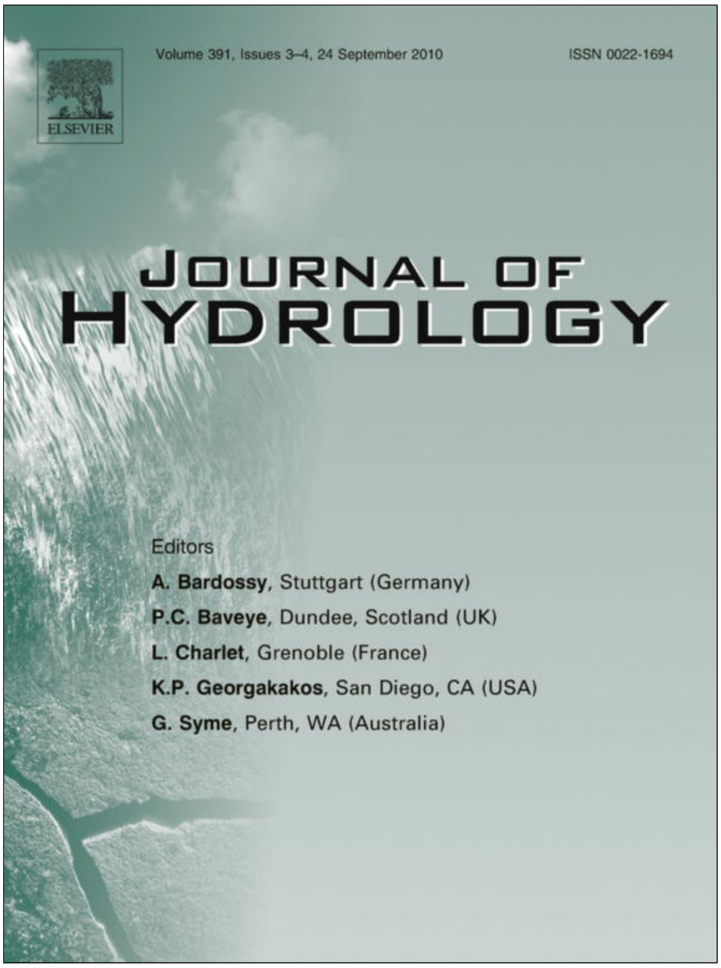
Volume 391, Issues 3–4, 24 September 2010
ISSN 0022-1694
ELSEVIER
JOURNAL OF
HYDROLOGY
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Journal of Hydrology 391 (2010) 333–350

Contents lists available at ScienceDirect

Journal of Hydrology

journal homepage: www.elsevier.com/locate/jhydrol

# National scale assessment of climate change impacts on flooding in Finland

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ARTICLE INFO

*Article history:*
Received 7 January 2010
Received in revised form 13 June 2010
Accepted 24 July 2010

This manuscript was handled by K. Georgakakos, Editor-in-Chief, with the assistance of Ercan Kahya, Associate Editor

*Keywords:*
Climate change
Flood
Hydrological modelling
Flood inundation area
Hydraulic modelling
Finland

SUMMARY

This paper provides a general overview of changes in flooding caused by climate change in Finland for the periods 2010–2039 and 2070–2099. Changes in flooding were evaluated at 67 sites in Finland with variable sizes of runoff areas using a conceptual hydrological model and 20 climate scenarios from both global and regional climate models with the delta change approach. Floods with a 100-year return period were estimated with frequency analysis using the Gumbel distribution. At four study sites depicting different watershed types and hydrology, the inundation areas of the 100-year floods were simulated with a 2D hydraulic model. The results demonstrate that the impacts of climate change are not uniform within Finland due to regional differences in climatic conditions and watershed properties. In snowmelt-flood dominated areas, annual floods decreased or remained unchanged due to decreasing snow accumulation. On the other hand, increased precipitation resulted in growing floods in major central lakes and their outflow rivers. The changes in flood inundation did not linearly follow the changes in 100-year discharges, due to varying characteristics of river channels and floodplains. The results 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 should be avoided in countries with variable hydrological conditions.



## 1. Introduction

Climate change has a multifaceted impact on river discharges: on the one hand it poses a risk of increased flooding, whereas decreasing trends may be expected in regions where precipitation decreases or where snow accumulation decreases (Booij, 2005; Dankers et al., 2007). The hydrological response of a catchment can vary substantially not only due to its location but also depending on the characteristics of the catchment and river networks (Acreman and Sinclair, 1986; Beven et al., 1988), and the same applies to catchment response to climate change.

Efforts have been made to assess these changes on a continental scale (Lehner et al., 2006; Dankers and Feyen, 2008) to produce a general overview, but the reliability of such large scale evaluations on the national scale is unknown. Two recent continental scale flood hazard evaluations by Lehner et al. (2006) and Dankers and Feyen (2008) in Europe yield contradictory results on the changes in floods in many parts of Europe, including Finland. Dankers and Feyen (2008) reported a considerable reduction of 10–40% in 100-year discharges in Finland, much of northern Sweden and north-western Russia by the end of the century due to decrease in snow accumulation; however Lehner et al. (2006) evaluated that the 100-year floods in the same areas will occur more frequently by the 2070s. Both studies used only a few scenarios and since they were performed on a continental scale they include some modelling limitation in representation of the watersheds. Lehner et al. (2006) used baseline values from monthly observed meteorological data disaggregated to daily values and changed these with the delta change approach with results from two coarse resolution global climate model (GCMs). Dankers and Feyen (2008) used more detailed direct daily inputs from higher resolution regional climate model (RCM) and used three scenarios, but only from one RCM (HIRHAM) with one boundary GCM (HadCM3) without bias correction, and without representation of the lake systems common in Finland. The results from the two continental scale studies differed from each other also elsewhere in Europe, for example in Ireland. A smaller scale study in Ireland including several of the same watersheds as the European scale studies differed in some watersheds from both of them (Steele-Dunne et al., 2008).

Globally, numerous studies about impacts of climate change on floods are available for different regions, mostly as case studies on a catchment scale (Andréasson et al., 2004; Simonovic and Li, 2004; Graham et al., 2007; Lenderink et al., 2007; Akhtar et al., 2008; Bates et al., 2008; Kiem et al., 2008; Minville et al., 2008). Several studies have estimated floods with different climate sce-

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0022-1694/$ - see front matter © 2010 Elsevier B.V. All rights reserved.
doi:10.1016/j.jhydrol.2010.07.035

narios from GCMs or RCMs, and with different emission scenarios (e.g. Menzel et al., 2006; Minville et al., 2008; Prudhomme and Davies, 2008). Prudhomme and Davies (2008) analysed uncertainties from natural variability, hydrological modelling, GCMs, emission scenarios and downscaling method and concluded that GCMs are the largest source of uncertainty for estimation of future flows. Similar finding have been made in other studies (Déqué et al., 2007; Minville et al., 2008) and it is therefore recommended that climate change impact studies should always use outputs from several GCMs (e.g. Prudhomme and Davies, 2008). In flood studies, the transfer and downscaling methods can have a major impact on the results (Graham et al., 2007; Lenderink et al., 2007; Akhtar et al., 2008; Beldring et al., 2008). Hydrological modelling of changes in floods includes a lengthy estimation process from emission scenarios to hydrological modelling and flood frequency analysis with uncertainties included in every step. Thus the cumulative uncertainties from the whole model chain may become so large that conclusions about development of extreme floods are very difficult to draw (Menzel et al., 2006).

The Floods Directive (European commission, 2007) instructs the EU member states to perform preliminary flood risk assessments, flood hazard and flood risk mapping and flood risk management planning by 2011–2015. The directive advises that the impacts of climate change on the occurrence of floods should be taken into account when assessing the flood risks. It also poses new demands for general evaluations of changes of flood discharges, flood inundation areas and possible flood hazard due to climate change in different parts of Europe. Both short-term and long-term estimates are needed for different planning time-horizons, since the changes in floods may not be linear. Hydraulic modelling has been the main tool for evaluation of flood inundation (Horritt and Bates, 2002; Hunter et al., 2007; Käyhkö et al., 2007; Pender and Néelz, 2007; Alho et al., 2008). The most common way of implementing the Floods Directive has been to produce flood extent or inundation maps, which are already carried out in 23 European countries (de Moel et al., 2009).

In Nordic climatic conditions, where snow plays an important role in hydrology, climate change may either increase or decrease floods (Vehviläinen and Huttunen, 1997; Beldring et al., 2006). Floods could become more severe, since annual precipitation is expected to increase in Finland by 13–26% by the 2080s (Ruosteenoja and Jylhä, 2007) and extreme precipitations are expected to increase (Beniston et al., 2007). On the other hand, temperature increases of 2–6 °C by the end of the century are estimated to decrease the snow accumulation by 40–70% by the same period (Vehviläinen and Huttunen, 1997; Beldring et al., 2006; Ruosteenoja and Jylhä, 2007; Jylhä et al., 2008; Räisänen, 2008) and to decrease snowmelt floods, which are currently the largest floods in most parts of Finland. Significant changes in seasonality of runoff and floods may occur in areas where a large proportion of runoff is from snowmelt (e.g. Lettenmaier et al., 1999; Bates et al., 2008).

Finland extends from 70° North with sub-arctic climate to 60° North in the margins of maritime and continental climate regimes. In addition the watersheds in Finland range from small coastal rivers to large and complex lake networks and therefore the effect of climate change on hydrology and floods is probably not uniform in the entire country. Discharge trends in Finland analysed until 2004 showed an increase in winter runoff and earlier peak flows in spring, but very few significant changes in annual flood magnitudes (Korhonen and Kuusisto, 2010). The previous information of climate change effects on flooding in Finland is based on case studies made at individual sites and with varying methodological approaches (Vehviläinen and Huttunen, 1997; Käyhkö et al., 2007; Veijalainen and Vehviläinen, 2008; Lotsari et al., 2010).

The overall picture of the changes in flood hazard in Finland with consistent methods and scenarios has been missing, since the European scale assessments are contradictory, do not cover smaller watersheds and may be unreliable in some areas due to limitations in continental scale modelling. In this assessment on a national scale, more detailed hydrological models and several climate scenarios are used. This study aims at: (1) providing an overall picture (67 sites of varying runoff area sizes) of the changes in floods by 2010–2039 and 2070–2099 using conceptual hydrological modelling and several climate scenarios and (2) estimating the consequent changes in flood inundation at four selected settlements using 2D hydraulic modelling. A further goal is (3) to outline climate change effects regionally as well as in different types of catchments (e.g. size, location, lake percentage) and (4) to evaluate the usefulness of continental scale hydrological scenarios on a national scale in a country with variable hydrological conditions. The results can be utilized in preliminary flood risk evaluation required by EU Floods Directive, when lowest building elevation, flood risk areas and flood adaptation options are planned, and to evaluate the need for further and more detailed case studies.

## 2. Study area

### 2.1. Climate and hydrology in Finland

The climate of Finland is controlled by several factors such as latitudinal gradient, maritime climate from the Atlantic Ocean and continental climate from Eurasia, the Scandinavian mountain range and the Baltic Sea (Atlas of Finland, 1987; Käyhkö, 2004). In 1971–2000 the average annual temperature varied from 5 °C to −2 °C and precipitation from 450 mm to 700 mm (Drebs et al., 2002). Finland is a long country and the temperature gradient is strong especially in winter (Fig. 1a), which affects the accumulation and melting of snow.

In south-western Finland the thermal winter lasts on average for 100 days whereas in northern Finland this season is about 100 days longer and the permanent snow season lasts 150–190 days (Vehviläinen and Huttunen, 1997; Drebs et al., 2002). According to Köppen–Geiger climate classification, Finland belongs to the cold climate with no dry season (Df), with cold summers in most of the country (Dfc) and warm summers (Dfb) in a small area near the coast in southern Finland (e.g. Peel et al., 2007).

Watersheds in Finland can be divided into three categories: those characterized by numerous lakes in the central part of the country; small and medium sized coastal rivers; and large and medium sized rivers of northern Finland (Fig. 1b) (Mustonen, 1986; Korhonen and Kuusisto, 2010). Thousands of lakes (4500 over 0.5 km$^2$ and 188,000 lakes of at least 0.05 ha) that cover about 10% of the total area of Finland give the watersheds in central Finland their unique characteristics. Topography, soil types and land use follow approximately the same distribution, with hilly till covered areas in the north, flat clay agricultural areas near the coast and forested till areas with lakes in central Finland.

