The effect of climate change on design floods of high hazard dams in Finland

Noora Veijalainen and Bertel Vehviläinen

ABSTRACT

The effects of climate change on design floods of high hazard dams were studied in Finland. Design floods were calculated with model simulation methods where design precipitation was combined with 40 years of weather data. The combination of design precipitation and baseline weather that produced the largest flood was researched and this flood was used as the design flood of the dam with a return period of 5,000–10,000 years. Design floods were first simulated for the baseline period (1961–2000) and for a future period (2070–2100) and these two floods were compared. The baseline temperatures and precipitations were changed with delta-change approach using five climate scenarios for 2070–2100 and the design precipitation was changed according to two projections. Of the 34 dams included in this study, the effect of climate change varied depending on the location of the dam, the type of the basin and the primary cause of the flood. In northern Finland, where the simulated design floods were mainly caused by spring snowmelt, the design floods did not change significantly. In southern and western Finland, the design floods were mostly summer floods which increased mainly due to the increase in the design precipitation.

Key words | climate change, dam safety, design flood, floods

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INTRODUCTION

Climate change scenarios project an increase of 2–7°C in the average yearly temperature of Finland by the 2080s. The average yearly precipitation would increase 5–40% during the same period with largest increases occurring during winter (Jylhä *et al.* 2004). As well as changes in the average values, the changes in extremes of weather are important; even small changes in averages can mean large changes in extreme values. Extremes, especially in precipitation, may change differently from the averages. This should be considered when estimating the effects of climate change on extreme floods. In many studies, future extreme precipitation events have been estimated to increase by larger than average increases in precipitation (Hennessy *et al.* 1997; Tuomenvirta *et al.* 2000; IPCC 2001; Christensen & Christensen 2004; Frei *et al.* 2006). The estimation of changes in the extreme events is however difficult, since observations are only available from short time periods and climate models are not well suited for the description of extremes. The simulation periods of climate models are short and, because of their coarse resolution, global climate models have difficulties in describing the largest precipitations occurring on a smaller scale than the model grid. The resolution of regional climate models is smaller, but they are still dependent on the global models used as boundary conditions (Hennessy *et al.* 1997; IPCC 2001; Jylhä *et al.* 2004).

Climate change may affect floods and dam safety in many ways. Increases in average and extreme precipitations may lead to increases in floods, especially during summer and autumn, and more frequent warm spells during winter could cause larger winter floods. On the other hand, most of the severe floods in Finland are presently caused by

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snowmelt during spring (Kuusisto & Leppäjärvi 1979). Increased temperatures would probably decrease snow accumulated during winter and decrease the spring floods. Climate change therefore has both increasing and decreasing effects on floods and the final outcome varies in different parts of Finland.

The goal of this study was to evaluate the effects of climate change on the design floods of high hazard dams in Finland. The study was commissioned by the Finnish Ministry of Agriculture and Forestry, which is responsible for the supervision of dams. The results will be used to evaluate if climate change causes major risks to dam safety in Finland. High hazard 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). High hazard dams are called P-dams and they are designed to withstand floods with a return period of 5,000–10,000 years. The floods simulated in this study should therefore have corresponding return periods.

Water power-production is increasing in Finland due to EU goals to increase renewable energy production. Dams that exist today are therefore also likely to exist at the end of the century. Reservoir siltation in Finnish conditions is not a serious problem because the sediment transport rates are low due to moderate precipitation amounts, low flow rates and soils resistant to erosion (Mustonen 1986). Aging of the dam materials will occur, but dams will be maintained and renewed or even rebuilt if necessary. It is important to have estimates of climate change effects so that possible modifications, e.g. increasing outflow capacity, can be made as part of normal renovation. The results are already used in dam safety inspections.

METHODS

The effects of climate change were evaluated on 34 P-dams located in different parts of Finland (Figure 1). These evaluated dams include all the P-dams in Finland in 2006 where design flood is needed for the design and safety of the dam. Excluded P-dams are those connected to waste material reservoirs, which are designed without flood evaluation. The runoff areas of P-dams vary greatly in size and properties with locations from northern to southern Finland and areas 0.7–61,000 km^2. Many of the dams are in connection with a reservoir or lake that can be regulated by the dam.

Figure 1 | The location of the evaluated dams in Finland and the names of the watersheds.

In this study, the 5,000–10,000 year floods using conditions from the baseline period 1961–2000 were first simulated. These are the presently realistic design floods for the P-dams and can be compared to the current design flood values and spillway capacities. Secondly, the same design floods were simulated with the same conditions for the period 2070–2100. The assumption used here is that the same method will produce floods with the same or similar return periods as in the baseline period. These two floods were then compared to obtain the change in design flood.

The simulations were carried out using the Watershed Simulation and Forecasting System (WSFS), developed and operated by the Finnish Environment Institute (Vehviläinen *et al.* 2006). The WSFS includes a conceptual watershed model based originally on the concept of the HBV (Hydrologiska Byråns Vatternbalansavdelning) model (Bergström 1976). The WSFS hydrological model is divided into small sub-basins, each with parameters and water balance simulation. Physical processes described in WSFS are spatial precipitation, snow accumulation and melt, soil moisture, evapotranspiration, lake evaporation, groundwater storage and runoff, subsurface runoff and river and lake network simulations. The WSFS has been calibrated with approximately 20 years of observations of snow volume, water level and discharge (Vehviläinen *et al.* 2006).

