulated with the WSFS hydrological model with the four scenarios and four catchments (Fig. 8a) used in paper (V). These results are based on the simulations made for papers (IV) and (V), but are not presented in those papers. The results show that the direct RCM data produced on average smaller decreases in 100-year floods in Juutuanjoki and larger decreases in Hypöistenkoski than the delta change approach (Table 6, Fig. 18). In Nilakka and Kitusjärvi the average changes were very similar in both methods, but the range of changes was wider with the direct RCM data. Even when the average results are not markedly different, some individual scenarios produce very different results with different methods (Table 6).

The wider range in results from direct RCM data can be partly explained by the changes in annual and interannual variability of the direct RCM data. The other explanation is the use of different control period values for each scenario in the direct RCM data compared to the single control period value for all scenarios in the delta change approach. With some scenarios the control period 100-year floods based the direct RCM data differed considerably (-19–+11%) from 100-year floods based on observations. For example in Juutuanjoki the increase in 100-year flood with the HIRH-A-A1B scenario (Table 6) with direct RCM data was partly caused by the low estimate for 100-year flood magnitude in the control period for this scenario. This underestimation of the control period 100-year flood (19 % smaller than the 100-year flood estimated from observations of 1971–2000) may have been caused by natural variability in the 30 year control period, remaining biases in the RCM data and inaccuracies of the hydrological model.

In Juutuanjoki higher snow accumulation and later snowmelt peak was simulated in 2070–2099 with the direct RCM data than with the delta change approach (Fig. 18a,b). Snow accumulation especially during spring, when air temperature fluctuates close to the freezing point, was very sensitive to changes in temperature. In principle the direct RCM data can better take into account the changes in variability of temperature. During colder years a large amount of snow can still accumulate especially with the increases in precipitation, and large snowmelt floods still occasionally occur.

Table 6. Change in 100-year floods (in %) in 2070–2099 compared to 1971–2000 in four catchments with the delta change approach (IV) and the direct bias corrected RCM data (V). Flood magnitudes are calculated with the Gumbel distribution.

Method Scenario	**a) Juutuanjoki (%)**	**b) Nilakka (%)**	**c) Kitusjärvi (%)**	**d) Hypöistenkoski (%)**
Delta change				
REMO-E-A1B	-15	-6.8	-41	-14
RCA3-H-A1B	-18	+13	-26	-13
HadRM-H-A1B	-26	-3.4	-24	-19
HIRH-A-A1B	-19	-10	-40	-21
Average	-20	-1.8	-33	-17
Direct bias corrected RCM data				
REMO-E-A1B	-41	-22	-47	-17
RCA3-H-A1B	-17	+16	-13	-16
HadRM-H-A1B	-0.1	+8.8	-20	-24
HIRH-A-A1B	+13	-10	-43	-39
Average	-11	-1.8	-31	-24

Since the quantile-quantile mapping bias correction method is limited to the 99 percent tail of precipitation, the very extreme precipitation values of the control period may not correspond to the observed values. This may influence the simulated extreme floods especially in Hypöistenkoski, where single extreme precipitation event can cause severe floods. In the other catchments floods are caused by longer periods of heavy precipitation or snowmelt. The inability of the bias corrected time series to correctly represent the extreme precipitation in the control period will also be reflected in the values of extreme precipitation and consequent floods in the future. Other bias correction methods such as the use of gamma distribution (e.g. Piani et al. 2010), which also corrects the tail of the distribution, may be more suitable for studying changes in extreme floods caused by extreme precipitation. However, since the distribution parameters of the gamma distribution are dominated by most frequently occurring values, a single distribution may not be sufficient to accurately describe the properties of extreme values (Yang et al. 2010).

In Hypöistenkoski the largest difference between the methods was produced with one scenario, the HIRH-A-A1B (Table 6). In Hypöistenkoski this scenario produced smaller floods in 2070–2099 with the direct RCM data than with the delta change approach. The larger decreases in 100-year floods appear to be caused by underestimation of extreme precipitation and consequently summer and autumn floods in the HIRH-A-A1B scenario with the direct RCM data. Hypöistenkoski has a small catchment area (smallest in paper (V), 350 km^2) with no lakes and therefore extreme precipitation is a more important factor in Hypöistenkoski than in the three other catchments included in the comparison. Hypöistenkoski is clearly more sensitive to remaining errors in the RCM daily precipitation than the other catchments. Since the catchment area is smaller than the grid size of the RCM (25*25km=625 km^2) and the bias correction in the quantile-quantile mapping method is limited to the 99 percentile of precipitation, the extreme precipitation may not be well represented in Hypöistenkoski.

Improvements are still needed in the procedure concerning how extreme precipitation is handled in the direct RCM data especially for small catchments, both with regard to the scale of RCMs, the interpolation of precipitation to the WSFS model scale, and the bias correction method.