Hydrology in Finland is characterized by strong snow-dominated seasonality with snow accumulation in winter and snow melt in spring. A second, but usually smaller, increase in runoff occurs in the autumn. In northern Finland more than 95% of annual maximum floods are caused by spring snowmelt (cf. Fig. 7a). Also the small upstream lakes in the northern part of the lake area and the northernmost of the coastal rivers fall mainly into this category. In most coastal rivers the major floods can be caused by either snowmelt or heavy rain events. Especially in Southern Finland mild periods with snowmelt and flooding are not uncommon in winter. In the lake area the largest floods of the central lakes and their outflow rivers are long-lasting volume floods caused by either prolonged heavy rain or melting of deep snowpack or both. (Mustonen, 1986).

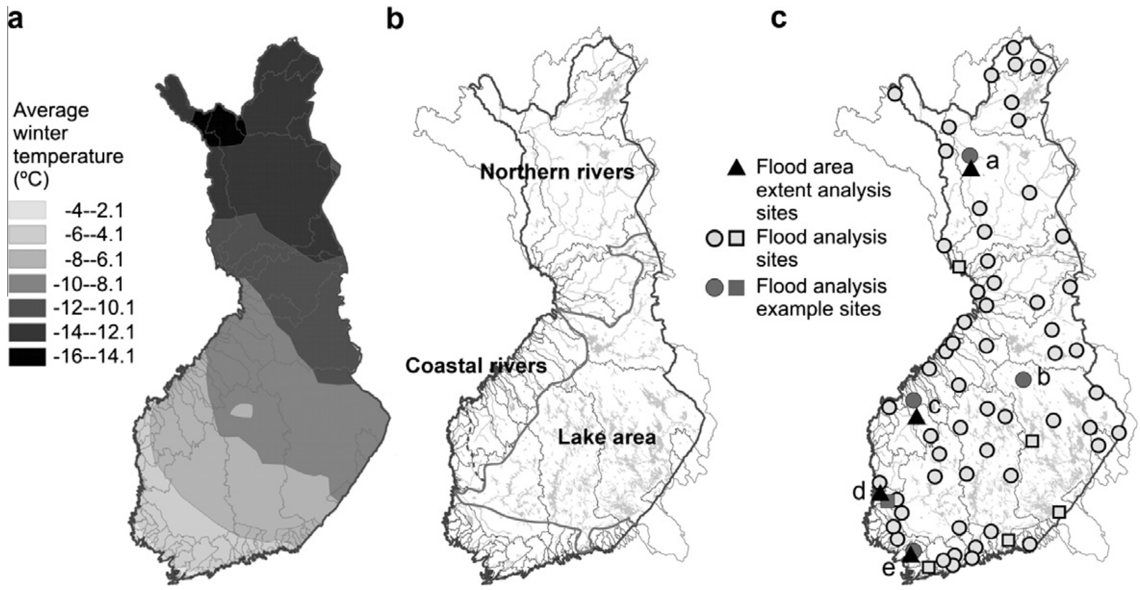


**Fig. 1.** (a) Average winter temperature (December–February) in Finland in 1971–2000 (Source: Finnish Meteorological Institute, 2009), (b) watersheds and hydrological regions in Finland (based on Korhonen and Kuusisto, 2010), and (c) location of the study sites, which correspond to the discharge observation stations. Study sites (a–e) selected for further evaluation are described in Table 1. Circles are unregulated and squares regulated sites.

### 2.2. Study sites

Fig. 1c shows the location of the 67 study sites in Finland. The sites were chosen with the following criteria: length and quality of the discharge observations, relative independence of the sites from each other and covering many types and sizes of watersheds in the entire country. The sites are not totally independent from each other, since some sites are located within the runoff area of the sites with larger catchment areas. Most sites were also selected as being not significantly affected by regulation, which complicates the modelling and flood frequency analysis. However, some sites moderately affected by regulation were included because of their importance for the evaluation of flood hazard. Altogether 15 sites can be classified as being slightly affected by regulation and at six sites (Kallavesi, Vuoksi, Kymijoki, Peltokoski, Harjavalta and Isohaara marked with squares in Fig. 1c) the effect of regulation on discharges is significant (the daily discharges differ on average by more than 5% from the natural situation).

The runoff areas of the sites are between 86 km$^2$ and 61,000 km$^2$ and lake percentage varies from 0 to 22. All the sites have at least 29 years of daily discharge observation and over 60% of the sites have at least 50 years of observations with an average of 67 years. Five sites representing different hydrological regions were chosen as example locations for the flood discharge analysis (Fig. 1c, Table 1) and four sites for the flood inundation analysis (Fig. 1c, Table 1, a and c–d). Four of the five example sites for flood discharge analysis are located near the flood inundation analysis sites.

The four sites for flood inundation analysis were selected from areas where major flood damages have occurred and which are listed as flood prone areas by Timonen et al. (2003). The national flood hazard mapping with 20–1000 year floods, based on observed and extrapolated flood discharges, was also carried out in these sites by the Finnish Environment Institute and Regional Environment Centers. These four areas represent different watershed categories; northern, coastal and lake area watersheds. The vicinity of discharge and water level measurement stations was also an important criterion for selection of the study areas, since the water level and discharge observations are used for the 2D hydraulic model calibration (Table 1).

## 3. Methods

The main parts of the modelling are climate scenarios, transfer of the climate change to the hydrological model, hydrological modelling, frequency analysis and flood inundation analysis with hydraulic modelling (Fig. 2); these are presented in more detail in the following sections. Each part of the modelling chain contains uncertainties and by the end of the chain the cascade of uncertainty becomes greater, which is always the case in this kind of complex analysis of climate change and extreme events (e.g. Menzel et al., 2006).

### 3.1. Climate scenarios

The climate scenarios in this study are from four global climate models (GCM) and means of 19 global climate models with three SRES (IPCC, 2000) emission scenarios (A2, B1 and A1B) and four regional climate models (RCM) (see Table 2). The RCM scenarios are with three GCMs as boundary conditions, and all with the A1B emission scenario. In all, 20 climate scenarios are used in this study for the periods 2010–2039 and 2070–2099, with 1971–2000 as the reference period. These scenarios were chosen based on availability, model performance as presented by IPCC (2007), past experiences and their use in other studies in the Northern Hemisphere. The climate scenarios were used as gridded data of monthly changes with 2.5° grid for GCMs and 0.5° grid for RCMs.

This study utilizes the strategy proposed by Fronzek and Carter (2007), in which the use of both GCM and RCM scenarios enables combining the advantage of the GCMs, the existence of many models with many emission scenarios, with the more accurate representation of small scale variation of RCMs (Wood et al., 2004; Christensen and Christensen, 2007). Use of scenarios from several GCMs is the generally recommended principle of all the latest studies (Déqué et al., 2007; Prudhomme and Davies, 2008), since different GCMs can produce very different results (Christensen and Christensen, 2007; Déqué et al., 2007; Minville et al., 2008; Prudhomme and Davies, 2008).

The projected annual temperature increases by the different climate scenarios in Finland are between 1.8 and 5.4 °C in 2070–2099

**Table 1**
Selected example areas for closer evaluation of climate change impacts on flood discharges and flood inundation area extents. Q is discharge and WSE water surface elevation.

| Map Ref. Fig. 1c | Q gauge station | Region type | Catchment area, Q station (km$^2$) | Lake percentage (%) | Settlement for inundation analysis | Boundary conditions of the 2D model |
|---|---|---|---|---|---|---|
| a | Köngäs Ounasjoki | Small/medium, northern river | 4488 | 4.2 | Kittilä | Upstream : Q; Downstream : river WSE |
| b | Sonkajärvi | Small, lake | 946 | 4.4 | – | – |
| c | Keppo Lapuanjoki | Small/medium, coastal river | 3949 | 3.0 | Lapua | Upstream : Q; Downstream river WSE |
| d | Harjavalta Kokemäenjoki | Large, lake area river | 26,117 | 11.3 | Pori | Upstream : Q; Downstream: sea-level |
| e | Kaukolankoski Uskelanjoki | Small, coastal river | 481 | 0.7 | Salo | Upstream : Q; Downstream: sea-level |

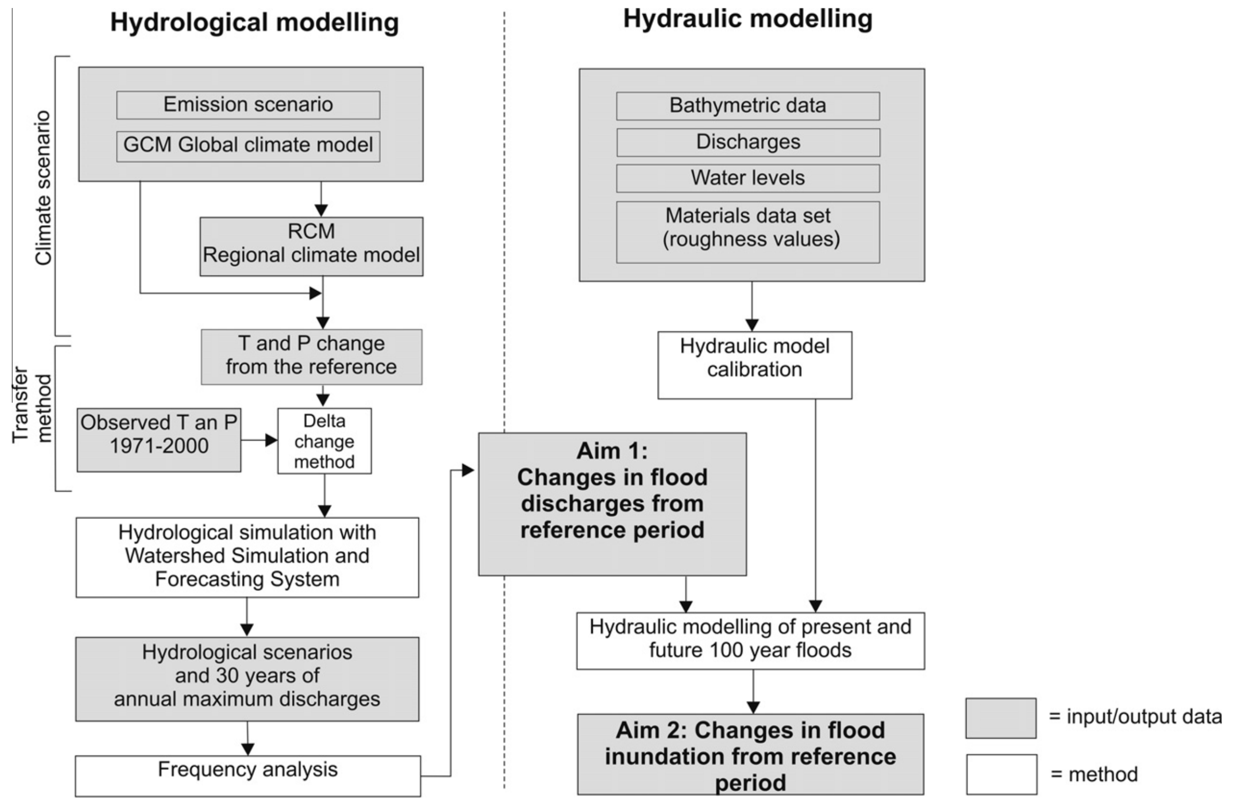


**Fig. 2.** Schematic representation of the method used in flood assessment. Climate scenario information is transferred to the hydrological model with the delta change approach and frequency analysis is performed on the simulated hydrological scenarios. The results of the hydrological modelling are used as input for flood inundation analysis.

(Table 2); in the winter they are almost twice as high as in summer. Precipitation changes are between 8% and 22%, without clear seasonal variation. RCM results can differ significantly from the GCM results from which they have been downscaled. It should be noted that the RCA3-H-A1B scenario is from a different version of the HadCM3 than the other scenarios from this model. This low sensitivity version (Q3) is part of a perturbed parameter ensemble of the HadCM3 model and produces smaller increases in temperature in 2070–2099 than the standard unperturbed version (Q0) (Collins et al., 2005). The perturbed version was simulated as part of an ensemble of HadCM3 model where poorly constrained land surface, sea ice and atmospheric parameters were slightly varied from the values in the standard version to enable systematic sampling of modelling uncertainties (Collins et al., 2005).