Description of the method

The design floods were evaluated using a method based on the Swedish design flood calculation method described in the Swedish guidelines for design flood evaluation for large dams (Flödeskommittén 1990). Many of the choices described below, such as the duration and shape of the design precipitation period, are based on these guidelines. The Swedish guidelines were modified to suit the Finnish conditions and the goals of this study. This method was chosen because it is versatile enough to be used for very different watersheds and for both rainfall and snowmelt floods. It does not necessarily require observations from the dam site. The method can be used to simulate floods with long return periods and to simulate floods in different climatic conditions. The disadvantages of this method include certain subjectivity, especially in the choice of the regulation strategy and uncertainty of the model results in calculating floods larger than in the calibration period of the model. Evaluation of extreme floods is always linked to much uncertainty, regardless of the method.

In the method, the design flood was evaluated by combining rare weather conditions in a way that generates the largest flood. This was done by moving the 14 day design precipitation period, which had a return period of approximately 1,000 years, through 40 years of observations of temperature and precipitation from the baseline period 1961–2000, and searching for the most severe flood (Figure 2). The observed precipitation of the 14 day period was replaced by the design precipitation, but observed temperatures were still used. An exception to this was made if the temperatures during the design precipitation period in spring or summer were high, above the 95% observed fractal for the given month (Heino & Hellsten 1983). In this case the temperatures were limited so that unrealistic combinations of high temperatures, associated with high pressures and extreme precipitation, were avoided. Evaporation and snow were calculated in the watershed model based on the precipitation and temperature observations. The most severe flood in the simulations was used as the design flood of the dam, which should have a return period of about 5,000–10,000 years. The most severe flood was defined as the flood that causes the highest outflow demand and water level on the dam. The largest flood was the flood causing the largest daily outflow demand on the dam.

With reasonable choices of the operating rule, the outflow is a better measure of the severity of the design floods than the inflow, since it can be compared with the spillway capacity. The inflow is more independent, but does not always measure correctly the severity of the flood to the dam. For example, spring flood with larger inflow can be less severe than summer flood with smaller inflow because the reservoirs are empty during spring and can store the inflows. The disadvantage is that in many dams the outflow depends on the operating rule and is therefore affected by the subjective choice of the best regulation strategy.

When the timing of the most severe flood for the dam in question had been identified, the design situation was checked in more detail with special emphasis on the outflow of regulated lakes. In many cases, the reservoir operating rule chosen for the design flood simulation had large effects on the results. In the baseline period, the water levels in reservoirs and regulated lakes before the beginning of the flood were near the average water levels during that time of year or near the observed values of the baseline year. The operating rules followed the current regulation rules and practices for the dams as much as possible.

Modifications were made in operating rules during the simulations of 2070–2100 if the current regulation rules were no longer working properly. There are plans to modify some lake and reservoir regulation limits in the near future to adapt to climate change. At many of the dams, the current regulation practices are already flexible enough and can be changed annually based on the amounts of water storage in lakes and spatial snow amount. This means that during mild winters the lakes and reservoirs are not drawn down as low as during winters with a lot of snow and large spring inflows. The operating rules used in the simulations are, however, not as flexible as the regulation practices in reality. The modifications took these flexibilities into