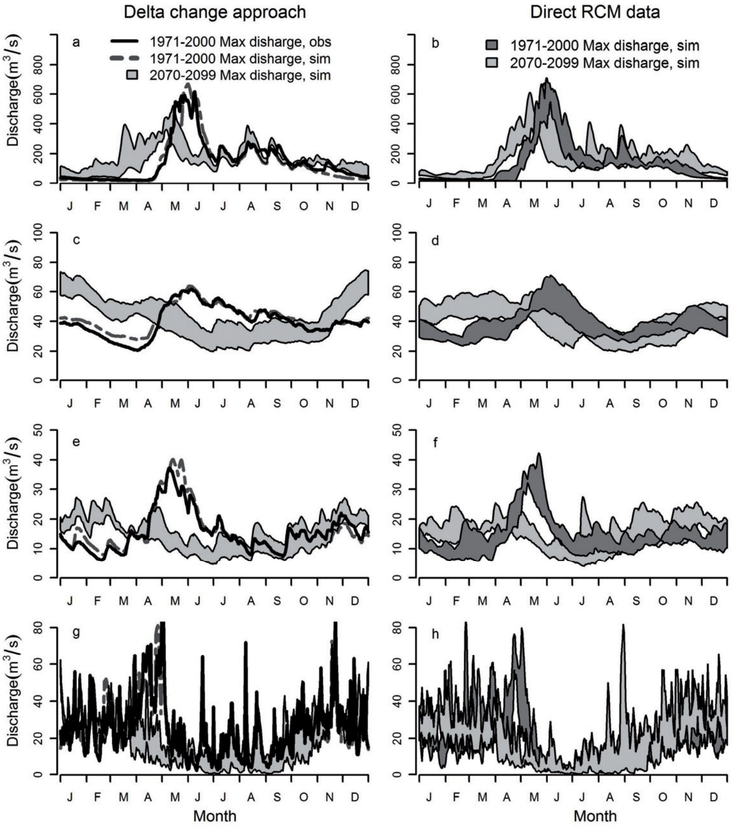

Figure 18. Daily maximum discharge from four scenarios with the delta change approach (left) and direct bias corrected RCM data (right). a–b) Juutuanjoki, c–d) Nilakka, e–f) Kitusjärvi, g–h) Hypöistenkoski.

4.4 Discussion on transfer and bias correction methods (II-V)

Two different methods were used to transfer the climate change to the hydrological model; the delta change approach (I, II, III, IV) and the direct bias corrected RCM data as input to the hydrological model (V). Both methods have their advantages and disadvantages.

The advantages of the delta change approach include its simplicity, robustness and ease of application. The simulated hydrology of the control period does not differ significantly from the observed hydrology of the same period, as long as the hydrological model performs well. Since relative change of the meteorological variables from climate models are used, climate model biases do not directly affect the results. The assumption is that even though the absolute values simulated by climate models may not be reliable at scales needed for hydrological modelling, the changes between future and control conditions are (Prudhomme et al. 2002). The relative changes simulated by GCMs are closer to each other than the absolute values (Jylhä et al. 2004; Christensen and Christensen 2007), although the climate model performance in absolute terms is still important to produce a credible climate change signal. The temperature-dependent temperature change (section 3.2.1) added to the delta change approach to account for the different changes in temperature in different parts of the distribution (Andréasson et al. 2004) resulted in smaller reduction of snow than the standard delta change approach. In light of the daily RCM results this is a more realistic result than the use of the standard delta change approach for temperature, in which all temperature values in the same month increase by the same amount.

Climate change results with the delta change approach depend on the properties of the control periods. The disadvantages of the delta change approach include the facts that all days with precipitation within the same month are changed by the same factor and that the number of wet days does not change. Thus the frequency of precipitation does not change, changes in extreme precipitation values are proportionally the same as all other precipitation values and interannual variability is smoothed (Bergström et al. 2001; Graham et al. 2007a). Many studies indicate that extreme precipitation will change more than average precipitation (Frei et al. 2006; Beniston 2007; IPCC 2007a). When considering changes in average discharge, these limitations may not be very important. However, when floods are considered as in papers (II and IV), they may considerably affect the results (Graham et al. 2007a), since for floods changes in variability are usually more important than changes in mean values (Katz and Brown 1992). As discussed in section 4.3, in most of the catchments in Finland most floods are caused by either snowmelt or prolonged precipitation, but in small coastal catchments especially in southern Finland floods can be caused also by short-term extreme precipitation. In these catchments the delta change approach may produce unreliable results.

The advantages of direct RCM data are that the approach better preserves the future variability in temperature and precipitation produced by the RCMs, can represent complex changes in climate related to changes in circulation types, enables continuous transient simulations and can continue to develop as RCMs and GCMs develop in the future (Lenderink et al. 2007; Beldring et al. 2008; Graham et al. 2007a; Yang et al. 2010). The disadvantage of using RCM data as input to the hydrological model is the need for bias correction. The RCM simulated precipitation and air temperature contain systematic biases (e.g. Jacob et al. 2007), which if not removed will cause significant deviation from observed hydrology in the control period (Lenderink et al. 2007). The bias correction is based on the assumption that bias correction functions made for the control period still remain valid in the future, but the validity of this assumption cannot be verified (Hay et al. 2002; Boé et al. 2007; van Pelt et al. 2009). Terink et al. (2010) demonstrated that the assumption of constant bias may not hold. Other limitations of bias correction methods are that most methods, such as the quantile-quantile mapping method used in paper (V), do not correct the spatial pattern or the temporal properties i.e. the autocorrelation properties of the variables and correct each variable independently, even though they are correlated (Déqué 2007; Seguí et al. 2010). The remaining biases after the bias correction may also influence the results, especially when simulating floods, which are often sensitive to remaining biases.

The different bias correction methods proposed in previous studies range from simple monthly or seasonal constant correction factors (Graham et al. 2007a; Lenderink et al. 2007) to more complex correction of both mean and variance of temperature and precipitation (Leander and Buishand 2007; Boé et al. 2007) and use of gamma distributions for precipitation (Hay et al. 2002; Piani et al. 2010; Yang et al. 2010). In paper (V) a rather complex bias correction, quantile-quantile mapping (Déqué 2007), was used to remove the biases in the distribution of temperature and precipitation. The biases in different RCMs were different to such an extent that the simple methods tested did not function with all the scenarios and in all catchments. Linear correction of precipitation is reported to cause underestimation in the extreme precipitation quantiles and underestimation of extreme discharges (Leander and Buishand 2007). Salathé (2005) argued that simple local scaling exposes the capacity of the model to simulate the current conditions (Salathé 2005), but the use of climate scenarios from several GCMs in climate change impact studies is also strongly recommended (e.g. Prudhomme et al. 2003; Prudhomme and Davies 2009), although this has not often been accomplished in the previous studies involving bias correction (Leander and Buishand 2007; Yang et al. 2010). Therefore there is a trade-off between the number of scenarios producing acceptable results and the simplicity of the bias correction method. Results of paper (V) demonstrate that using several climate scenarios and study catchments places higher demands on the bias correction methods than when single scenarios and catchments are studied. Different climate scenarios have different types of biases, and in different catchments with a variety of climatic conditions different biases influence the simulated discharge. This may lead to a need for complex bias correction methods, which correct the entire distribution of the RCM variables. Another conclusion from results of paper (V) is that bias correction of temperature is as important as correction of precipitation in conditions where temperature frequently fluctuates relatively close to zero.