The performance of the climate models in simulating the climate of Finland, Scandinavia or Northern Europe has been addressed in several studies (Jylhä et al., 2004; IPCC, 2007; Jacob et al., 2007; Boberg et al., in press; Kjellstöm and Lind, 2009). Jylhä et al. (2004) compared five GCMs and found that the annual cycle of temperature was simulated qualitatively well, but some of the models tended to have a cold bias and too continental climate for Finland. Some RCMs have on the other hand been found to have warm winter bias over Scandinavia (Jacob et al., 2007) and Baltic Sea drainage basin (Kjellstöm and Lind, 2009).

On average GCMs included in the IPCC fourth assessment report (2007) simulated precipitation in Finland relatively well, within 30 mm (±5%) of the annual average observed precipitation (IPCC, 2007), but they were often unable to produce the observed seasonal cycle with too much precipitation in winter and too little in summer (Jylhä et al., 2004). The GCMs chosen for this study are mostly among the ones that perform better than average in this region (IPCC, 2007). The RCM biases can differ from biases of the driving GCMs (Jacob et al., 2007) and the biases in GCM can be amplified by the RCM (Kjellstöm and Lind, 2009). Kjellstöm and Lind (2009) found that a systematic wet bias of 10–15% in precipitation of the ECHAM5 GCM was increased to 20–30% in the RCM

**Table 2**
Climate scenarios used in the study (Finnish Meteorological Institute, ENSEMBLES data archive) and their projected annual changes in temperature and precipitation in Finland by 2070–2099 compared with the reference period 1971–2000. The greatest and the smallest changes are bolded.

| No. | GCM (see IPCC, 2007) | RCM | Emission scenario | Abbreviation | *T* change (°C) | *P* change (%) |
|---|---|---|---|---|---|---|
| 1 | 19 GCM mean | – | A2 | Mean-A2 | 5.03 | 18.7 |
| 2 | 19 GCM mean | – | A1B | Mean-A1B | 4.42 | 16.2 |
| 3 | 19 GCM mean | – | B1 | Mean-B1 | 3.20 | 12.1 |
| 4 | ECHAM5/MPI-OM | – | A2 | Echam5-A2 | 4.31 | 19.3 |
| 5 | ECHAM5/MPI-OM | – | A1B | Echam5-A1B | 4.12 | 18.2 |
| 6 | ECHAM5/MPI-OM | – | B1 | Echam5-B1 | 3.17 | 13.2 |
| 7 | UKMO-HadCM3-Q0[a] | – | A2 | HadCM3-A2 | 5.35 | 14.1 |
| 8 | UKMO-HadCM3-Q0[a] | – | A1B | HadCM3-A1B | **5.44** | 16.8 |
| 9 | UKMO-HadCM3-Q0[a] | – | B1 | HadCM3-B1 | 3.93 | 15.8 |
| 10 | CCSM3 | – | A2 | CCSM3-A2 | 4.75 | 14.9 |
| 11 | CCSM3 | – | A1B | CCSM3-A1B | 3.54 | 12.9 |
| 12 | CCSM3 | – | B1 | CCSM3-B1 | 2.72 | 7.8 |
| 13 | CNRM-CM3 | – | A2 | CNRM-A2 | 3.50 | 15.4 |
| 14 | CNRM-CM3 | – | A1B | CNRM-A1B | 3.16 | 12.3 |
| 15 | CNRM-CM3 | – | B1 | CNRM-B1 | **1.80** | 7.8 |
| 16 | ECHAM5/MPI-OM | RCA3 | A1B | RCA3-E-A1B | 3.50 | 20.3 |
| 17 | ECHAM5/MPI-OM | REMO | A1B | REMO-E-A1B | 3.36 | 12.8 |
| 18 | UKMO-HadCM3-Q3[b] | RCA3 | A1B | RCA3-H-A1B | 3.50 | **22.1** |
| 19 | UKMO-HadCM3-Q0[a] | HadRM | A1B | HadRM-H-A1B | 5.07 | 18.9 |
| 20 | ARPEGE/CNRM-CM3 | HIRHAM | A1B | HIRH-A-A1B | 3.63 | **7.6** |

[a] Mean sensitivity version (see text for details).
[b] Low sensitivity version.

RCA3 in the Baltic Sea drainage basin that includes most of Finland. Jacob et al. (2007) found the RCM simulated inter-annual precipitation variability to be in relatively good agreement with observations. Boberg et al. (in press) compared RCM simulated precipitation probability density functions (PDFs) with the observed ones and noted that the PDFs, including their tails, were mostly in good agreement with observations. Additionally the three RCMs that were in common with the study by Boberg et al. and this study (HadRM-H-A1B, REMO-E-A1B, HIRH-A-A1B, see Table 2) were among the best performing RCMs in Scandinavia. Christensen and Christensen (2007) noted that RCMs with quite different biases are much closer to each other when simulating climate change impact since part of the biases is cancelled out by the relative change. Jylhä et al. (2004) made similar findings about changes in GCMs in Finland. However, even when the relative changes are used in the delta change approach, the climate model performance is still important to produce a credible climate change signal.

### 3.2. Method of transferring climate change

The method used to transfer the climate change from the global climate model to the hydrological model was the delta change approach (also called the perturbation or change factor approach). In the delta change approach the monthly changes of temperature (in °C) projected by the climate scenarios are added to the observed temperature and changes of precipitations (in %) are multiplied with the observed precipitation values of the reference period. This is the most widely used method in impact studies in the past (e.g. Minville et al., 2008; Prudhomme and Davies, 2008). The advantage of this approach is that it is robust and easy to apply, and since it uses temperature and precipitation observations in the reference period, the simulated discharges correspond well to observed discharges. The limitations of this method include the assumption that the number of wet days and the variability of temperature and precipitation do not change and thus extreme precipitations are modified by the same factor as all other precipitations (Graham et al., 2007). The results are also dependant on the properties of the reference period. These limitations may not be very significant when average hydrological conditions are examined, but when floods are studied the correct changes in extremes become important (Graham et al., 2007), especially in rainfall dominated watersheds. These limitations of the delta change approach are discussed more in Section 5.2.1.

For temperature, a modification to the basic delta change method proposed by Andréasson et al. (2004) was used (Eq. (1)), because results from climate models indicate that cold days in Finland will warm more than the average monthly temperature (Räisänen et al., 2004; IPCC, 2007). The delta change approach therefore included a temperature-dependent component so that the daily temperature change was based on seasonal linear transfer functions (Andréasson et al., 2004), where the temperature change depends on the reference period temperature. The temperature changes were scaled so that the average monthly temperature change in the 30 year period was the same as in the climate scenario (Eq. (1)).

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

where $T_{\mathrm{mod}}$ is the modified daily temperature, $T_{\mathrm{obs}}$ is the observed daily temperature in the reference period, $\Delta T$ is the temperature change, $s_m$ is the monthly scaling factor that scales the monthly changes to correspond 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 daily temperatures of the RCMs.

### 3.3. Hydrological modelling

The hydrological simulations were performed with the Watershed Simulation and Forecasting System (WSFS) developed and operated in the Finnish Environment Institute (Vehviläinen et al., 2005). The WSFS is used in Finland for operational hydrological forecasting and flood warnings (www.environment.fi/waterforecast/), regulation planning and research purposes (Vehviläinen and Huttunen, 1997; Veijalainen and Vehviläinen, 2008). The main part of the WSFS is a conceptual watershed model based on the HBV model (Bergström, 1976). The basic structure of the WSFS is the HBV model structure, but there are differences in the river routing, watershed description and some process models such as the snow model (Vehviläinen et al., 2005). Different versions of the HBV model have been used in many countries in hydrological climate change studies, and in Scandinavia HBV is the most commonly used model type (Vehviläinen and Huttunen, 1997; Andréasson et al., 2004; Booij, 2005; Akhtar et al., 2008; Beldring et al., 2008; Steele-Dunne et al., 2008).

The hydrological model of the WSFS is semi-distributed as it is divided to over 6000 small lumped sub-basins (~40–500 km$^2$) with their own water balance simulations (Vehviläinen et al., 2005). These sub-basins are connected to form the entire watersheds. The WSFS includes a precipitation model for evaluation of areal precipitation and its form, a snow model based on temperature index approach, a rainfall–runoff component that consists of a soil model with three stores, and lake and river routing scheme (Fig. 3). All lakes in Finland with an area over 100 ha, in total approximately 2600 lakes, are included in the model.

The input data in these simulations were daily precipitation and air temperature. Potential evaporation was calculated in the WSFS using air temperature, precipitation and time of year (an index for available net radiation) (Vehviläinen and Huttunen, 1997). This equation has been calibrated and verified against observations of Class A pan evaporation values (Vehviläinen and Huttunen, 1997). The actual evaporation is calculated from potential evaporation and the soil moisture deficit. The changes in temperature and precipitation affect the potential evaporation and in addition changes in soil moisture deficit affect actual evaporation. Evaporation has in many studies (Andréasson et al., 2004; Menzel et al., 2006; Steele-Dunne et al., 2008) been simulated with simple temperature-index models, but this may lead to larger increases of evaporatranspiration than given by climate models (Andréasson et al., 2004). The method used here has the time of year as index of available radiation, which limits the increases of potential evaporation especially in winter, but is similarly a simple method of estimating potential evaporation. Since this study focuses on estimation of floods, the changes in potential evaporation do not affect the results as much as if low flows were estimated.

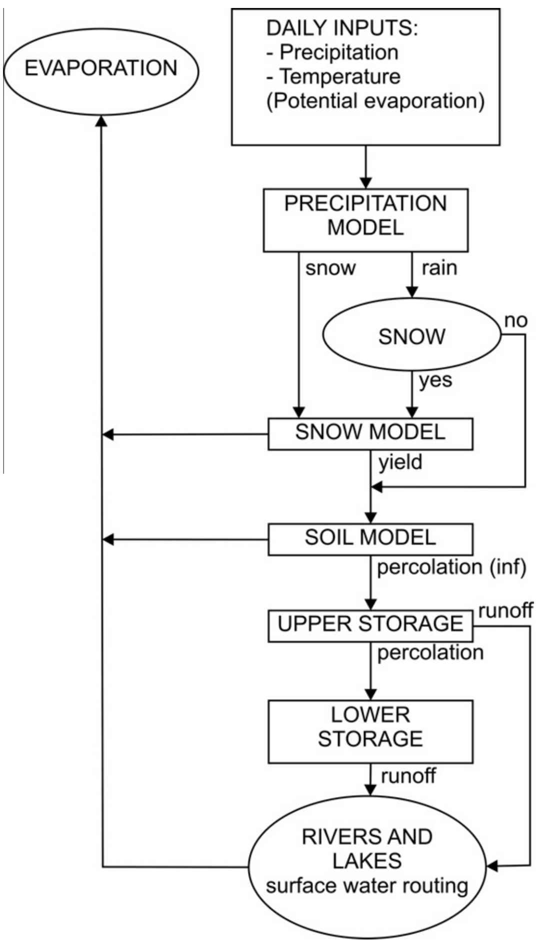


**Fig. 3.** The basic structure of the Finnish watershed model WSFS; see main text for further explanation (adapted from Vehviläinen et al., 2005).

The WSFS has been calibrated with observations of snow water equivalent, water level and discharge from 1981 to 2008 (see Section 4.1). The optimization criteria in the calibration were the sum of the square of the difference between the observed and simulated water equivalents of snow, discharge, and water level. Also satellite observations from snow cover were used in the calibration. These variables are combined in the calibration with weights based on the estimated relative reliabilities of the observed values and on experience of model performance with different weights. The calibration procedure used was a modification of the direct search Hooke–Jeeves optimization algorithm (Hooke and Jeeves, 1961), which has been developed into a fully automatic procedure. Calibrated parameters included parameters for areal temperature and precipitation, snow accumulation and melt, evaporation, runoff generation, storages and river and lake routing. Only one optimal parameter set was used in the modelling and thus modelling uncertainty was not estimated.