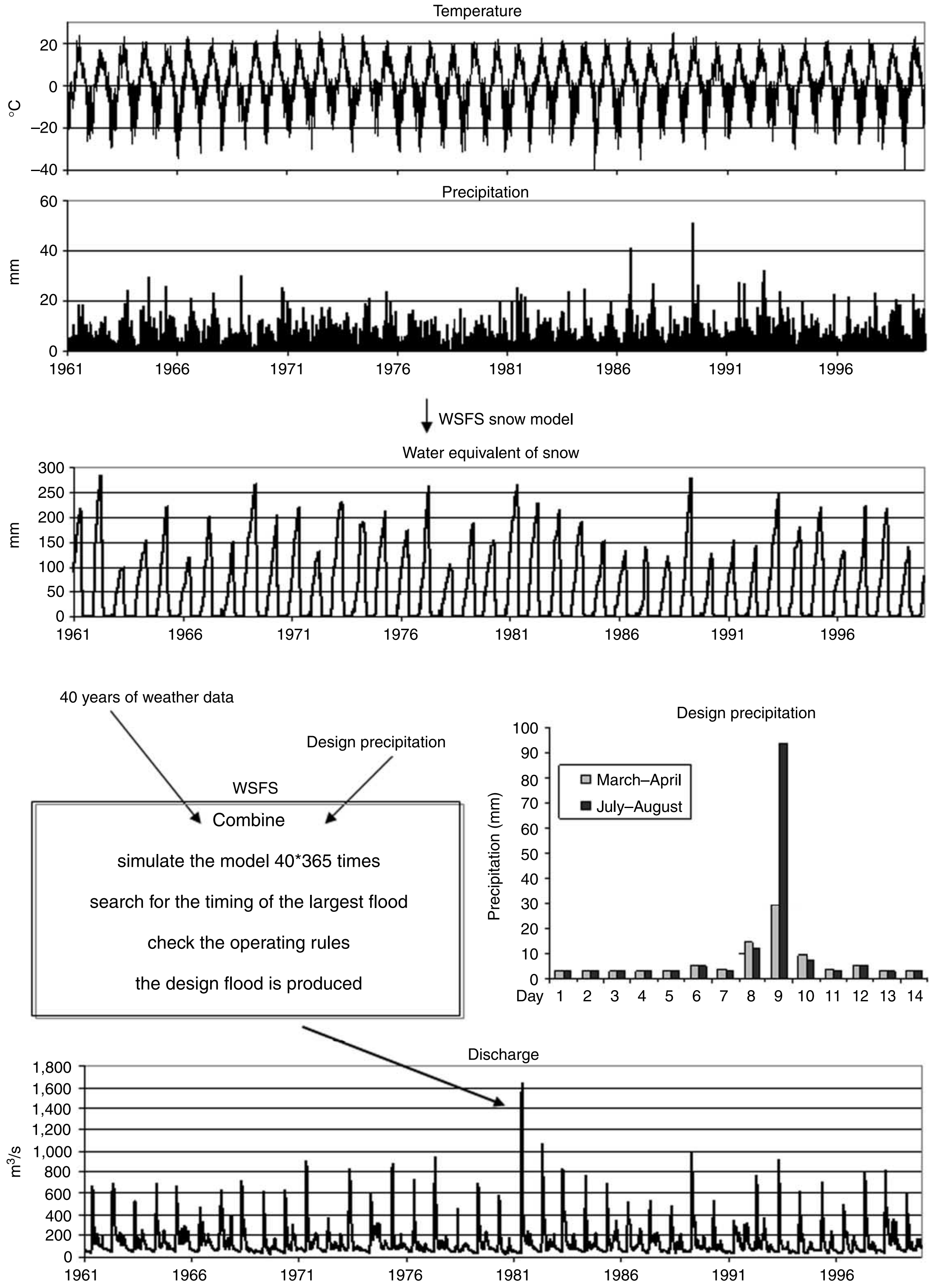

Figure 2 | Schematic presentation of the method used in design flood simulations. The data in the example is from Iijoki River at Pahkakoski dam in north Finland.

account to make the future regulation as realistic as possible. These modifications included an earlier spring drawdown of the reservoir and less drawdown in years with warm winters and less snow.

When the flood was rising, the actions on the dams were assumed to be fast and regulation of the dams and upstream reservoirs and lakes were assumed efficient. For example, the outflow of the dams was increased as soon as the seriousness of the rising flood is assumed to be known. During the flood, peak outflow from the upstream reservoirs was only as large as necessary. On sites where part of the inflow to the dam can be passed around the dam, the bypassing was initiated as soon as possible. If these assumptions are violated, the flood situations on the dams can become worse than in these simulations.

Most of the assumptions used in the method (i.e. the limitations to the temperatures during design precipitation and limitations of precipitation at the end and beginning of the design precipitation period) are based on the Swedish guidelines. There are, however, several differences between this method and the Swedish guidelines. The goal of this study is different from the Swedish guidelines i.e. to produce a 5,000–10,000 year flood whereas the Swedish guidelines also allow the production of considerably rarer and larger floods. Firstly, the design precipitations used here are specifically estimated for Finland with some different assumptions than in the Swedish design precipitations. Secondly, instead of using the snow equivalent with a 30 year return period as a value for snow before the beginning of snowmelt, the simulated value of snow was used. Thirdly, the simulation period is longer (40 years), which compensates for the different way the snow was handled. The design floods for P-dams would be too large for some of the dams if the 30 year maximum snow value was used. In addition, the longer period was necessary to assure that there were enough different weather situations to make the design flood rare enough in both present and future climate.

Our method has some similarities with Probable Maximum Flood (PMF) method, but the main difference is that our design precipitation is not as rare as the Probable Maximum Precipitation used in the PMF method. In addition, the other flood-inflicting conditions are not the worst expected but the worst observed. The consequences of these differences are that the floods simulated with this method are smaller than the PMF estimates, which was the aim as the design floods should have a return period of 5,000–10,000 years so that they can be used as design values for P-dams. To confirm the return period of the simulated design floods of the baseline period, they were compared with estimates made with three frequency distributions on sites with adequate observations (Results and Discussion).

Design precipitation

The magnitude of the design precipitation was evaluated in a report by the Finnish Meteorological Institute (Solantie & Uusitalo 2000). The magnitude and the distribution of the 14-day design precipitation depend on the time of year, the size of the area in question and the location in Finland. The design precipitation, which is an average area value for the entire watershed, should have a return period of approximately 1,000 years. Solantie & Uusitalo (2000) evaluated the magnitudes of precipitation with return period of 10,000 years and the magnitudes of the 1,000 year design precipitation was evaluated to be 17% smaller based on information in the same report.

The division of the design precipitation within the 14 day period (example in Figure 3) was such that the flood caused by the precipitation was severe enough in different lengths of the flood. The division was very similar as in the Swedish guidelines. The largest precipitation occurred on

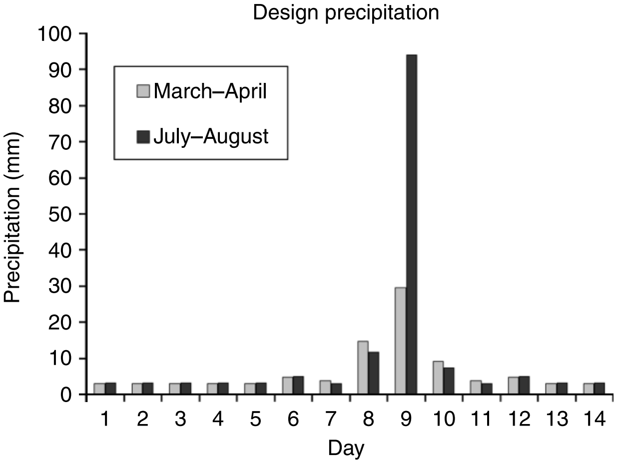

Figure 3 | The 14 day design precipitation period during May and August at Pahkakoski dam in Iijoki River and the distribution of the daily precipitations within it.

the 9th day of the period and corresponded to the 1,000 year maximum of 1 day precipitation. The precipitation sum of days 7–11 corresponded to the 1,000 year maximum 5 day precipitation. On small runoff areas, it is the magnitude of the largest daily precipitation of the 14 day precipitation period that mainly determines the flood magnitude.