The method used for bias correction of the direct daily RCM data affects the results of changes in water balance and discharge (Steele-Dunne et al. 2008; van Pelt et al. 2009; Seguí et al. 2010), and these effects can be rather complex (Schmidli et al. 2006). Not only the absolute values, but also relative changes are affected by the bias correction (Leander et al. 2008; van Pelt et al. 2009; Seguí et al. 2010). The more bias correction is used the further away one gets from the ‘direct’ use of RCM data (Graham et al. 2007a). The impact of the bias correction on uncertainty in the predictions will be the larger the worse the climate model performance in the control period is compared to observations (Yang et al. 2010).

Changes in extreme discharge are much more sensitive to the transfer and bias correction methods than changes in mean discharge (Graham et al. 2007a; Lenderink et al. 2007), although mean values can also be affected (van Pelt et al. 2009; Seguí et al. 2010). In the snowmelt flood-dominated Lule River in Sweden the direct bias corrected RCM data produced an increase in 20-year floods, whereas the delta change approach produced a decrease (Graham et al. 2007a). The bias correction of averages in monthly scale did not however support the reproduction of extreme discharges (Graham et al. 2007a). In Norway the delta change approach produced larger changes in both positive and negative directions than the more direct use of RCM data and the results were different in different catchments with varying flood producing mechanisms (Beldring et al. 2008). Larger reductions of accumulated snow were reported with the delta change approach than with the direct RCM data by both Graham et al. (2007a) and Beldring et al. (2008). Lenderink et al. (2007) reported larger increases in floods with the delta change approach in the river Rhine, dominated by rainfall floods. The differences between the results can be caused e.g. by different flood producing mechanisms in different catchments, changes in precipitation variability in the direct RCM data and larger increase in mild winter temperatures close to 0 ºC in the delta change approach, which leads to less accumulation of snow and smaller spring floods in snow-dominated areas (Andréasson et al. 2004; Beldring et al. 2008).

Sections 4.2.1 and 4.3.2 are a continuation of these earlier studies and present the first comparison between flood results produced by delta change (IV) and direct RCM data (V) in Finland. They represent one of the few studies comparing these methods and using several (four) climate scenarios and study catchments at the same time. The results support the findings of previous studies (Graham et al. 2007a; Beldring et al. 2008) with larger differences in changes in floods than in changes in average discharges projected by the two methods. Snow accumulation was also smaller in the delta change approach than in the direct RCM data, especially in the study catchment in northern Finland. The results show that whereas the two methods can produce similar results in some catchments and with some climate scenarios, in other cases there are marked differences between them.

As can be seen, both methods have their advantages and limitations. The delta change approach is easy to use and enables simulations of large ensembles with both GCMs and RCMs, but the extremes and changes in variability are poorly represented. The direct use of RCM data and bias correction offers more future potential, since it can develop together with RCMs and can handle changes in variability. However, the additional uncertainty from the bias correction, the validity of the assumption about unchanging bias correction function in the future, the remaining biases especially in extreme precipitation and the sensitivity of the simulated discharge to the quality of the RCM simulations remain the disadvantages of this method (Graham et al. 2007a; Lenderink et al. 2007; Yang et al. 2010). The development of the RCMs and the bias correction methods should be continued, while the delta change approach can still be used as a reference and quick overview of changes in averages.

4.5 Lake regulation and climate change adaptation (III)

The impact of climate change on current lake regulation practices and permits as well as adaptation possibilities through changes in lake regulation were studied in paper (III). Three lakes in the Vuoksi watershed in eastern

Finland were studied (Fig. 8b). The simulations were performed using two regulation strategies for each lake, and details of these strategies can be found in paper (III). The first strategy (unmodified) corresponds approximately to the current regulation of the lakes. The second strategy (modified) is modified with regard to the simulated changes in inflow caused by climate change. In Lake Pielinen the outflow of the lake was changed from a natural rating curve to a more regulated outflow (paper III, Fig. 2) based on a scheme presented by Verta et al. (2007). In Lake Syväri the modified regulation scheme includes a change from the current upper limit of the water level, which currently stipulates that the lake water level must be lowered in spring. At Lake Saimaa the outflow river of the lake, the Vuoksi River, is a trans-national river flowing to Russia, and the lake outflow is therefore determined according to an agreement between Finland and Russia. Increasing the outflow from Lake Saimaa above the defined maximum discharge would cause flood damages in Russian territory and would have to be agreed on by both parties. Modifications to the regulation of Lake Saimaa were performed only within the current agreement.

The seasonal rhythm of water levels of the study lakes was projected to change considerably from the present by 2040–69 (Fig. 19), with increases in winter and March-April water levels and decreases in summer water levels. In Lake Pielinen and Lake Saimaa autumn and winter floods were projected to increase by 2040–69 (Fig. 19a and 19c). Summer water levels decreased, causing potential problems for recreational use and navigation. In Lake Pielinen the new regulation scheme (Fig. 19a, modified) was able to decrease the highest water levels and increase the lowest levels, thus diminishing the negative impacts of climate change. At Lake Syväri there will probably be a need to change the regulation limits by 2040–2069 in order to reach the water level preferred by recreational and other users in summer (Fig. 19b, modified). The modification to regulation was necessary since the spring flood, which is the reason behind the present-day lowering of the water level, decreased and occurred earlier by 2040–69. In Lake Saimaa the possibilities to decrease the highest water levels were limited and the differences between the modelled regulation strategies were small, as long as there was no change in the current agreement between Finland and Russia (Fig. 19c).