Lake regulation, which influences the discharges especially in the lake area, was modelled with operating rules, where a certain water level of each day corresponds to a certain outflow. This approach reproduces on average well the actual regulation, but since the same rule is applied every year, the regulation is not optimal in all individual years. The regulation permits in Finland usually give freedom of choice for the actual day to day regulation to the operators within certain limits. The actual regulation can therefore be influenced by electricity prices and subjective decisions of the operators and cannot be modelled exactly. The operation rules were modified to function properly in climate change simulations with changing timing of spring floods. Only six study sites (marked with squares in Fig. 1c) are significantly affected by regulation, and with the largest floods the limited storage capacity reduces the effect of regulation. This approximation of regulation is still more accurate than ignoring the regulation altogether, as in the continental scale studies (Lehner et al., 2006; Dankers and Feyen, 2008).

### *3.4. Frequency analysis*

The 100-year floods were estimated on the basis of the annual maximum discharges of the hydrological year from September to August. The Extreme Value I, e.g. the Gumbel distribution was fitted to the unhomogenised maximum values from 30 years of simulated discharges. The hydrological year was used, since in the future the long lasting floods of the large watersheds often occur during winter. Thus the same flood would often be picked twice if calendar year would be used. This was not usually the case with hydrological year in Finland since major summer floods usually occur only in small watersheds where floods are short. The Gumbel distribution is the most commonly used and officially recommended distribution in Finland (Ministry of Agriculture and Forestry, 1997). For short records even one or two values can significantly affect the value of the shape parameter and thus a two parameter distribution, such as the Gumbel distribution, where the shape parameter is set in advance, provides more stable results when extrapolating to rare floods (Ward, 1978). Dankers and Feyen (2008) found that GEV distribution fitted to simulated annual maximum discharges did not provide significant improvement from the corresponding Gumbel distribution in most parts of Finland except in some northern rivers. The method of moments was used to estimate the parameters of the Gumbel distribution (Kite, 1977). See also Section 4.1 for goodness of fit of the Gumbel distribution to observations.

### 3.5. Hydraulic modelling

Flood inundation areas were simulated with a two-dimensional hydraulic model, Two-dimensional Unsteady FLOW (TUFLOW). It uses full two-dimensional, depth averaged, momentum and continuity equations for free-surface flow calculations and an alternating direction implicit (ADI) finite difference method as the computational procedure (TUFLOW, 2007).

The geometry data of the river channel and flood plain for the 2D hydraulic model were from the Finnish Environment Institute, Regional Environment Centres and the Department of Geography, University of Turku. The input data sets, from which the final grids were created, consisted of photogrammetric TIN (Triangulated Irregular Network) models in Lapua (with point density of c. 20 m and ±30 cm z accuracy) and Kittilä (with point density of 10–40 m and ±20 cm z accuracy), 10 m national Digital Terrain Models (DTM) in Kokemäenjoki and 25 m national DTM in Salo. The DTM in Salo was enhanced with point elevation data measured by the University of Turku, Southwest Finland Regional Environment Centre and the City of Salo (Selin, 2006). Contour lines (i.e. 2.5 m or 5 m interval, and accuracy of 5–20 m depending on the area) were also used in Salo and Kittilä for interpolation of the DTM grid. The river channel data consisted of sonar point data measured in cross-sections or longitudinal lines. The distance between cross-sections was in Lapua c. 200 m, in Pori 50–70 m and in Kittilä 40–200 m. In Salo the echo sounding was done in longitudinal lines, with point spacing 0.5–1 m and line spacing 2–10 m. For minimization of the interpolation errors, the channel was interpolated first separately before immersing it to the DTM of the surrounding areas. The compiled geometry data was converted to grid form with a resolution of 10 m.

The hydraulic model was calibrated in each study site by adjusting the Manning's *n* values of bed roughness and matching the modelled water levels with the observed ones. The observed water level and discharge data was from the national databases and from Regional Environment Centres. The observed discharge was set as an upstream boundary condition and water level as a downstream boundary condition. At the sites on the coast (Salo and Pori), the downstream boundary condition was the water level of the Baltic Sea. In both locations N60 vertical datum (based on 1960 mean sea water level at Helsinki) + 0.4 m was set to depict the normal water level situation (Selin, 2006). Based on the observed sea water levels, the values N60+1.2 m (Salo) and N60+1.4 m (Pori) were set to depict the extreme sea water levels.

After calibration, the flood inundation area extents were simulated as steady flow events (Fig. 2). The results of hydrological modelling, i.e. the minimum and maximum 100-year discharge scenarios in 2070–2099 and in the reference period, were used as upstream boundary conditions. The corresponding water levels were used as downstream boundary conditions. The sea water levels were used in Kokemäenjoki and Salo, but in Kittilä the downstream water levels were obtained by using power function fitted to the observed water levels and discharges. In Lapua the downstream water levels were based on values calculated with a rating curve, which had to be extrapolated beyond the observed range, from simulated discharges of the WSFS. The extents and changes of the inundation between different scenarios and the reference period were calculated with a resolution of 10 m.

## 4. Results

### 4.1. Validation

The hydrological model was rather well able to reproduce the observed discharges with the observed temperature and precipitation as input. The performance of the hydrological model can be evaluated with the Nash–Sutcliffe efficiency criteria $R^2$ (Nash and Sutcliffe, 1970), which was on average 0.87 (range 0.67–0.94) for the 67 study sites for the simulation period 1971–2000. The Nash–Sutcliffe efficiency criteria $R^2$ for the calibration period 1981–2008 was on average 0.86 (0.60–0.94) and for the validation period 1971–1980 also 0.86 (0.66–0.93). The sites with the lowest Nash–Sutcliffe efficiency criteria are the ones that are significantly regulated and the errors in the modelling of the regulation decrease the fit to observations.

The 100-year floods calculated with the Gumbel distribution from the simulated discharges of 1971–2000 and the corresponding floods based on observations of the same period (or shorter if length of the observation series was shorter) differed on average by only 2% (Fig. 4a). The variation was however considerable from −21 to +19%. The observed average discharges were on average 4% larger than the simulated discharges (Fig. 4b). From here on the reference period 100-year floods are the ones based on simulated discharges with the observed temperatures and precipitations from 1971 to 2000 as input. The simulated floods in 2010–2039 and 2070–2099 will be compared to these simulated floods of the reference period.

The fit of the Gumbel distribution to observed annual maximum discharges of 1971–2000 was estimated with two goodness of fit tests; the chi-square test (e.g. Kite, 1977) and the probability plot correlation coefficient test statistic (Heo et al., 2008). The null hypothesis that the observations could be from the Gumbel distribution was accepted with 0.05 significance level in all but six sites (9.0% of the sites) with the chi-square test and all but four sites (6.0%) with the probability plot correlation coefficient test statistic. Especially the probability plot correlation test statistic value was close to the expected non-acceptance rate of 5% and thus the use of the Gumbel distribution can be accepted.

### 4.2. Changes in flood discharges

According to the simulations, the 100-year floods in Finland decreased on average by 8–22% in 2070–2099 compared to the reference period (Fig. 5), but variation between different sites and regions was considerable (Fig. 6). When seasonal 100-year floods were estimated separately the average decrease in spring (March–June) floods was 15–40% by 2070–2099, whereas the corresponding floods in other seasons increased 12–40%. Decreases in the 100-year floods occurred by 2070–2099 in areas dominated by spring snowmelt floods in northern and most parts of central Finland because increased temperatures caused snow accumulation to decrease (Figs. 6 and 7). Decreases were largest and most consistent in central Finland; in the southern part of the northern rivers and in the northern part of the lake area. Further north the temperatures are colder at present and therefore more snow and larger snowmelt floods remained in 2070–2099, whereas further south the snowmelt floods are not as dominant even in the reference period.

Increases occurred especially in large central lakes and their outflow rivers in the lake area where the floods are currently long-lasting volume floods and already occur in autumn as well as in springtime (Figs. 6 and 7). These floods increased due to increased precipitation and wetter and milder autumns and winters. Increases also occurred in some small rivers along the southern coast. Autumn and winter floods increased considerably and they even became the largest floods in southern Finland (Fig. 7). Evaporation explains part of the change; in summer months the average evapotranspiration is higher than the average precipitation (Mustonen, 1986), whereas in winter the evapotranspiration is very low and thus lower precipitation amounts can cause flooding in winter.

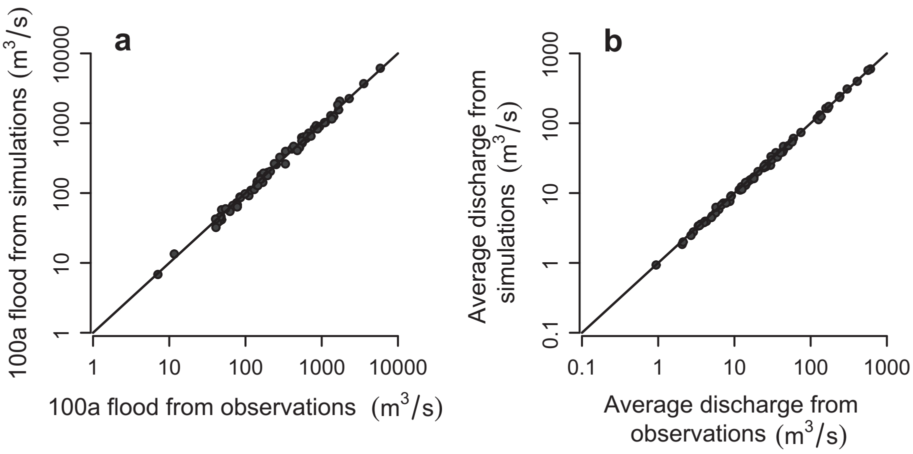


**Fig. 4.** Comparison of simulated (with observed temperatures and precipitations) and observed values in 1971–2000 at 67 sites: (a) 100-year floods with the Gumbel distribution and (b) average discharge.

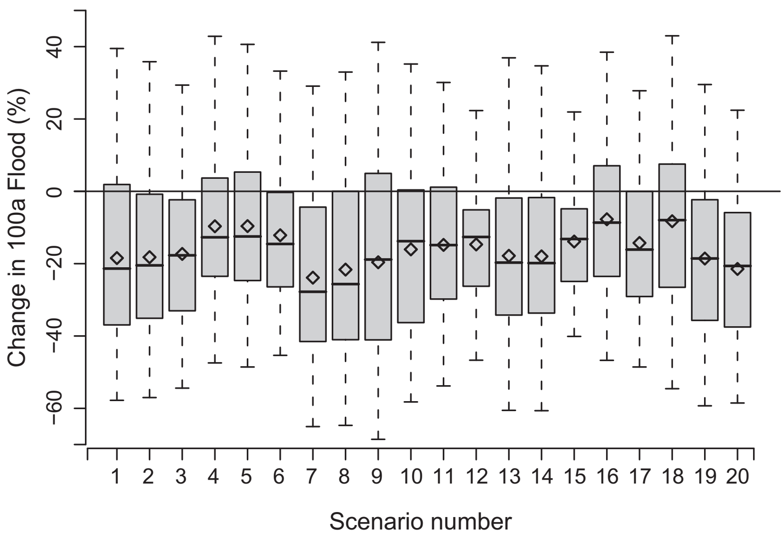


**Fig. 5.** Box plot (median, 25 and 75 percentiles, average [diamond], max and min) of changes in 100-year floods in 2070–2099 at the 67 sites with different scenarios. Numbering of the scenarios is according to Table 2.

The variability between the 20 climate scenarios was high and at 58% of the sites the changes were not significant (less than 10% change) at least with one scenario in 2070–2099. The average change in floods in the 67 sites in 2070–2099 with the minimum scenario (the scenario producing the smallest floods in future for each site, different scenario on different sites) was −30.5% while corresponding change with the maximum scenario (corresponding scenario for largest floods) was only −1.2%.