Unrealistically large 14 day precipitation sums were avoided by reducing the size of large observed precipitations occurring at the end and beginning of the design precipitation period. The criterion was that the 14 day precipitation sum must not exceed the precipitation sum of the 1,000 year design precipitation. The monthly precipitation sum was also reviewed so that it would not grow to be too large, which was important in large watersheds with long lake routes. The 30 day precipitation sum with a return period of 1,000 years was estimated to be 1.5 times the precipitation sum of the corresponding 14 day design precipitation (Solantie 2003, personal communication).

A limit value, which was not allowed to be exceeded for the 30 day precipitation sum, was set to 1.55 times the 14 day design precipitation sum. This was done to ensure that the design floods produced by the method would all have a return period of 5,000–10,000 years. Otherwise, the return period of the 1 month precipitation could be much rarer than 1,000 years and the floods with a long flooding time could become too rare. In the simulations of 2070–2100 floods, these precipitation limitations were set with the HadCM2 scenario (Table 1). The limitation remained the same with other climate scenario simulations to preserve the differences between climate scenarios.

Climate change

The design floods were first calculated in the baseline period with weather data from years 1961–2000 and then for the future climate corresponding to the period 2070–2100. Climate change by 2070–2100 was taken into account in two ways. First, the baseline temperatures and precipitations based on observations from 1961–2000 were changed with the delta-change approach. Second, the design precipitation was changed according to specific projections as described in the next section (Figure 4). The simulations were calculated for five different climate scenarios and two different changes in design precipitation, in order to gain an understanding of the uncertainties associated with climate change and their effect on the changes in design floods. The simulations were therefore calculated for 10 scenarios in total.

Table 1 | Climate scenarios used in the study

Abbreviation	Climate model	Emission scenario
HadCM2	HadCM2	IS92a
RH A2	RCAO/HadAM3H	A2
RH B2	RCAO/HadAM3H	B2
RE A2	RCAO/ECHAM4/OPYC3	A2
RE B2	RCAO/ECHAM4/OPYC3	B2

The estimations of the effect of climate change on temperature and precipitation varies greatly due to uncertainties about future emissions of carbon dioxide and other greenhouse gases as well as differences in the climate models. The design floods in 2070–2100 were simulated with five different climate scenarios from three different global climate models and three different emission scenarios (Table 1). As well as changes in temperature, precipitation and evaporation, there are other factors influenced by climate change such as changes in land use or vegetation type. These effects are not considered in this study.

The climate scenarios all have the same baseline period of 1961–1990 and the monthly changes are given relative to this period. One of the climate scenarios was from the older global circulation model HadCM2 (Johns *et al.* 1997) with the emission scenario IS92a for the period 2070–2099. Tuomenvirta *et al.* (2000) calculated the average monthly changes of temperature and precipitation of this scenario for Finland, and these values were used in this study. The other four climate scenarios for the period 2071–2100 were from global models HadAM3H (Gordon *et al.* 2000) and ECHAM4/OPYC3 (Roeckner *et al.* 1999) with emission scenarios A2 and B2 downscaled with the regional climate model RCAO (Rummukainen *et al.* 2001) developed at the Rossby Centre, Sweden. The regional climate model produces more spatially detailed scenarios and the changes of temperature and precipitation were given on a 0.5° grid for Finland. The A2 and B2 emission scenarios are part of the Special Report for Emission Scenarios (SRES) scenarios published by the IPCC in 2000 (IPCC 2000). The A2 represents larger emissions of carbon dioxide than the B2