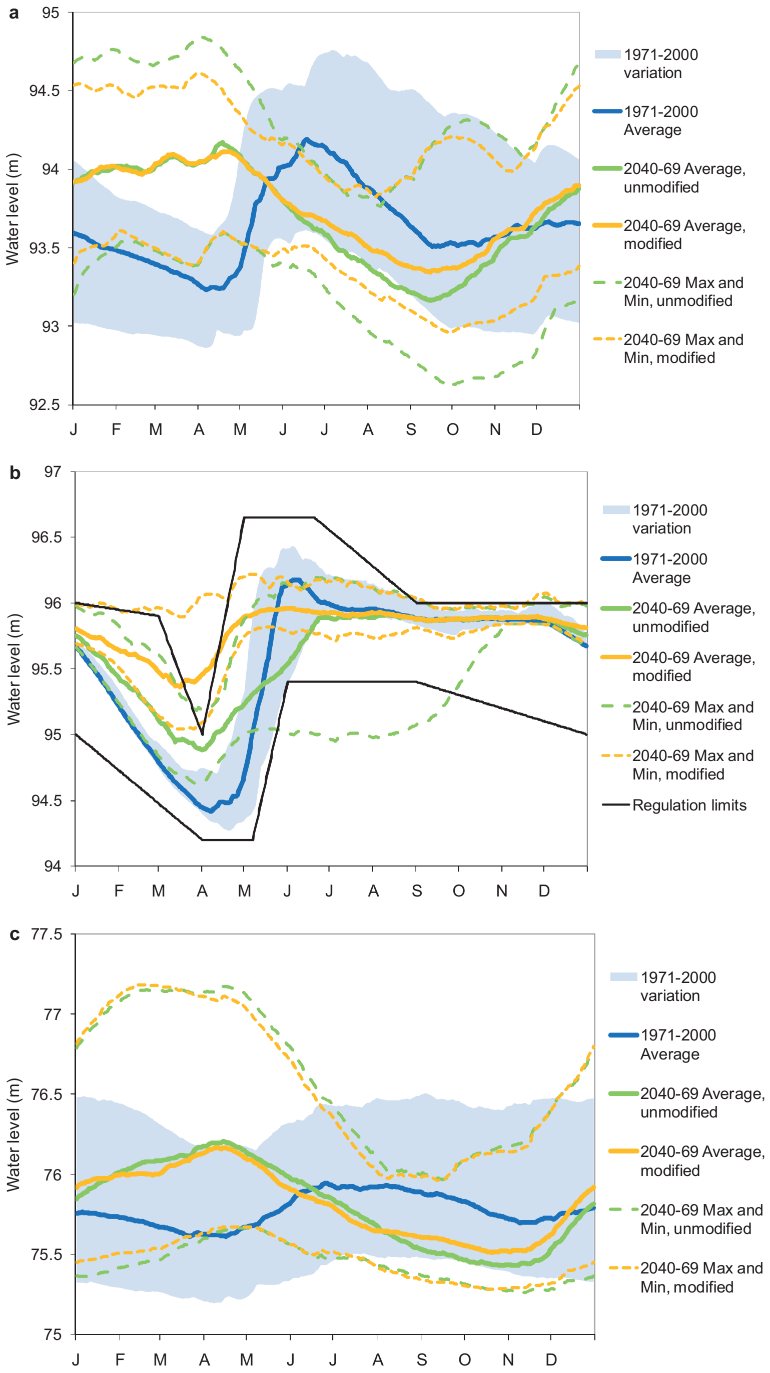

Figure 19. Simulated daily average, maximum and minimum water levels in 1971–2000 and 2040–2069 with two different regulation strategies in a) Lake Pielinen, b) Lake Syväri and c) Lake Saimaa. (Paper III)

The results demonstrate that climate change will lead to a situation in which the current regulation permits and limits in many lakes are unsuited for the new hydrological conditions. Many of the current regulation permits and practices were developed to decrease snowmelt floods during spring and summer, but instead the largest future challenges in eastern Finland will especially in large lakes be autumn and winter floods and occasional summer dryness. Changes in hydrological regime and the consequent mismatch between the hydrological regime and the current operating rules render it necessary to adapt the regulation and management of the lakes to climate change (Lettenmaier et al. 1999; Minville et al. 2009). This was the conclusion of studies carried out in the Great Lakes (Lee et al. 1997), Canada (Minville et al. 2009) and Colorado River (Lettenmaier et al. 1999). These are all regions with snow-influenced hydrology, where substantial changes in seasonal runoff patterns can occur due to climate change (Arnell 1999; Lettenmaier et al. 1999; Payne et al. 2004; Barnett 2005). Paper (III) was the first study in Finland and among the first in the Nordic countries (along with Bergström et al. 2006) to assess the needs and possibilities to adapt to climate change through modifications in lake regulation.

One conclusion of the study was that the new regulation permits and limits should be flexible in order to function properly in a variety of future conditions including not only warmer conditions but also remaining cold winters. The ‘no-regret and flexibility’ principle suggested by Middelkoop et al. (2001) offers a guideline for adaptation measures with uncertain future conditions. There are, however, limits to effectiveness of adaptation through flexible lake regulation. In some cases the minimum or maximum outflow capacity of the lakes cannot be easily changed due to either structural limitations or problems caused by changes further downstream. In these cases the adaptation against extreme floods and droughts through changes in regulation may be ineffective. The results show that it is important to assess the suitability of the current regulation permits and practices to future conditions in order to avoid situations in which unsuitable regulation will aggravate problems caused by climate change.

4.6 Uncertainties in hydrological modelling of climate change impacts (I–V)

Estimating climate change impacts on hydrology and floods with hydrological modelling includes many uncertainties from every step of the modelling chain (Fig. 11, Menzel et al. 2006; Lenderink et al. 2007). There are uncertainties involved in the future emissions of greenhouse gases (emission scenario), in the ability to estimate the impact of these emissions to the global and regional climate with climate models, and in downscaling the climate model result to smaller scales. The way in which the climate change signal is transferred to the hydrological model impacts the results as does the hydrological model, which includes uncertainty in both the structure of the model and the values of the parameters. In flood estimation the choice of the frequency distribution and its extrapolation into long return periods adds yet another source of uncertainty.