By 2010–2039 the changes from the reference period were smaller; with many scenarios the 100-year floods changed less than 10% from the reference period (Fig. 6). With the minimum scenarios, floods in 2010–2039 decreased in more sites than in 2070–2099, but the decreases were smaller in magnitude. In northern Finland the snowmelt floods on average remained unchanged in 2010–2039, since the temperature increase was not yet large enough to melt the snow significantly and the increase in snowfall compensated for most of the snowmelt caused by temperature increase. At some sites the floods first decreased in 2010–2039 and then increased in 2070–2099, which was caused by the transitional phase when the spring floods decreased and autumn and winter floods increased.

The differences between the scenarios were estimated by comparing the average changes of the scenarios (marked with diamonds in Fig. 5). The differences between different emission scenarios with the same GCM were rather small; the average changes in floods differed on average by 1.7% units in 2070–2099. The B1 scenario differs from the other emission scenarios in some models up to 4% units and also has smaller variance (Fig. 5). By comparison, the differences between results directly from GCM and the same GCM and emission scenario downscaled with RCM were on average 3.3% units, which is considerably higher than the difference between emission scenarios. The difference between different GCMs with the same emission scenario were even greater, on average 5.1% units (Fig. 5), indicating that the GCMs are a greater source of uncertainty than the choice of emission scenario or RCM.

The flow regimes in different regions in Finland are demonstrated with the five example hydrographs of the reference period and of 2070–2099 (Fig. 8a–e, see Fig. 1c for locations). In northern (Fig. 8a) and central (Fig. 8b) Finland the spring flood peaks are currently by far the largest floods and as they mostly decreased with climate change the magnitude of the annual 2 and 100-year floods decreased. In the north (Fig. 8a) some scenarios still produced large spring floods in 2070–2099. In southern Finland (in the coastal rivers Fig. 8e and in the lake area Fig. 8d) large floods occurred not only in spring but also in autumn and winter in the

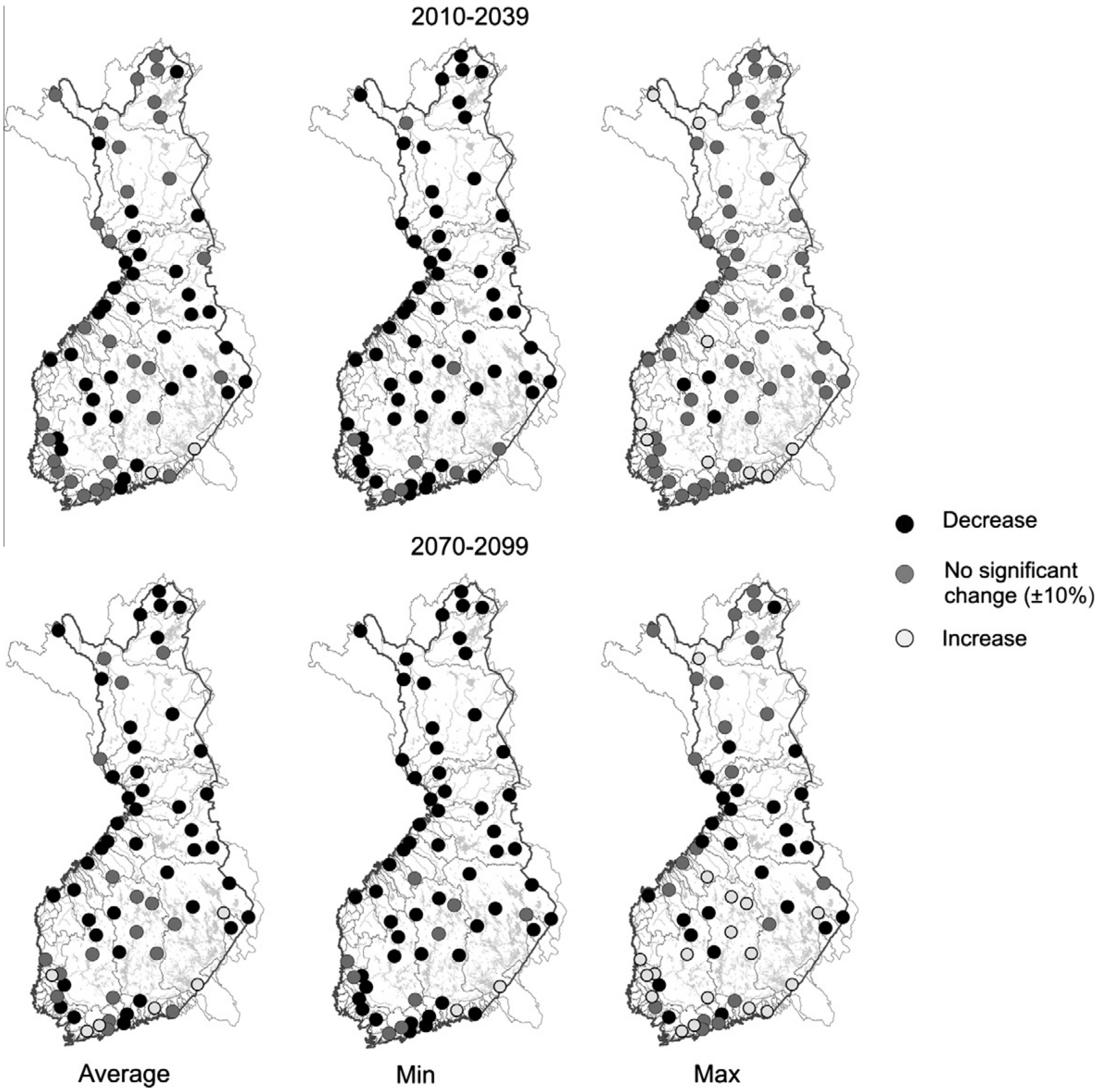


**Fig. 6.** Changes in 100-year floods by 2010–2039 (upper row) and 2070–2099 (lower row) from the reference period 1971–2000. Average change of the 20 scenarios (left) and minimum (middle) and maximum (right) changes of the 20 scenarios, which give the range of change.

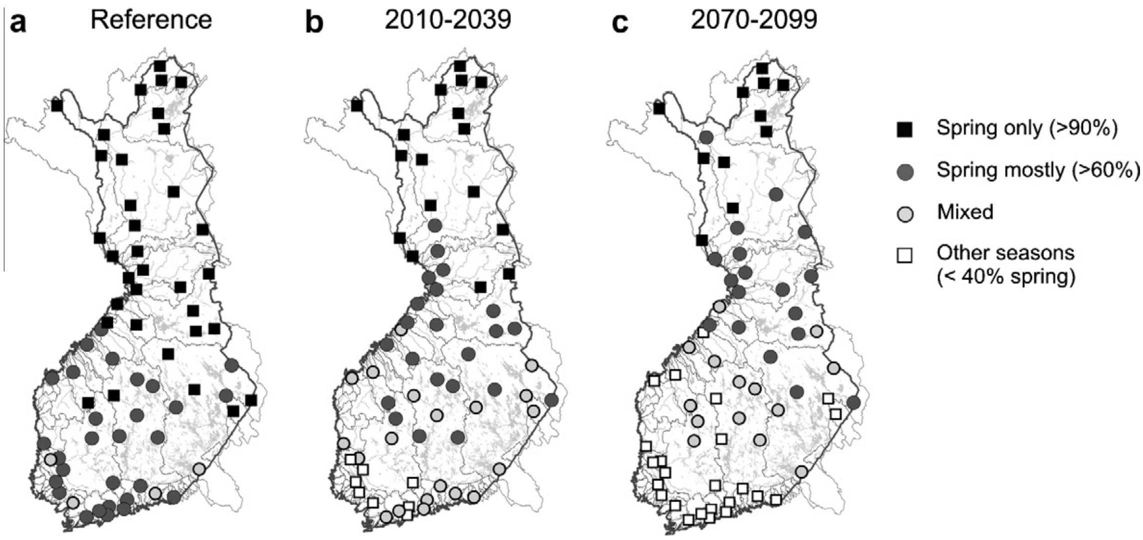


**Fig. 7.** Timing of the simulated annual maximum floods (% of spring floods, March–June) in the reference period (a, left), and in 2010–2039 (b, middle) and in 2070–2099 (c, right) with the median scenario.

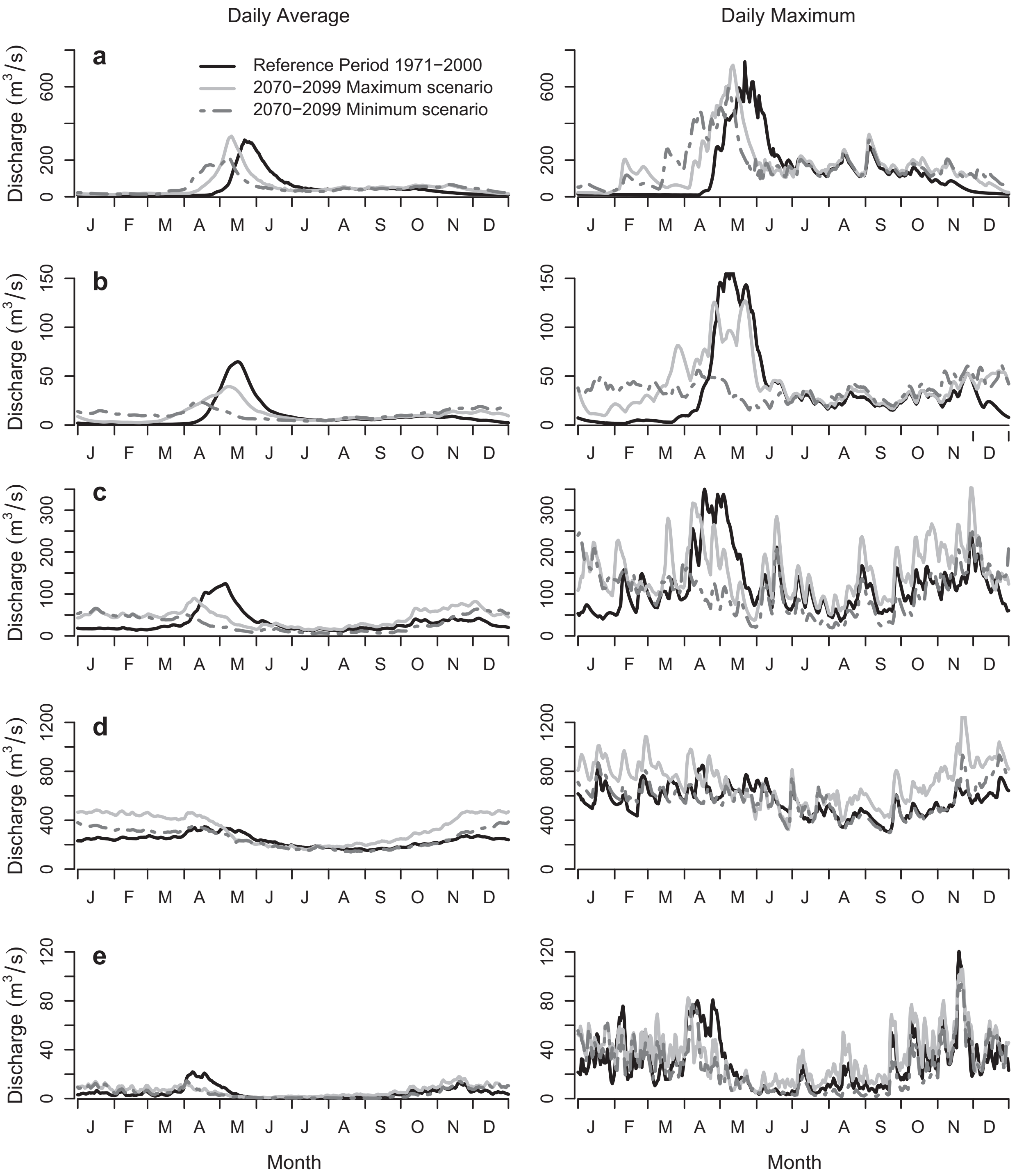


**Fig. 8.** Example hydrographs with daily average (averages of daily values from 30 years simulation period) (left) and maximum (corresponding daily maximum values) (right) discharges from five locations in 1971–2000 and in 2070–2099 with minimum and maximum scenarios: (a) Köngäs, (b) Sonkajärvi, (c) Keppo, (d) Harjavalta, (e) Uskelanjoki (see Fig. 1c for locations). The inundation area analysis was performed at or close to locations (a), (c–e). Note: scale of the *y*-axis varies in graphs a–e.

reference period and climate change increased these floods making them the largest floods. In the northern part of the coastal area the rate of change of discharges is rapid, but the spring floods were larger than floods in other seasons (Fig. 8c).