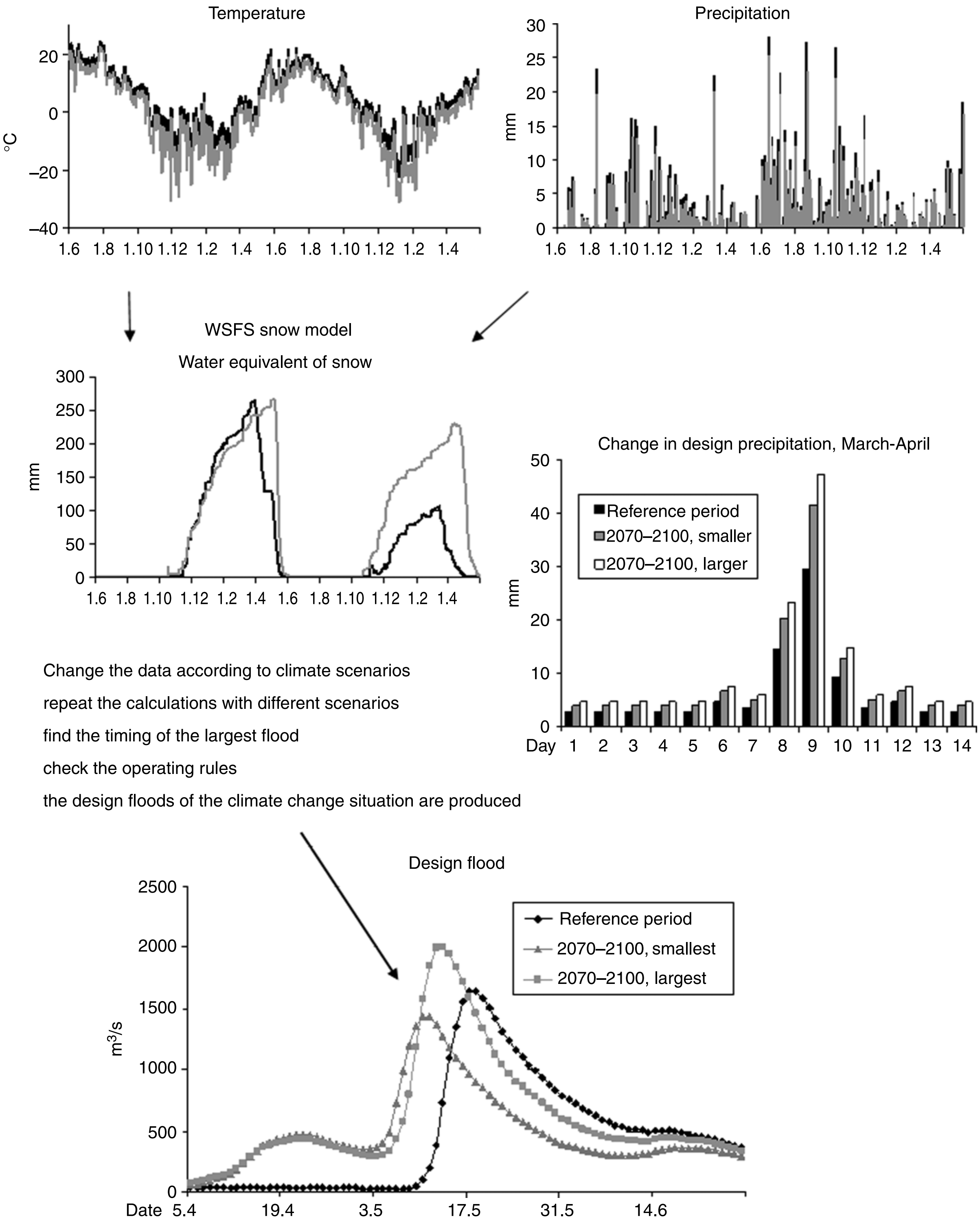

Figure 4 | Design flood simulation with climate change. The example is from Pahkakoski dam in north Finland, where the design flood occurs during spring in all simulations.

and the older IS92a emission scenario falls between the A2 and B2 emission scenarios.

Results from climate models indicate that cold periods in Finland will warm more than the average temperature (Rummukainen *et al.* 2000). Temperatures were therefore changed depending on the temperature in the baseline period. The correlation between the baseline temperature and the change in temperature by 2070–2100 was evaluated in Sweden by SweClim project based on the results from regional climate model RCA1 with global climate model HadCM2 (Rummukainen *et al.* 2000). According to this correlation, the lower the original temperature, the more it increased by 2070–2100, which leads to largest increases in cold winter days. The increases in temperature were scaled on a monthly basis so that the average monthly temperatures of the 40 year baseline period increased as much as in the climate scenario used.

Potential evaporation was calculated in the WSFS using the air temperature, precipitation and time of year, which is an index of available radiation (Vehviläinen & Huttunen 1997). The effect of climate change was taken into account via changes in temperature and precipitation. Land area evapotranspiration was calculated from the potential evaporation using a model based on soil moisture deficit. There are other factors affecting actual evaporation and its change due to climate change such as changes in wind and cloudiness, but these were not taken into account. This may cause some errors in the calculation of future evaporation and soil moisture deficit. For most floods, however, these amounts were small compared to the precipitation and the possible errors are not significant.

Change in design precipitation due to climate change

As described above, the observed precipitations are changed using the delta-change approach. The change in design precipitation due to climate change was carried out separately because the design precipitation is a rare extreme event which will probably change differently from the average precipitations. The changes in design precipitations by 2070–2099 were evaluated in the report *Climate change, design precipitation and dam safety* (Tuomenvirta *et al.* 2000) by the Finnish Meteorological Institute. The effects of climate change on design precipitation were evaluated by Tuomenvirta *et al.* (2000) from the results of the HadCM2 global climate model with emission scenario IS92a. The HadCM2 simulations were conducted for the baseline period of 1961–1990 and for 2070–2099 and 1, 5 and 14 day precipitations of these simulations were analysed for grid cells in or close to Finland. Each year was divided into six 2 month periods and the Gumbel distribution was fitted to the simulated maximum precipitations of each period. The 10,000 year precipitations for 1961–1990 and 2070–2099 were calculated by extrapolating the Gumbel distribution. The 10,000 year precipitations of the baseline and 2070–2099 were then compared and the changes of the 10,000 year precipitations due to climate change were calculated in each grid cell. Based on the grid cell values, the changes for the whole of Finland were estimated for each 2 month period.

The results of Tuomenvirta *et al.* (2000) are based on a global climate model version of HadCM2, which is already dated; both the climate models and emission scenarios have developed. Similar analysis based on the latest regional models and emission scenarios is, however, still to be carried out. The average monthly changes in precipitation and temperature in HadCM2 IS92a climate scenario are mostly within the ranges of latest climate scenarios calculated with several models and emission scenarios. (Jylhä *et al.* 2004).