Several studies evaluating the relative proportions of different sources of uncertainty in hydrological modelling of climate change impacts conclude that the largest source of uncertainty is the choice of GCM (Prudhomme et al. 2003; Déqué et al. 2007; Minville et al. 2008; Steele-Dunne et al. 2008; Kay et al. 2009; Prudhomme and Davies 2009; Olsson et al. 2010), although other sources can also be important. In papers (I–V) several climate scenarios including scenarios based on at least three GCMs were used (five climate scenarios in paper (I), eight in paper (II), 14 in paper (III), 20 in paper (IV) and four in paper (V)). The use of several climate scenarios enabled the estimation of some of the most important uncertainties in climate change impact studies and provided a wide range of results in all the papers.

Climate is not completely stationary even without anthropogenic changes. Natural multi-decadal climatic variability strongly influences especially flood estimates. Since the commonly used simulation period of 30 years is rather short for the estimation of rare floods, different 30 year representations produce different results and thus natural variability as such is a source of uncertainty (Arnell 2003; Leander and Buishand 2007; Kay et al. 2009). Quantification of the natural variability enables evaluation of the importance of the climate change induced changes in relation to the bounds of natural variability. Previous studies have used stochastic weather generators (Minville et al. 2008), resampling observations or RCM output (Leander and Buishand 2007; Kay et al. 2009; Prudhomme and Davies 2009) and bootstrapping techniques (Lenderink et al. 2007) to estimate the magnitude of natural variability in extreme flood estimates. Prudhomme and Davies (2009) found that in test catchments in the UK 50 % of changes projected by the 2080s were significantly larger than the estimated natural variability in the control period.

In papers (I–V), the simulations were carried out with only one hydrological model and one calibrated optimal parameter set for each catchment. During the course of the studies, changes took place in the hydrological model versions and the parameter values and these changes may affect the simulated results of climate change impacts. Especially changes in extreme floods may be sensitive to changes in parameter values. Modelling uncertainty arising from different sources was not systematically estimated. In reality the equifinality of the parameters means that several parameter sets with as good or nearly as good performance in the calibration period exist (Beven 2001). Furthermore the conceptual hydrological model was used beyond the conditions to which it was calibrated, which diminishes the model reliability (Seibert 2003). The validity of the hydrological models and parameters in the future climate conditions is unknown (Minville et al. 2008; Beldring et al. 2008). This problem is hard to overcome as long as hydrological models need calibration. Despite the development of physically based models, hydrological models are still likely to require calibration in the foreseeable future due to the lack of data at appropriate scales to establish parameter values without calibration (Beven 1996; Bergström et al. 2001). There are generally no observations in climatic conditions similar to those expected in the future, and therefore calibration against future conditions is not possible (Prudhomme and Davies 2009). However, some evidence is available that non-stationary climate does not necessarily cause parameter instability (Niel et al. 2003) and that the parameter range for some conceptual models is relatively narrow in a variety of different climates (Andréasson et al. 2004).

Previous studies point out that although the hydrological modelling uncertainty can be considerable, it is usually not the largest uncertainty in climate change impact studies (Minville et al. 2008; Steele-Dunne et al. 2008; Prudhomme and Davies 2009; Kay et al. 2009; Lawrence and Haddeland 2011). Kay et al. (2009) reported that uncertainty from hydrological model parameters was in most cases smaller than uncertainties from GCMs, RCMs, emission scenarios and downscaling methods. The uncertainty from hydrological model structure was larger than parameter uncertainty, but still not among the largest uncertainties (Kay et al. 2009). Lawrence and Haddeland (2011) found that parameter uncertainty in the HBV hydrological model contributed significantly to the overall spread of the magnitude of mean annual flood in some regions in Norway, whereas in other regions parameter uncertainty was relatively small. The impact depended on the flood producing mechanism and constraints on the parameter values, with far greater influence of parameters in the rain-dominated than in the snowmelt-dominated areas in Norway (Lawrence and Haddeland 2011). Similarly the WSFS parameters may be an important source of uncertainty, and the estimation of this uncertainty would warrant further studies. The differences between the two hydrological models and between the meteorological and hydrological conditions in Finland and Norway make it difficult to assess whether the conclusion in Norway about the influence of flood producing mechanism to parameter uncertainty is also valid for WSFS applications in Finland.

The structure of the hydrological model may also influence the results. Jiang et al. (2007) compared six simple monthly water balance models and found that even though the model capabilities in reproducing the historical water balance components were similar, their responses to climate change showed greater differences. Especially models without an upper threshold in soil moisture produced greater changes in soil moisture than those with a threshold. Jiang et al. (2007) used simple lumped water balance models with one to five storages and some of the model structures may have been too simple for the purpose of climate change simulation. The impact of model structure is however also noted elsewhere (Boorman and Sefton 1997), although Kay et al. (2009) found relatively small differences between two hydrological models with different structures.