In southern Finland the changes in future precipitation have the greatest effect on the flood discharges in 2070–2099 (Fig. 9, Table 2). Most of the largest floods in the coastal rivers and the lake area in 2070–2099 are produced by a scenario with large precipitation increases (scenario number 18, RCA3-H-A1B) and the smallest floods by a scenario with small increases in precipitation (No. 20, HIRH-A-A1B). In the spring flood dominated northern rivers region the temperature change is the most important factor determining the magnitude of floods in 2070–2099, and scenarios with small temperature increases (No. 10–12, CCSM3 and No. 16–17, RCM Echam5) produce the largest floods and scenarios with large temperature increases (No. 7–9, HadCM3) produce the smallest floods.

The catchment characteristics and current hydrological properties can be used to explain the results and their correlations with the average changes in 100-year floods by 2010–2039 and 2070–

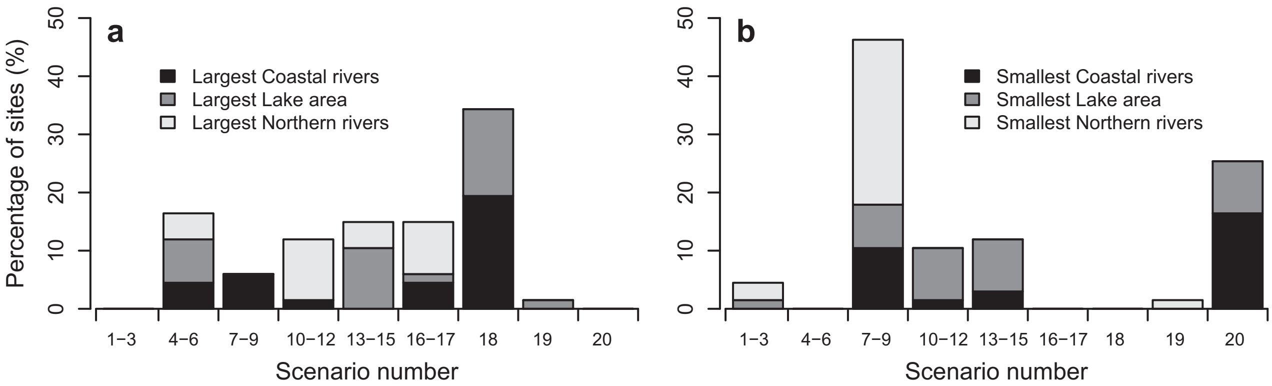


**Fig. 9.** Climate scenarios producing the largest (a) and smallest (b) flood discharges out of the 20 scenarios in 2070–2099 (as percentage of sites and in different regions, see Fig. 1b for regions). Numbering of the scenarios is according to Table 2.

**Table 3**
Correlation between the average changes of 100-year floods from the 20 scenarios and the properties of the study sites. Statistically significant correlations ($P < 0.05$, $N = 67$) are marked with an asterisk.

| Watershed properties | Correlation $r$ | |
|---|---|---|
| | 2010–2039 Average change | 2070–2099 Average change |
| Percentage of spring floods | −0.519* | −0.703* |
| Ratio of spring 100 year floods to floods in other seasons | −0.482* | −0.731* |
| Latitude | −0.097 | −0.345* |
| Longitude | −0.153 | 0.265* |
| Winter temperature | 0.056 | 0.321* |
| Annual maximum SWE | −0.187 | −0.452* |
| Size of the watershed (km$^2$) | 0.368* | 0.343* |
| Lake percentage | 0.185 | 0.408* |

* Statistically significant correlation.

2099 were calculated. These relationships can be used to understand the factors affecting the results and to regionalize the results. The best correlations with a single explanatory variable for the changes by 2070–2099 were found with the percentage of spring flood out of annual maximum floods in the reference period (−0.703) and the ratio of spring flood magnitude to the magnitude of other floods (−0.731) (Table 3 and Fig. 7). The more spring floods occurred in the reference period and the larger the ratio between spring and other floods, the more the floods on average decreased. Other variables that were correlated with the results included latitude, longitude, lake percentage, size of the watershed, average winter temperature and average maximum snow water equivalent (SWE). The coefficient of multiple correlation $R$ for all these variables was 0.88 in 2070–2099 and 0.77 in 2010–2039 and thus the average changes in floods can be explained to a large extent by the watershed properties. The relationship between the average change of 100-year floods and all the eight variables of Table 3 was determined by fitting an equation with eight linear predictors to the changes of floods with method of least squares and calculating first the coefficient of determination $R^2$ and then the coefficient of multiple correlation $R$. An even better fit was obtained if the three regions were examined separately; then the coefficient of multiple correlation in 2070–2099 with all the variables was 0.96 for the lake area, 0.95 for the coastal rivers and 0.95 for the northern rivers. The greatest decreases in 100-year floods in this study are around latitudes 65–66° north and the decreases become smaller further south and north.

### 4.3. Changes in flood areas

The changes in 100-year discharges in 2070–2099 (Tables 4 and 5) were reflected in the changes of the flood inundation; the increasing future discharges resulted in increasing inundation and decreasing discharges in reduction of flood area, but no linear relation was found. For example, in Lapua the relative change in flood area was greater than in discharges, whereas in Salo the discharge change was many times larger than the change in inundation area (Table 5).

The range of changes (in m$^2$ and %) was greatest in Lapua (river Lapuanjoki) (Table 5 and Fig. 10). The area is topographical smooth and therefore even small changes in discharges and water levels can easily cause changes in inundation extent. In the Lapua settlements the inundation area of the 100-year flood decreased from the reference period by 12% with the maximum scenario and as much as 90% with the minimum scenario (Tables 4 and 5). The great reduction in inundation area with minimum scenario was a result of 1.38 m reduction in water level (Table 6). The corresponding decreases in discharges were 11% and 32%, which were the greatest of the four study locations. In the minimum 100-year flood scenario the water did not exit the river channel and inundation area was formed only in a narrow stretch of the study reach.

The city of Pori (river Kokemäenjoki), located on the topographically low lying delta area, is one of the most flood prone areas in Finland and the results indicate that flooding would increase in the future. The inundation area extents of both maximum (RCA3-H-A1B) and minimum (CNRM-B1) 100-year flood scenarios increased in 2070–2099 compared to control period, +31.3 and

**Table 4**
100-year discharges (Q) and downstream water surface elevation (WSE) used for flood inundation modelling.

| Study site | Reference 1971–2000 Q (m$^3$/s) | Reference 1971–2000 WSE (m) | 2070–2099 max 100-year scenario: Q (m$^3$/s) | 2070–2099 max 100-year WSE (m) | 2070–2099 min 100-year scenario: Q (m$^3$/s) | 2070–2099 min 100-year WSE (m) |
|---|---|---|---|---|---|---|
| Kittilä (a) | 1058 | 177.13 | CCSM3-B1: 1097 | 177.23 | Mean-A2: 758 | 176.18 |
| Lapua (c) | 241 | 29.95 | RCA3-H-A1B: 215 | 29.78 | HaCM3-A2: 164 | 28.5 |
| Pori (d) | 1029 | 1.4 and 0.4 | RCA3-H-A1B: 1429 | 1.4 and 0.4 | CNRM-B1: 1093 | 1.4 and 0.4 |
| Salo (e) | 113 | 1.2 and 0.4 | RCA3-H-A1B: 100 | 1.2 and 0.4 | CNRM-A1B: 88 | 1.2 and 0.4 |

**Table 5**
Flood inundation area extents calculated in four areas (Fig. 1c, Table 1, a and c–e). In Salo and Pori, the modelling was made by using two different sea water levels. Inundation area extents of minimum and maximum scenarios in 2070–2099 were compared to reference period flood area extents.

| Study site | Reference ($km^2$) | Max 2070–2099 ($km^2$) | Change in area ($km^2$) | Change in area (%) | Change in discharges (%) | Min 2070–2099 ($km^2$) | Change in area ($km^2$) | Change in area (%) | Change in discharges (%) |
|---|---|---|---|---|---|---|---|---|---|
| Lapua | 3.7 | 3.3 | −0.5 | −12.1 | −10.9 | 0.4 | −3.4 | −90.1 | −31.9 |
| Pori (WSE 0.4 m) | 29.86 | 39.2 | +9.3 | +31.3 | +38.9 | 31.83 | +1.97 | +6.6 | +6.2 |
| Pori (WSE 1.4 m) | 37.2 | 41.8 | +4.6 | +12.2 | +38.9 | 38.27 | +1.1 | +3 | +6.2 |
| Salo (WSE 0.4 m) | 1.2 | 1.2 | 0 | 0 | −8.7 | 1.2 | 0 | −0.8 | −20.9 |
| Salo (WSE 1.2 m) | 1.98 | 1.97 | −0.02 | −1 | −8.7 | 1.94 | −0.04 | −2 | −20.9 |
| Kittilä | 9.3 | 10 | +0.7 | +7 | +3.7 | 7.7 | −1.7 | −17.7 | −28.4 |

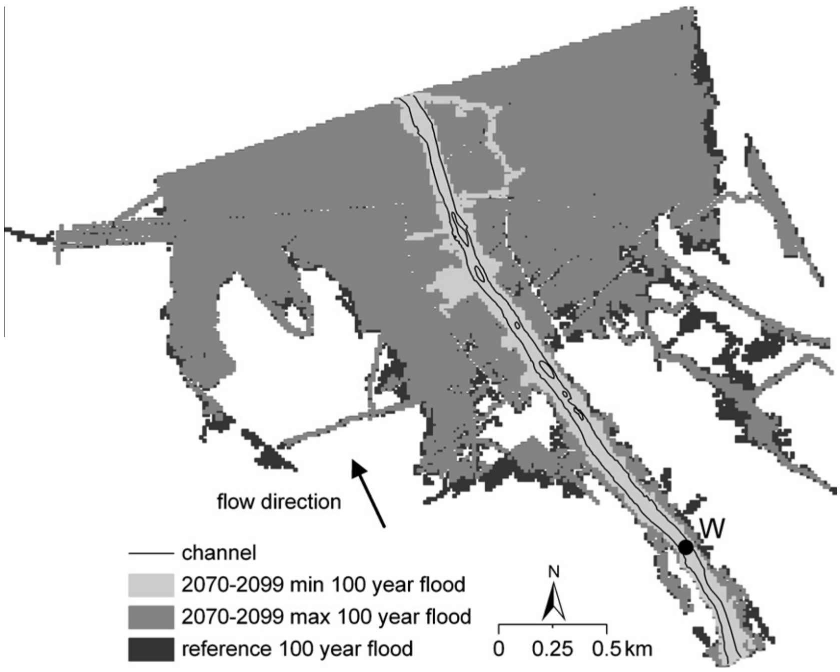


**Fig. 10.** Lapuanjoki north-west from the Lapua settlement center. The area consists mainly of fields and housing areas. Inundation area was reduced greatly in the minimum future scenario compared to the reference period. W = location of water levels showed in Table 6.

**Table 6**
The modelled water levels in the reference period and in 2070–2099 with the minimum and maximum scenarios at the settlements of Kittilä, Lapua, Pori and Salo (see also Figs. 10–12).

| Water level (W) at city centers | Reference period (m) | Max 100-year 2070–2099 (m) | Min 100-year 2070–2099 (m) |
|---|---|---|---|
| Lapua | 30.08 | 29.90 | 28.70 |
| Pori (Sea level = 0.4 m) | 2.25 | 2.61 | 2.32 |
| Pori (Sea level = 1.4 m) | 2.40 | 2.71 | 2.46 |
| Salo (Sea level = 0.4 m) | 1.21 | 1.12 | 0.98 |
| Salo (Sea level = 1.2 m) | 1.69 | 1.61 | 1.51 |
| Kittilä | 177.64 | 177.74 | 176.70 |

+6.6% with 0.4 m sea water level and +12.2 and +3% with 1.4 m sea water level. In the hydraulic modelling, an assumption was made that the flood protection terraces fail and the water has easy access to the city center. The water level at the city center, where the river branches to multiple channels, was with the maximum flood scenario 2.71 m (when downstream water level was 1.4 m) (Table 6). Without high flood protection terraces, the city encounters enormous flooding and high potential damage for over 5000 buildings (Alho et al., 2007) with all the 100-year floods modelled (Fig. 11). The sea level mainly affects the inundation of the low lying delta area. Elevating the existing flood protection terraces by approximately 0.3–1.5 m and building new terraces has already been planned (Pöyry, 2007). The new terraces at location W (Fig. 11) are planned to withstand high water levels of 2.90 m. With these elevated terraces, the city is protected from the 100-year floods of the magnitude studied here (Table 6).