Two different projections of design precipitation increase were used in this study. The smaller changes in the design precipitation were increases of 12–40%. The larger changes in the design precipitation were 35–60% increases for large areas and 35–85% increases for small areas (Figure 5). The smaller changes were the averages of the calculated changes of the 14 day precipitations in all the grid cells in Finland. The larger changes were the values Tuomenvirta *et al.* (2000) recommended for use. The recommended values are larger than the average values to ensure the changes are large enough for most of Finland. However, the recommended changes were still smaller than the largest calculated changes in single grid cells. The changes in design floods were evaluated to assess the possible risks to dam safety from climate change when it is important not to underestimate the risks. Therefore, it is justifiable to use changes that are at least large enough rather than to use changes which would be too small in some parts of Finland.

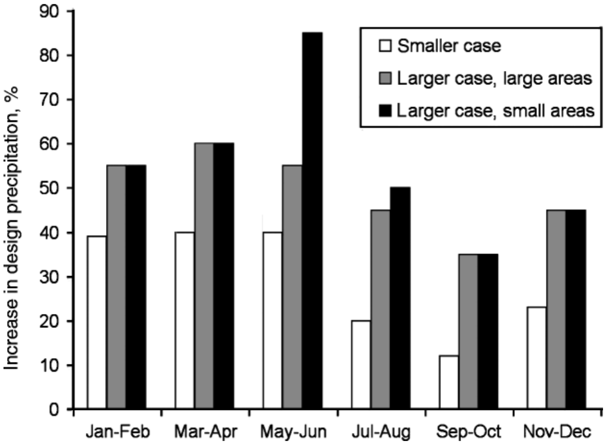

Figure 5 | Change in design precipitation from baseline period 1961–1990 to 2070–2099 with different projections and areas. Large areas are approximately 50,000 km^2 and small areas 1,000 km^2.

RESULTS AND DISCUSSION

Comparison of present design floods

The main goal of the study was the evaluation of the changes in design floods due to climate change. The evaluation of the absolute magnitudes of the design floods was not as important. However, a goal was that the simulated floods would be of the correct magnitude for use as design floods of high hazard dams. To determine if this goal was achieved, the simulated floods of the baseline period 1961–2000 were compared with previous estimates as well as estimates from frequency distributions.

Most of the simulated floods were comparable to previous design flood estimates from the official dam design reports, although there were also some differences. For some large watersheds, the simulated floods were larger then the previous estimates. This could be attributed to the magnitude of the design precipitation, which did not decrease very much with an increase in area with very large watersheds (Solantie & Uusitalo 2000).

The simulated floods of the baseline period 1961–2000 were compared with 5,000 and 10,000 year floods calculated with frequency distributions for selected dams, using long observation series up to 2004. The assumption behind this comparison was that climate change had not affected the flood discharges by 2004 by an amount which would violate the flood frequency distributions assumptions. This assumption is affirmed by Korhonen (2007), who found no significant trends in the yearly largest discharges of unregulated locations in Finland in a study including most of the long observation series up to the end of 2004. The design floods of 2070–2100 were not compared with the frequency estimates, as the climate will have changed so much that the past observations no longer represent the new situation.

The return period of the flood produced by the simulations should be 5,000–10,000 years, which is the return period required for the design of P-dams by dam safety law in Finland. To establish that this is the case in the baseline period, the floods simulated using the data from 1961–2000 were compared with estimates made with frequency distributions for 5,000 and 10,000 year flood magnitudes. This kind of extrapolation to extreme return periods is seldom done and is not recommended; the extrapolation described here is only for comparison.

On six dams, where there were enough discharge observations and the assumptions of independent and random observations were met well enough, three frequency distributions were fitted to the yearly maximum discharge data. The three distributions used were Pearson type 3, log-Pearson type 3 and Gumbel. The Gumbel distribution is the most commonly used and officially recommended distribution in Finland. Discharge series for the six sites were observed until 2004 and had a length of 39–95 years. On two sites, Pahkakoski and Valajaskoski, the record lengths were less than 75 years. Even with these relatively long time series, the extrapolation of frequency distributions to extreme return periods such as 5,000–10,000 years will contain huge uncertainty.

The estimates for discharges with return period of 5,000 and 10,000 years were compared with the corresponding design floods of the baseline period calculated with the model simulations (Table 2). The simulated design floods were of the same magnitude or smaller than the estimates with Gumbel distribution and of the same magnitude or larger than Pearson 3 and log-Pearson 3 distribution estimates. The differences between the frequency distributions were large due to different coefficients of skew and their effect on the extrapolation of the distributions to very large return periods. It could not be assessed which was the best or worst distribution, although the log-Pearson type 3 distribution had negative coefficients of skew on most of the

Table 2 | Design floods of six dams and the 5,000 and 10,000 year flood peak estimates with three frequency distributions for the same locations (m^3/s)

	Gumbel		Log-Pearson 3		Pearson 3		Design flood
Return period (yr)	**5,000**	**10,000**	**5,000**	**10,000**	**5,000**	**10,000**	**Simulations**
Valajaskoski	7,215	7,620	6,239	6,491	5,910	6,125	6,188
Isohaara	7,996	8,433	6,256	6,425	6,017	6,180	6,860
Pahkakoski	1,916	2,024	1,595	1,652	1,511	1,561	1,524
Raasakka	2,310	2,438	2,037	2,124	1,920	1,991	2,260
Harjavalta	1,553	1,637	1,063	1,077	1,104	1,127	1,322
Kaltimo	822	934	714	730	753	776	860

sites and could therefore give too small estimates for discharges with large return periods.