Within the sub-models of the WSFS model, the calculation of evapotranspiration is an important source of uncertainty. The empirical equations used to calculate potential evapotranspiration used air temperature, precipitation and time of year as input (Vehviläinen and Huttunen 1997) and were calibrated based on Pan Class A evaporation measurement. Actual evapotranspiration was calculated from the potential evapotranspiration and soil moisture deficit. This method does not consider changes in other important factors affecting evapotranspiration such as cloudiness, air humidity, wind speed, vegetation cover, length of the growing season or impact of increased CO_2 concentrations on stomatal resistance and transpiration of plants (Wigley and Jones 1985; Betts et al. 2007). However, changes in these factors and their combined effect on evapotranspiration are uncertain (Beldring et al. 2008), since cloudiness, humidity and wind are among the variables least reliably simulated by climate models (IPCC 2007a) and the climate change impact on plants and transpiration is even more uncertain (Boorman and Sefton 1997). Evapotranspiration simulated by RCMs often differs from observed values in the present climate (Graham et al. 2007b; Beldring et al. 2008). Failure to consider the decrease of transpiration due to plant responses to increasing CO_2 concentrations can lead to underestimation of future increases in runoff and overestimation of decreases (Betts et al. 2007). The decrease of soil moisture during summer, which is due to earlier snowmelt and higher evaporation in spring, causes increase in evaporative resistance and thus a negative feedback for evapotranspiration change in snowmelt-dominated regions (Barnett et al. 2005). This, combined with the relatively moderate evapotranspiration rates in Finland, causes the changes in precipitation to be usually more influential for changes in average and high discharge than changes in evapotranspiration. However, if low flows were studied more emphasis would need to be given to the simulation of evapotranspiration in the hydrological model.

An important WSFS sub-model for the conditions in Finland is the snow model. Complex snow processes are represented in a simplified way in the temperature-index/degree-day based snow model implemented in the WSFS. More physically based snow model could utilize larger set of RCM data as input and could likely offer more reliable estimate of future changes. Haddeland et al. (2011) found large differences between the results of the physically based energy balance snow models used in land surface models and the results of the degree-day snow models although these were both global scale models. Availability of relatively good quality snow course data for the calibration and validation of the WSFS snow model improves its reliability. Vehviläinen (1992) found that the degree-day model produced slightly better results on catchment scale than the physically based snow models in present day conditions in Finland. Bergström et al. (1992) showed that the performance of the degree-day snow model was relatively stable over a range of climates. Further comparison of degree-day and physically based snow models should be carried out to refine the role of the snow processes in the hydrological response of boreal catchments to climate change.

Possible land use and vegetation changes and their impact on hydrology are another issue not addressed in these studies. Finland is predominately forested and peatland areas are common. There were changes in land use during the last centuries as forest areas were changed to agricultural land and peatland areas were drained for forestry. These changes have altered the hydrological conditions during the time when discharge was measured (Seuna 1981; Koivusalo et al. 2008). In larger catchments the role of these changes are usually smaller due to different timing of the land use change in different parts of the catchment, differences in short and long term impacts of land use changes and the complexity of the runoff generation process (Hyvärinen and Vehviläinen 1981; Seuna 1981; Korhonen 2007; Koivusalo et al. 2008). In the future, land use change and change of forest into a different type of forest can occur in response to global warming to the extent that it is reflected in runoff generation processes. These issues were not addressed, since scenarios of land use or vegetation changes until the end of the 21st century are not available for Finland, and since the parameters of the conceptual WSFS model cannot be directly attributed to physical catchment characteristics. Reynard et al. (2001) found that moderate changes in land use produced very little difference in catchment response to climate change compared to unchanged land use. Dramatic changes in land use were needed in order to produce large shifts in discharge duration and flood frequency curves.

The differences and uncertainties associated with methods of transferring the climate signal to the hydrological model were already discussed in section 4.4. The impact of the transfer method can be notable especially when changes in floods are modelled (Graham et al. 2007a; Lenderink et al. 2007; Beldring et al. 2008, van Pelt et al. 2009). When using the direct RCM data as input to the hydrological model, the necessary bias correction adds another source of uncertainty to the modelling process (van Pelt et al. 2009), which was also discussed in section 4.4.

When floods of a certain return period were estimated based on frequency analysis (papers I, II and IV), there was also uncertainty involved in the choice of the frequency distribution. Papers (II and IV) only used one distribution (Gumbel distribution) with a set value of coefficient of skewness, and this distribution was then extrapolated to high return periods from a relatively short record length. Use of the Gumbel distribution can be justified by the status it has in Finland as the most commonly used and officially recommended distribution (Ministry of Agriculture and Forestry 1997). In paper (I) three different frequency distributions were used for the validation of design floods and they produced very different results due to different coefficients of skewness and extrapolation to long return periods. Lawrence and Hisdal (2011) reported that the uncertainty introduced by flood frequency analysis with the GEV (Generalized Extreme Value) distribution in estimated change in 200-year floods from a 30 year simulation period was even larger than the uncertainty from climate scenarios or hydrological modelling. The uncertainty from the 2-parameter Gumbel distribution was considerably smaller than from the 3-parameter GEV-distribution.

Modelling of regulation was one further source of uncertainty in papers (I, III, IV). In paper (I) the choice of the model operating rule for the regulated lakes during the design floods was somewhat subjective, since no clear rules have been established for regulation during such extreme events. In papers (III, IV) regulation was based on observed practices and permits, but since the same model operation rules were used for the entire 30 year period, not all years were optimally regulated. In reality the regulation practices are more flexible between the years and the day to day regulated outflow can be decided within certain limits. Therefore the regulation is difficult to model, since it includes subjective decisions by the holder of the regulation permit. The regulation was not always optimal, but the results provided an overview of the changes in discharges and the challenges and possibilities of regulation.

Every step in the long modelling chain of estimating climate change impacts on hydrology and floods contains some uncertainties, most of which were not quantified in this study (Menzel et al. 2006; Lenderink et al. 2007). Therefore the cumulative uncertainties in the end of the estimation process become considerable (Menzel et al. 2006). The results should therefore be interpreted with care and without overstating the confidence of possibly weak signals. The more extreme the studied phenomenon is, the larger the uncertainties become, whereas changes in mean values are more stable (Menzel et al. 2006). Further studies concerning the impact of bias correction method and model parameters on uncertainty propagation should be carried out in order to better quantify the range of uncertainties.