In Salo and Kittilä the change in inundation was not as great as in the two previous study areas. The river Uskelanjoki at the city of Salo cannot be regarded as a typical watershed in southern Finland. The discharges decreased in all 2070–2099 scenarios, unlike in other nearby watersheds. However, the differences between inundation area extents compared to the reference period were small and water levels exceeded the bank elevations mainly only in the areas closest to the Baltic Sea (Fig. 12a and Table 6). The flooding was therefore substantially dependent on the changes in sea level and not on the actual changes in discharges. Even though −8.9 and

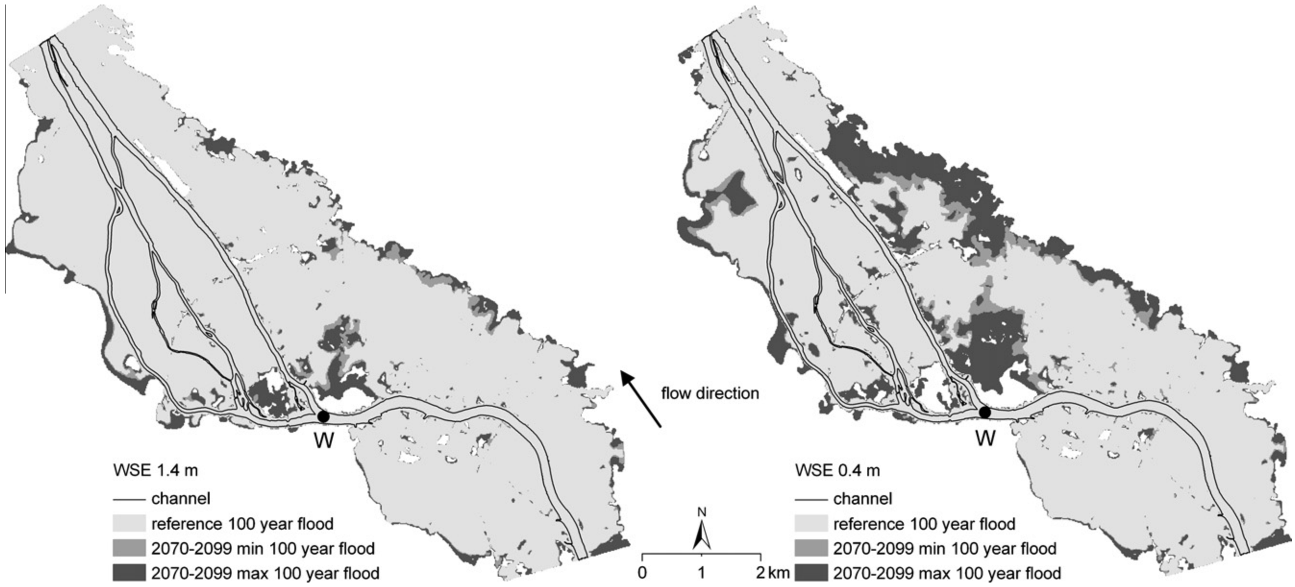


**Fig. 11.** Present and future inundation areas along Kokemäenjoki at the city of Pori. The 100-year flood simulations were performed for downstream boundary water surface elevations (WSE) of 1.4 and 0.4 m. W = location of water levels presented in Table 6.

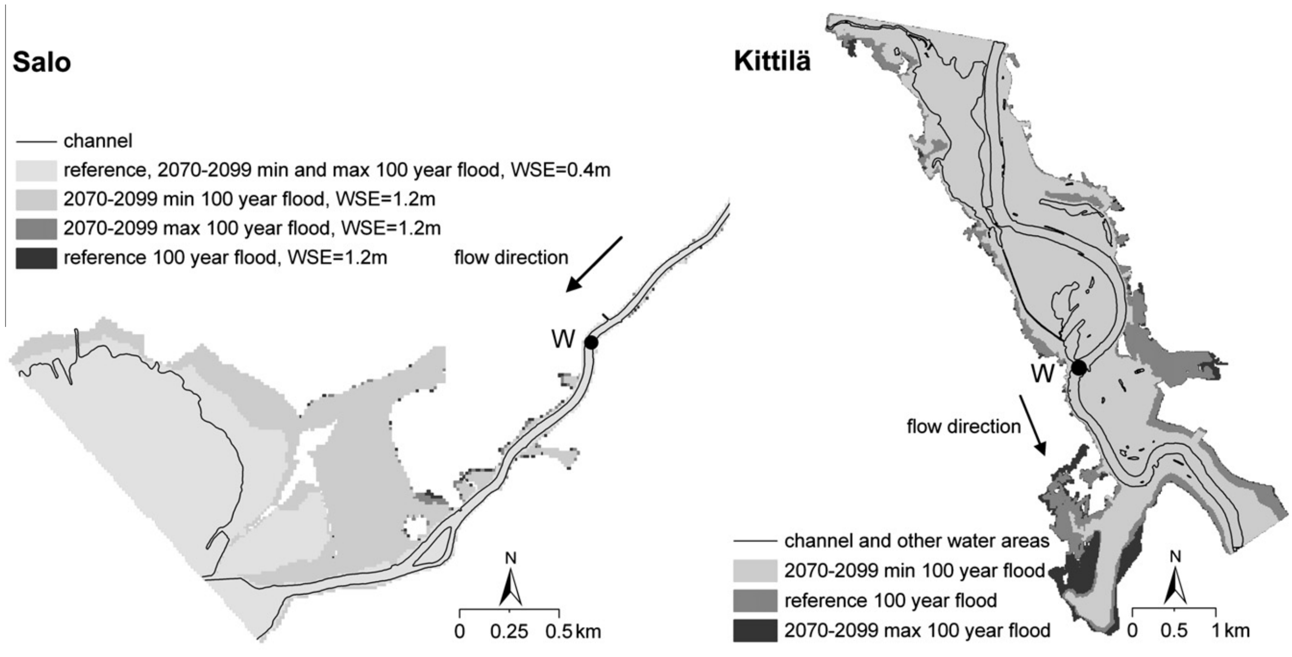


**Fig. 12.** The rivers Uskelanjoki at the city of Salo (left) and Ounasjoki at Kittilä municipality center (right). In Salo, simulations were performed for downstream boundary water surface elevations (WSE) 1.2 and 0.4 m. With 0.4 m WSE (lightest color), the inundation extents were almost equal with reference period, but also future minimum and maximum discharge scenarios. W = location of water levels shown in Table 5.

−20.9% decreases in discharges occurred compared to reference period, only 0–2% reductions in flood area were found. If the sea water level was set to 0.4 m, the reference period and maximum and minimum 2070–2099 inundation area extents were the same (Fig. 12a). If the water level was set to the extreme level of 1.2 m, the differences in spatial extent between scenarios were small; 1–2% decrease (Table 5). If climate change causes significant changes in sea level in this area, the flood risk will be affected, but this issue is out of the scope of this study.

The topographical variations of the northernmost study area, Kittilä, are the greatest of these four study sites. The flood inundated area is delimited in the valley of the surrounding fjells and 5–10 m relative elevation variations occur in close proximity to Kittilä settlement. The changes in inundation of Kittilä (Ounasjoki) were between +7 (RCA-E-A1B) and −18% (Mean-A2), which was close to the range of change in discharges (Table 5). The corresponding change in flood water level was between +0.1 and −1.04 m (Table 6). The area affected by 100-year flooding will most probably also be close to the reference period in the years 2070–2099 (Fig. 12b).

## 5. Discussion

### 5.1. Changes in floods and flood areas

The results are in agreement with results from previous studies in Finland (Vehviläinen and Huttunen, 1997; Silander et al., 2006) and in the neighbouring countries Sweden and Norway (Andréasson et al., 2004; Beldring et al., 2008). Spring snowmelt floods are estimated to decrease except in some of the coldest regions in the north (e.g. Andréasson et al., 2004; Beldring et al., 2008), and floods in the large central lakes in the lake areas are expected to increase (Vehviläinen and Huttunen, 1997; Bergström et al., 2006).

Compared to the continental scale studies (Lehner et al., 2006; Dankers and Feyen, 2008), which produced contradictory results, the results of the present study are more similar to the results of Dankers and Feyen (2008), who found decreases in floods in Finland. The results of Lehner et al. (2006) which indicated increases in flood risks in northern Europe appear to ignore the decreases in snow, which could be caused by error in the simple snow model together with the disaggregation of monthly means to daily data and this error appears even in model validation. The areas where this study, unlike that of Dankers and Feyen, found increasing flood trends are some small watersheds in the coastal and the lake areas where the difference is explained by the lack of lakes in the model used by Dankers and Feyen. This controversy can be explained by differences in study methodologies and models, one main difference being the WSFS hydrological model employed here, with thousands of lakes included in the database. These data were not accessible to Dankers and Feyen. In this respect the results of this study are more reliable since the lakes are an important part of the hydrology in this area and should not be ignored. This study uses a wider range of scenarios than previous studies and therefore the range of changes in floods was somewhat larger than in many other studies in this region.

In southern Finland there is considerable variation even between sites close to each other (Fig. 6). This indicates that wider conclusions based on few individual case studies in this area could be misleading. The variability in southern Finland can to some extent be explained by combination of the watershed properties and climatology, with the best explanatory variables being lake percentage and maximum snow water equivalent.

Although the floods remained unchanged or decreased at most of the 67 study sites, some of the most important flood risk areas are located in areas where floods were found to increase. Most of the largest cities are in the south and many important flood risk areas are on the shores of the large lakes or their outflow rivers. Ollila et al. (2000) have estimated flood damages of present day 250-year flood in different parts of Finland as part of a large national project involving regional state authorities. On average the floods in 2070–2099 increased only at 7.5% of the study sites, but based on a coarse estimate using the damages in different areas presented by Ollila et al. (2000) approximately 30–35% of the flood damages of an extreme flood were in these areas. Approximately 20% of flood damages were in areas with no significant change and 40–50% in the areas with decreasing flood trends in 2070–2099. This estimation is coarse approximation since not all sites and watersheds with damages were included in this study. With the maximum scenario more flood damages were in areas with increasing floods than in the areas of decreasing floods.

These results indicate that the changes in the extents of the studied flood hazard areas do not reflect linearly the changes in flood discharges. The decrease in flood inundation was clear in the topographically plane Lapua, where even small changes in discharges affected the inundation areas. Similar results can be expected in other rivers in the same region. At least in Pori even more attention should be paid to flood protection in the future, since the modelled water levels in 2070–2099 were higher than in the reference period with all scenarios. In Pori the difference between the maximum 2070–2099 scenario and the reference period was 31–36 cm, depending on the downstream boundary water level (Table 6).

The number of studies concerning climate change impacts on discharges and inundation extents simultaneously is very small. Basically, we have come across only one such study, by Lane et al. (2007) on an upland river in the UK. They found that the inundation extent of the one- in-0.5-year return period flood increased 12.2% for the 2050s and 21.6% for the 2080s, when the corresponding changes in flood discharges were only +8.2% and +14.7% (Lane et al., 2007). Although the return periods are very different, this is a similar pattern than in our investigation of the 100-year flood for Pori, where the increase in the inundation area extent was also greater than the increase in discharge. In other countries, the flood inundation mapping has been often done based on present day hydrological data without the climate change aspect (Schmidt-Thomé et al., 2006; Koivumäki et al., 2010) or the climate change effects on flooding have been estimated only in simulation of discharges and not flood areas (e.g. Andréasson et al., 2004; Dankers et al., 2007; Lenderink et al., 2007; Beldring et al., 2008). Thus, there is potential for studies in different countries of changes in future flood inundation areas based on multiple future discharge simulations.