In general, given the large uncertainties involved, the simulated design floods were of similar magnitude as estimates given by the studied frequency distributions. They can therefore be considered to be of approximately correct magnitude for design floods of high hazard dams in Finland. The exact return period of the simulated floods cannot, however, be assessed.

Timing of design floods

The timing of the design floods depends mainly on the characteristics of the catchment and baseline weather, on the magnitude of the design precipitation during different months and on the regulation capacity of the reservoirs and lakes above the dam. The time of the design flood was mostly during summer in southern and central Finland, both during the baseline period and for 2070–2100 (Figure 6), partly due to the regulation of reservoirs. In northern Finland, the design floods of the baseline period were spring floods caused by a combination of snowmelt and rainfall; spring floods also remained as the largest floods in the future period. On some dams in central and eastern Finland, the timing of the design flood changed from spring to summer. On two dams in central Finland with large catchments and many lakes, the time of the design flood in 2070–2100 was early winter during a very mild and rainy winter after a rainy autumn.

The timing of the design floods was partly due to the properties of the dams and their watersheds. Many of the dams are connected to a reservoir or lake, emptied during winter to make room for spring floods and full during summer and autumn. At many dams, the inflows to the dam reservoirs were largest during spring. However, due to available storage the highest water levels and outflow demands occurred during summer floods when reservoirs were full at the beginning of the flood.

Change in the magnitude of design floods

The design flood simulations were made for the baseline period and for future conditions of 2070–2100 to estimate the change in design floods. These floods were then compared and the percentage change was calculated. The largest and the smallest of the future design floods out of the ten design flood scenarios simulated gave the range of the change due to climate change (Figure 7). The ten future design flood scenarios were constructed from five different climate scenarios and two different design precipitation change projections. The range of the changes in design

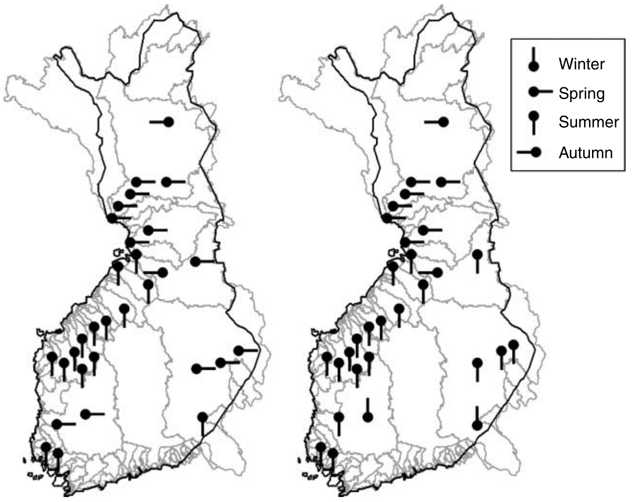

Figure 6 | Timing of the design flood in baseline period (left) and in 2070–2100 (right).

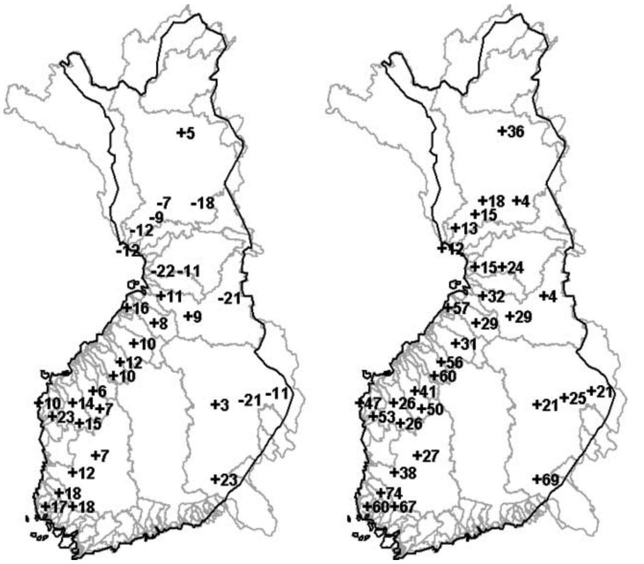

Figure 7 | The change in design floods from baseline to 2070–2100. Of all the floods calculated with ten different scenarios, the smallest design floods are on the left and the largest are on the right.

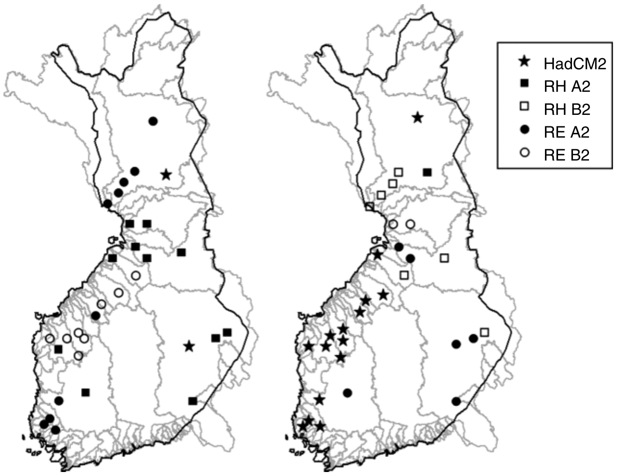

Figure 8 | The climate scenario producing the smallest (left) and largest (right) design floods together with the smaller or larger changes in design precipitation.

floods was quite large, highlighting the uncertainties involved. However, on dams in western and central Finland, the design floods increased (by 6–74%) with all scenarios. On dams in northern and eastern Finland, the results show both increases and decreases depending on the scenario.