Given the unknown future emissions, the impact of natural variability and the chaotic and complex nature of the climate system, there will always remain wide confidence intervals in any future projections. Even though many uncertainties were ignored, the source of the largest uncertainty, which according to several studies is the climate scenarios and more specifically GCMs (Minville et al. 2008; Steele-Dunne et al. 2008; Kay et al. 2009; Prudhomme and Davies 2009), was taken into account in papers (I–V). As shown by the results of these papers, the range of results projected by the several climate scenarios is often wide, but some results such as increases in winter discharge are robust with all scenarios and in all studies. As Boorman and Sefton (1997) wrote in their review and study of rainfall-runoff modelling of climate change impacts, ‘the limitations and uncertainties of this type of approach... are not so severe that they invalidate it’.

The results of papers (I–V) can be used to identify the likely ‘limits’ of potential climate change impacts on hydrology and expected direction of change (Fowler 1999) and to identify the most vulnerable areas. Further studies with more emphasis on quantifying and understanding the uncertainties can then be directed to the areas with the most pressing adaptation needs. At least the seasonal changes are large and robust enough to be taken into account in the planning and design of adaptation measures in relevant cases. The remaining uncertainties should be incorporated in the planning and decision making processes as part of risk assessment and management (Varis et al. 2004).

5 Conclusions

Impacts on hydrology (II–V)

The results presented in this overview and in papers (I–V) show that climate change has strong seasonal impacts on hydrology in Finland, but the differences between results from different climate scenarios and methods remain large. The average changes in mean annual discharge were moderate increases (approximately 10 % by 2070–2099), but differences between climate scenarios were large (annual change with 20 scenarios ranged from -2 to +29 % in 2070–2099). All scenarios and methods pointed towards considerable (61–170 %) increases in winter discharge caused by warmer winters with more rainfall and snowmelt. Decreases in spring discharge were projected to occur in southern and central Finland, whereas in the north and in large lakes the earlier spring caused a shift from summer discharge to spring discharge. The clearest and most consistent trends in discharge were related to increase in air temperature rather than to changes in precipitation. Projected temperature increases are more consistent among the climate scenarios (Barnett et al. 2005) and are more clearly outside natural variability than the projected precipitation changes (Räisänen and Ruokolainen 2006). Thus far the observed trends in discharge have also been related to air temperature change (Hisdal et al. 2007; Korhonen and Kuusisto 2010; Wilson et al. 2010). Also consistent changes in discharge related to precipitation changes were produced especially in northern Finland, where mean annual discharge increased with all climate scenarios due to projected increases in precipitation.

Evaluation of the water balance components of transient scenarios for 1951–2099 shows that increases in precipitation were generally larger than increases in runoff, because of higher evapotranspiration caused by warming and the lengthening of the growing season. Increases in potential evapotranspiration were larger than increases in actual evapotranspiration, because decreasing soil moisture in summer limited the increase in actual evapotranspiration.

Impacts on floods (I, II, IV)

The results of paper (IV) provide, for the first time in Finland, an overview of changes in floods throughout the country during the 21st century. The impacts of climate change on 100-year floods in Finland varied considerably depending on the location, catchment characteristics, season, and climate scenario. In areas currently dominated by snowmelt floods, a decrease in flood discharges and flood hazard was mainly found by 2070–2099 due to decrease in snow accumulation. However, in some catchments in northern Finland changes in flood magnitudes were on average small due to the colder winters with more snow remaining and increase in precipitation. Autumn and winter floods increased and in catchments where these floods currently occur frequently, flood risk may increase. Increases occurred especially in large central lakes and their outflow rivers, where the largest floods are generated slowly by long periods of excess water from rain or snowmelt. The existence of large lakes and lake routes affects the catchment hydrological characteristics and the flood producing mechanisms and thus also affects the catchment response to climate change. In some regions, especially at the coastal areas, the changes in floods showed no clear climate change signal and the results from different scenarios produced increases and decreases in floods.

Current hydrological and climatological variables such as timing of floods, importance of snowmelt floods, latitude, lake percentage, snow water equivalent and catchment size can be used to explain the projected changes in floods. Combining these factors can explain most of the average changes in different study catchments, and their explanatory power improves when applied separately to different hydrological regions. The results demonstrate that changes in floods can vary considerably even within relatively small regions and that uncertainties involved in climate scenarios remain large. This highlights the need for climate change impact studies at appropriate scales, with adequate data and local knowledge and using several climate scenarios.

Changes in design floods of high hazard dams by 2070–2100 (paper I) were in many ways similar to changes in floods with shorter return periods, but on average the design floods increased more or decreased less than the 100-year floods. The main differences between the results arise from the different methodologies, from the larger increase in the extremely rare design precipitation than in average precipitation, and from the differences between the properties of the dam catchments compared with the rest of the catchments. As was the case with 100-year floods, the influence of climate change on the simulated design floods depended on the flood producing mechanisms. Snowmelt floods in northern Finland remained on average approximately the same size as at present and were sensitive to the choice of climate scenario. On the other hand the design floods increased due to increase in design precipitation in the dams in western Finland, where the design floods were mostly summer or autumn floods caused by heavy precipitation. The timing of the design floods in western Finland is partly explained by the artificial reservoirs, which are situated at or upstream of the dams and are capable of storing part of the otherwise larger spring snowmelt floods. For large central lakes of the large catchments, the design floods became winter floods in 2070–2100 and increased from present. From dam safety perspective the high hazard dams with increasing design floods should be monitored more closely, although most of the dams where increases were projected have adequate spillway capacity to handle the increasing design floods.