The results can be utilized in the preliminary flood risk assessments and flood mapping performed according to the EU Flood Directive, in which climate change must be taken into account. The 67 sites where climate change impacts on floods were estimated include many of the same rivers where flood hazard mapping based on observed data has been performed. These simulated future discharges of the 67 study sites could therefore be used in estimating changes in flood inundation areas in other flood prone areas in Finland than only the four example sites for flood inundation analysis. The interpretation of the results should be performed with care, because of limitations of this study and major uncertainties in climate change impacts on flooding and flood area extents.

### *5.2. Uncertainties and limitations of the study*

Some of the major uncertainties included in estimation of extreme events and climate change impacts are demonstrated in this study. Many choices and assumptions affect the results, including the climate scenarios, method of transferring climate change to hydrological model, frequency distribution, hydrological model and its parameters.

The results provide a general overview of expected changes in fluvial floods in Finland. Changes in coastal floods caused by sea level rise, urban floods caused by extreme precipitations and frazil ice floods have not been estimated. Many important cities are located on the coast and therefore sea level rise could have a serious impact on flood damages. The inundation modelling in Pori and especially Salo showed that sea level affects the flood extent of these cities considerably. Changes in extreme precipitations have been projected (Beniston et al., 2007), which could increase risk for urban floods. In these flood simulations, no ice dams or frazil ice was taken into account. Floods caused by river ice have occurred in many study sites (Timonen et al., 2003). The changes in timing of floods towards winter months and decrease in the length of the ice cover period are expected to cause more frazil ice floods (Huokuna et al., 2009). Frazil ice problems were experienced during the mild winters of 2006–2008. The study sites did not include the most heavily regulated sites, where the results may be different since the current regulation efficiently decreases the spring floods and thus changes the hydrological characteristics.

#### *5.2.1. Climate scenarios and hydrological modelling*

Climate scenarios are a large source of uncertainty and the use of 20 different scenarios provides a wide range of results. The results showed that largest differences between the climate scenarios were on average between scenarios from different GCMs. This indicates that GCMs are a major source of uncertainty, as has been found in previous studies (Minville et al., 2008; Prudhomme and Davies, 2008; Steele-Dunne et al., 2008). The simulation period of 30 years is rather short for estimation of 100-year floods, and thus natural variability is also a source of uncertainty that has not been examined (Arnell, 2003; Minville et al., 2008).

The calculations were carried out with only one watershed model and one calibrated set of parameters and thus the modelling uncertainty was not estimated at all. The differences between the modelled and the observed discharges are explained by several factors including deficiencies in the model performance, errors in observations caused by rating curve extrapolation and ice jams, errors in spatial precipitation from deficiencies in the precipitation observation network and, in some sites, differences between modelled and observed regulation. The conceptual watershed model was at some sites used beyond the conditions to which it had been calibrated, which diminishes the model reliability (Seibert, 2003). Previous studies have found that the hydrological modelling uncertainty can be a significant, although not usually as large as uncertainties associated with GCMs (Prudhomme and Davies, 2008; Steele-Dunne et al., 2008; Lawrence et al., 2008). The calculation of evaporation from only temperature, precipitation, time of year and soil moisture deficit (Vehviläinen and Huttunen, 1997) without considering changes in other important factors such as air humidity, wind and vegetation cover is an important uncertainty in the hydrological modelling, although not as important when floods are examined as in other types of studies.

#### *5.2.2. Method of transferring the climate signal to the hydrological model*

In this study only one method, the delta change approach, was used to transfer the climate change to the hydrological model. In the delta change approach all days with precipitation within the same month are changed with the same factor. Thus the potential changes in rainfall variability and intensification of extreme precipitations are ignored, which can affect flooding substantially. This limitation is especially important in areas where floods are caused by short-term extreme precipitation and thus depend more on changes of extreme (e.g. one or several day maximum precipitation) than average precipitation. On most study sites the largest floods are caused by snowmelt or the floods are long lasting due to large runoff areas and high lake percentage. This limits the effect of short time extreme precipitation and thus the delta change approach is likely to provide adequate results on most study sites. However, in the small watersheds in coastal area especially in southern Finland summer extreme precipitation may cause large floods, although these have not been very common (Fig. 8e). Jylhä et al. (2007) compared average and 5 day maximum precipitations of several RCMs in Finland and found that the maximums increased more than averages with most models in summer and to a lesser extent in spring. The differences were however not very large; the increases in average summer precipitation were 5–22% while the 5 day maximum summer precipitations increased 8–24%. The increase in extreme precipitation can influence the results especially on small coastal rivers in southern Finland and cause the future floods to be larger (increase more or decrease less) than the results of this study would indicate. This issue will be addressed in future studies.

Beldring et al. (2008), Lenderink et al. (2007) and Graham et al. (2007) have reported that the method used to transfer climate change to the hydrological model can have a significant effect on floods, even when the average discharges are similar. In these studies, the delta change approach produced larger decreases in floods than methods using more direct data from the RCMs (Graham et al., 2007; Beldring et al., 2008). Besides changes in precipitation variability, one reason is that in the delta change approach the increase in mild temperatures close to 0 °C in winter is usually higher, which leads to less accumulation of snow and smaller spring floods. The temperature dependant temperature change (Eq. (1); Andréasson et al., 2004) used here within the delta change approach partly takes this phenomenon into account by changing the lower winter and spring temperatures more than the higher temperatures as estimated from the daily RCM temperature data. The possibility still remains that the deceases in spring floods estimated here are greater than with some other methods (Graham et al., 2007; Beldring et al., 2008).

Another method for transferring the climate change to the hydrological model was also preliminarily tested. This method uses direct daily RCM results as input to the hydrological model, which has become more popular as the quality and resolution of the climate models have improved (e.g. Graham et al., 2007; Beldring et al., 2008; Dankers and Feyen, 2008). The advantage is that the changing distributions are taken into account and more information from the RCMs is used (Graham et al., 2007). However, when tested, the biases in RCM simulated temperatures and precipitations led to a poor reproduction of the reference period hydrology and floods. When the temperatures and precipitations of the five RCM scenarios (Table 2; No. 16–20) were used directly without corrections, the simulated 100-year floods were on average 18–86% greater than the 100-year floods based on observations, and the timing of floods and runoff was incorrect. The biases affect both the simulation of the reference period and also the climate change simulations and could lead to misleading results. Therefore, this method was not taken into use at this stage, before a satisfactory bias correction method for the RCM temperatures and precipitation has been implemented, tested and compared in Finland as a part of future studies.

#### *5.2.3. Hydraulic modelling*

In estimation of flood hazard and inundation area extent the uncertainties and limitations relate largely to geometry and the calibration data sets used in the 2D hydraulic model (Hardy et al., 1999; Horritt and Bates, 2002; Hunter et al., 2007; Pender and Néelz, 2007; Merwade et al., 2008; Apel et al., 2009). In this study, available measurement and observation data was used, since carrying out field measurements or ground truthing was not possible. The aim was to estimate in the test sites whether the simulated changes in discharges are also reflected in the extents of flood inundation areas. These results are not meant to be used in detailed scale (building scale) estimations of possible changes in flood damages.

A new $2 \times 2$ m national DTM based on laser scanning data (LiDAR), is being developed by Land Survey of Finland. National laser scanning has already been performed in other countries, such as Netherlands, Switzerland and several states in Germany and the USA (Alho et al., 2009). This provides significant potential for more accurate flood inundation estimations in future and local scale studies. In the creation of future geometry data sets, the isostatic land uplift should also be taken into account especially in coastal Finland. For example, in the river Kokemäenjoki estuary in Pori the uplift may affect the development of spatial extents of future flood inundation areas as the ground elevations and sedimentation increase more in the estuary than in the head water areas.

## 6. Conclusions

This study demonstrates that the impacts of climate change on floods in Finland vary considerably depending on the location, watershed characteristics and climate scenario employed in the simulation. A significant shift was found in the seasonality of runoff and floods, with increasing floods during autumn and winter, and diminishing floods in spring especially in southern and central Finland. In areas currently dominated by snowmelt floods, a decrease in flood discharges and flood hazard is expected by 2070–2099, except in some northern watersheds where floods will remain unchanged with some scenarios. In areas where autumn and winter flooding currently occur frequently, the projected increases in temperature and precipitation will increase these floods, and even the annual floods. A clear signal of increasing floods was found in the central lakes and their outflow rivers, where the largest floods are long-lasting volume floods. Lakes and lake routes are an important and typical characteristic of Finnish watersheds, and should not be ignored in any hydrological estimation in this area. This study had the benefit of fine spatial scale and large database of lakes and discharge and water level observations that enabled detailed modelling of the study region. In 2010–2039, the trends were mostly similar but the amplitude of changes was smaller, as is expected.

Important explanatory variables in the changes of floods are many characteristics such as timing of floods, importance of snowmelt floods, latitude, lake percentage, snow water equivalent, winter temperature, watershed size etc. These factors combined can explain most of the average changes in different sites and their explanatory power improves when applied separately to different hydrological regions. These variables provide a basis for possible regionalization of the results within Finland.

The changes in flood area extent did not linearly reflect the changes in discharges. The characteristics of river channels and the floodplain influence greatly the spatial extent of flood inundation. Inundation on a flat floodplain showed a larger change than the flood discharges, whereas rivers with greater variations in floodplain topography experienced smaller changes in inundations even when greater changes in discharges occurred. Sea level affected flooding substantially at two coastal study sites. The complexity of local factors makes it difficult to generalize climate change impacts on flood area extents. However, significant increases in discharges and water levels should be taken into account in future land use planning. The high variability in flood hazard (i.e. inundation area) changes indicates that any conclusions about increasing or decreasing damages should be made cautiously.

These results demonstrate that we should avoid generalisations of the impact of climate change on flooding based on only a few case study sites or broad-brush continental scale assessments with only a few climate scenarios. Local hydrological characteristics and climate should be taken into account when climate change impacts are estimated, as they can have a major effect on the hydrological response. In Finland, floods decreased at most sites with most scenarios, but increased in central lakes and their outflow rivers and in some southern watersheds including some of the most important flood hazard regions with high potential damages. Therefore, the overall impact of climate change on flood risk and possible damages could be even disadvantageous. The results also indicate that different GCMs can give very different results and thus it is important in impact studies to use scenarios from several GCMs.

In climate change studies, more understanding is still needed concerning the impact of changes in distribution of precipitation and temperature on flooding and the differences between methods to transfer climate change to the hydrological model. The main limitation of the delta change approach used in this study is that all precipitations within the same month change by the same factors and thus possibly different changes in extreme precipitation are not accounted for. This could influence especially floods caused by extreme precipitations in summer and therefore results of the small coastal rivers in southern Finland, where these floods are more important than in other parts of the country. The improving quality of RCMs means that the daily results from RCMs could be used more directly, but the remaining significant biases mean that bias correction is still needed. The development of bias correction methods is currently being investigated in many parts of Europe (e.g. Graham et al., 2007; Lenderink et al., 2007) and these methods could also be compared and used in future studies in Finland.

## Acknowledgements

This study was carried out in the Freshwater centre of the Finnish Environment Institute and in the Department of Geography of the University of Turku. The study is part of the Future of Floods in Finland (TULeVAT) research project financed by the Academy of Finland, WaterAdapt research project financed by the Finnish Ministry of Agriculture and Forestry as part of the Finnish Climate Change Adaptation Research Programme ISTO, Climate and Energy Systems (CES) research project funded by the Nordic Energy Research, GIFLOOD research project funded by TEKES and FLOOD-AWARE research project funded by Maj & Tor Nessling Foundation. We gratefully acknowledge the support of the Finnish Meteorological Institute and the EU FP6 Integrated Project ENSEMBLES, who provided the climate scenario data used in this study. We also thank Regional Environment Centres for providing us data sets and Esko Kuusisto, Hanne Laine-Kaulio, Harri Koivusalo, Johanna Korhonen, Juho Jakkila and the reviewers for their valuable comments on this article.

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