The smallest design floods were generated with the smaller increases in design precipitation and the largest design floods with the larger increases. The climate scenario that generated the smallest and the largest design floods was different depending on the location and properties of the dam site and the timing of the flood (Figure 8). The smallest design floods in northern Finland in 2070–2100 were generated by the HadCM2 scenario, since the winter precipitations increase less than in the other climate scenarios. The largest design floods were produced by either scenarios with large increases in winter precipitation (RE B2) or scenarios with small increases in temperature (RH B2). At these dams, the design floods occurred during spring and the climate scenario had a large influence on the magnitude of the design flood of 2070–2100.

In southern and central Finland, the design floods were mostly summer and autumn floods caused mainly by the design precipitation. The differences between design floods simulated with different climate scenarios were small. In the large watersheds of Oulujoki, Kokemäenjoki and Vuoksi, the design floods lasted for months due to the long lake routes; the differences between climate scenarios were larger. In these catchments with autumn and winter floods, the largest future floods were generated by the RE A2 scenario, which has large increases in winter precipitation and temperature.

Uncertainty and sensitivity

The range of the changes in the simulated design floods due to climate change was large at most of the dams due to the differences in the scenarios for 2070–2100. However, this range is obtained using results from only three global climate models and emission scenarios and two projected changes in extreme precipitation. There are climate models and emission scenarios which produce both larger and smaller changes in precipitation and temperature than those used in this study. In addition, the uncertainties in the model predictions caused by e.g. model parameters and structure, assumptions about evaporation change and flood areas are not included in this range. The possible range of changes in design floods is therefore even larger than the range given here.

The calculations were done with only one watershed model and one calibrated set of parameters. The conceptual watershed model was used outwith the conditions it has been calibrated for, which diminishes the model reliability (Seibert 2003). Because the model cannot be tested or verified against observation with very extreme floods, there is uncertainty in the model results.

The sensitivity of the design floods to the changes in design precipitation and temperatures was also analysed. The change in design precipitation had a clear effect on design floods: 10% increase or decrease in design precipitation increased/decreased the design flood by 4–11%. The design floods changed more in smaller watersheds with small storages and less during spring floods, in which the snowmelt forms a large part of the flood. Changes in temperature had little or no effect on summer and autumn floods, but affected spring floods strongly.

At many of the dams with summer and autumn design floods, the changes in design floods were approximately as large as the increases in design precipitation. In the case of the larger projected changes of design precipitation, the increases during summer were 45–50% and the corresponding increases in summer design floods were 24–74%. In the case of smaller design precipitation changes, the design precipitation in summer increased by 20% and the summer design floods increased by 6–29%. The largest changes in design floods due to design precipitation change were in small watersheds.

CONCLUSIONS

The exact return period of the simulated design floods was hard to evaluate since the design floods were based on the combination of rare events. The design floods were compared with previous design flood estimates from the official dam design reports and results of three frequency distributions fitted to observations on six dams. We concluded that the design floods calculated with the method of this paper are, on average, rare enough to be suitable for the design of P-dams i.e. their return period is at least 5,000 years. The return period is not constant but can vary on different dams depending on the time of the flood, the size of the runoff area, properties of the 40 years weather data and model accuracy. On some dams, the return period of the calculated flood can be larger than 5,000 years.

Based on the results, the effect of climate change on the magnitude of the simulated design floods appeared to depend on the cause of the flood. In northern Finland, where the design floods were caused mainly by snowmelt (as in 2070–2100 also), the floods remained on average about the same size as at present. There were, however, large differences between climate scenarios. Warmer winters with shorter snow accumulation period were partly compensated by the increases in winter and spring precipitation. On dams in western and central Finland, where the design floods were summer or autumn floods both in the baseline period and in the future, the design floods increased. On these sites, the timing of the design floods stayed unchanged but the increase in the design precipitation increased the design floods of 2070–2100. On dams in eastern Finland, where the time of the design floods changed from spring to summer or autumn in 2070–2100, the change in design flood magnitude varied from decrease to increase depending on the scenario and the dominance of the spring floods at present. On large central lakes of large watersheds, the design floods became winter floods in 2070–2100 and increased from present.

The results can be used to identify the dams where climate change will cause the largest risks of dam failure due to increases in extreme floods. At each dam, the present spillway capacity was compared to the future design flood. At most dams, the spillways could conduct even the increased design floods if the regulation and management was done properly. However, a few dams were identified where the outflow capacity might not be adequate. Further studies can evaluate the possible adaptation needs and options on these dams. These results will be used as part of regular dam safety inspections.

The results of the study are specific to the sites and return periods in question and they cannot be directly generalized. Floods which are more common than these design floods may change differently than the simulated floods because of nonlinearities in the runoff generation and precipitation changes. More common precipitations will probably not change as much as the design precipitation. The design floods are affected by the properties of the dam sites, reservoir and runoff areas. The changes in design floods therefore cannot be directly linked to the changes of floods in other locations.

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