Methodologies (III–V)

Two methods to transfer the climate change signal from the climate model to the hydrological model were used and compared: the delta change approach and the direct bias corrected RCM data. The latter method was used for the first time in hydrological analysis in Finland (paper V). Both methods have their advantages and disadvantages: the delta change approach is easy to use, transparent and can be used with both RCM and GCM scenarios, which enables ensembles of larger numbers of climate scenarios to be used. The direct RCM data on the other hand includes better the changes in variability, enables transient scenarios and has future potential to develop together with RCMs and GCM, but also requires more work and currently needs a bias correction step. More realistic projections in variance of meteorological variables can offer improvement in flood analysis, and transient scenarios enable the use of non-stationary flood frequency analysis (Cox et al. 2002; Kay and Jones 2012). Because of the biases in the RCMs (Jacob et al. 2007; Kjellström and Lind 2009), bias correction is necessary to reproduce the key statistical properties of the observed hydrology in the control period. However, the bias correction also adds another source of uncertainty to the process of impact assessment. Results of paper (V) show that more complex bias correction methods for both temperature and precipitation are needed when several climate scenarios and study catchments are used in boreal conditions. The more complex bias correction methods correct the entire distribution of both the RCM simulated precipitation and temperature, and are therefore able to function better with different scenarios and in a variety of conditions, where different biases are influential.

The results of both methods were rather similar with respect to mean values with 2.5 percentage points larger increase in mean annual discharge by 2070–2099 using the direct RCM data than with the delta change approach. The largest differences by the end of the century were during spring in northern Finland, apparently due to sensitivity of the snow accumulation and melt processes. Larger differences were found in projected changes in floods. The floods simulated by using the two methods differed from each other with several scenarios and the range of projected changes was usually wider when using the direct RCM data than with the delta change approach.

In future work, the delta change approach could be used as a benchmark method and for gaining an overview of the average changes with a larger ensemble of scenarios. Direct RCM data has more future potential, but still needs improvements in the accuracy and spatial scale of the RCM simulations as well as the bias correction methods, before it can be used reliably for climate change impact assessments. In the meantime the use of methods side by side could offer the best solution.

Adaptation (III, IV)

Adapting to climate change is necessary in order to decrease the negative impacts and make use of the positive impacts of climate change. Paper (III) presents the first study in Finland on the need to change the management and permits of many of the regulated lakes in Finland. The results show that changes in regulation will become necessary as the hydrological regime used to plan the current regulation permits and practices will change due to climate change. Earlier timing and decrease in magnitude of spring snowmelt floods, longer summers with more evapotranspiration and lake evaporation and increase in autumn and winter rains and floods will in the future cause challenges for the management of Finnish lakes. Whether the regulation permits need to be changed or not depends greatly on how they are defined at present. If the current regulation rules are inflexible especially with regard to the timing of the lowering of water levels in winter and early spring, they will more probably require revision. The new regulation permits should be made flexible in order to be adaptable to both mild winters and cold and snowy conditions. Changing the regulation permits and limits is a cost-effective adaptation measure, since it uses the existing dams and does not require any new large investments.

Uncertainties (I–V)

Uncertainties in estimating climate change impacts on hydrology and especially floods are large and arise from several sources including emission scenarios, climate models, downscaling and transfer methods, hydrological model and frequency analysis. As results from paper (IV) along with previous studies (Kay et al. 2009; Prudhomme and Davies 2009) indicate, the GCMs are one of the largest sources of uncertainty and therefore climate scenarios from several GCMs should always be used. Using only one or two climate scenarios can result in misleading interpretations of the future hydrological changes. Uncertainties related to the method of transfer and the hydrological model should not be forgotten, even though it is not always possible to quantify them.

Final remarks and future directions

Projected climate change impacts on hydrology and floods in Finland are considerable. The changes in mean annual discharge are on average moderate, but the seasonal changes are clearly higher. The flood risk for fluvial floods increases in some regions but decreases in others depending on the flood producing mechanisms. In areas with increasing floods adaptation can help reduce the flood risk. Adaptation could include changes in regulation permits and practices, municipal planning (prohibiting construction on flood risk areas), permanent and temporary embankments and other protection measures. Issues not addressed in this study such as urban flood, frazil ice floods and sea level rise may also cause considerable risks at certain locations in the future.

Water resources in Finland are plentiful, but these water resources are not evenly distributed and some regions are vulnerable to droughts in both current and future conditions. With regard to the risk of flooding, Finland is currently one of the least vulnerable regions in Europe (Schmidt-Thomé et al. 2006), and the annual damages caused by floods are relatively low (Tulvariskityöryhmä 2009). Although the changes in different regions of Finland in fluvial flood risk may be substantial, there is no indication that this general situation would dramatically change due to climate change. The direct climate change impacts on hydrology in Finland during the 21st century appear to be for most parts manageable. There may even be some positive impacts in the form of increased hydro-power production. As a country with high technological capacity and high economical resources, Finland appears to be well equipped to adapt to the direct impacts of climate change on hydrology. It is however possible that adaptation to the indirect impacts of climate change in water resources in Finland will be more demanding. These include changes in water temperature, water quality and ecology that may occur due to increasing air temperature, changes in timing and magnitudes of discharge, changes in nutrient leakage, and/or changes in land use. Multi-disciplinary studies are needed to address these issues.

Additional issues which should be studied further include representation of some of the most important physical processes in the hydrological models, most importantly evapotranspiration and snow processes. More physically based process models could help to diminish the uncertainties involved in estimating the climate change impacts on these processes. A wider use of information from the climate model results, e.g. about the changes in variability and extremes and the changes in other meteorological variables besides air temperature and precipitation, should be part of future hydrological analysis. The future development of the land surface models of the RCMs and their improved hydrological simulations may mean less need for off-line hydrological modelling in the long term. In the meantime the use of direct RCM data as input to hydrological models and the related downscaling and bias correction methods should be studied in more detail. An important research area is the systematic assessment of uncertainties in hydrological climate change studies, including uncertainties in the full modelling chain from climate to hydrological models.

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Climate scenarios project increases in air temperature and precipitation in Finland during the 21st century and the projected changes will alter the hydrological conditions. In Finland the current hydrological regime is characterised by temperature-sensitive snow-dominated seasonality. Therefore climate change can have substantial impact on seasonal runoff patterns in Finland. In this thesis, these processes were studied with the use of climate scenarios and hydrological modelling. The results provide estimates of projected changes in discharge and floods in different parts of the country and in different types of catchments. The results can be used in future planning and evaluation of adaptation needs.

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