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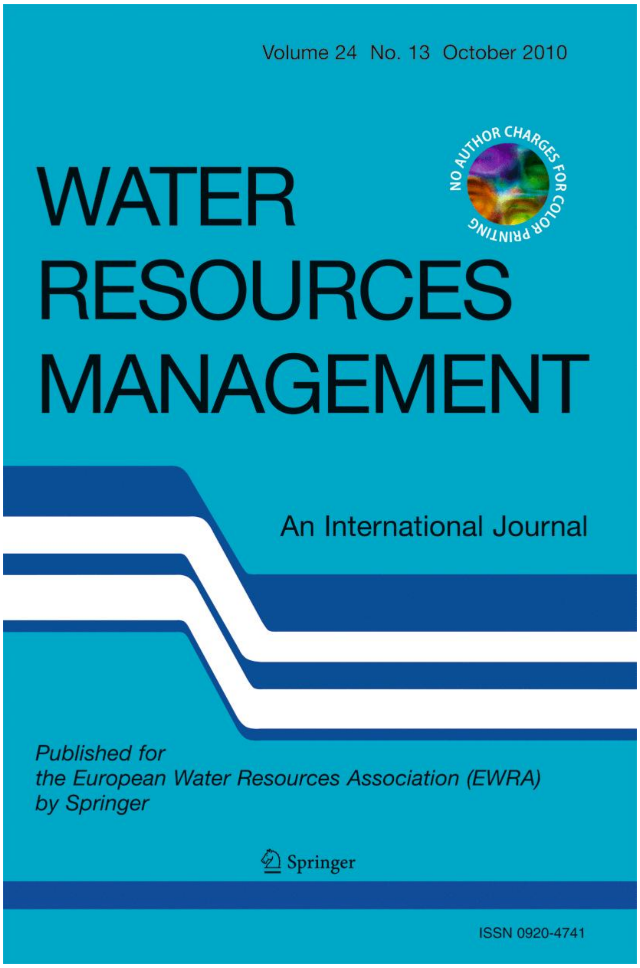

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Climate Change Impacts on Water Resources and Lake Regulation in the Vuoksi Watershed in Finland

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Abstract The impacts of climate change on hydrology and water resources in the Vuoksi watershed in eastern Finland were studied in order to assess the possibilities to adapt lake regulation to the projected changes. A conceptual watershed model and several climate scenarios were used to estimate the effects of climate change on three lakes in the Vuoksi watershed for 2010–2039, 2040–2069 and 2070–2099. The adaptation possibilities were studied by using alternative regulation strategies. In Lake Pielinen the impacts of these water level changes on social, economic and ecological indicators were assessed with two different outflow strategies. According to the results, climate change will alter snow accumulation and melt and therefore cause large seasonal changes in runoff and water levels. Runoff and water levels will decrease during late spring and summer and increase during late autumn and winter. In some lakes current calendar-based regulation practices and limits, which have been developed based on past hydrology, may not be appropriate in the future. Modifying the regulation practices and limits is a necessary and effective way to adapt to climate change.

Keywords Watercourse regulation · Climate change · Adaptation · Hydrological modelling · Impact assessment

1 Introduction

Climate change is predicted to affect the hydrology of Finland considerably. By the 2080s average annual temperature in Finland is expected to increase by 3–7°C and average precipitation by 13–26%, with the largest increases during winter (IPCC 2007; Ruosteenoja and Jylhä 2007). The hydrology of Finland is characterised by temperature-sensitive snow-dominated seasonality, with snow accumulating during

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winter and snowmelt during spring. This makes the area especially susceptible to major seasonal hydrological changes due to climate change, since relatively modest increases in temperature can result in substantial changes in runoff patterns (Arnell 1999; Lettenmaier et al. 1999; Payne et al. 2004). Previous studies on climate change impacts (Beldring et al. 2006; Silander et al. 2006; Vehviläinen and Huttunen 1997) have found that during warmer winters with more rain and increased snowmelt winter runoff will increase in southern and central Finland, whereas warmer and longer summers may decrease soil moisture, runoff and water levels during summer. This would alter the current seasonal cycle of runoff and water levels in Finland's numerous lakes.

Finland has 4,500 lakes with an area exceeding 0.5 km^2 and more than 330 of them are regulated mainly for hydropower, flood protection and recreational purposes (Marttunen et al. 2001). Most of the largest and most important lakes in Finland are regulated, and thus one third (about 11,000 km^2) of the lake area is covered by regulated lakes (Marttunen et al. 2001). This study was performed in the river Vuoksi watershed in eastern Finland, which is the region with the most lakes. Lake regulation requires a legal permit, which often includes upper and lower limits for water level defined as certain water levels on specific dates. These regulation limits often include a mandatory draw-down of water level during late winter and early spring in order to make storage space for the snowmelt flood. The regulation permits and limits have been developed using past observations based on an assumption of stable hydrology (Kundzewicz et al. 2008), which may no longer be valid in the future. When the snowmelt floods during spring decrease and occur earlier, the inflows may become mismatched with the regulation permits, causing the current permits to function poorly and creating a need for adjustment. Studies in the USA showed that this may be the case especially in basins with snowmelt as a major component of runoff (Lettenmaier et al. 1999). Adaptation of water resources management in response to climate change is therefore necessary (Minville et al. 2009a). It has been estimated that more than half of the regulation permits in Finland may need revision due to climate change (Silander et al. 2006).

Changes in lake water levels due to either climate change or water level regulation may have a substantial effect on the lakes and a careful impact assessment process is therefore important. To obtain a proper overall picture, the economic, social and ecological impacts should be assessed. This information can be utilized in the evaluation of the importance of hydrological changes in relation to different uses and users and for comparison of the advantages and disadvantages of different adaptation measures. Economic analysis can be used to assess the consequences and cost-effectiveness of alternative management plans (Heinz et al. 2007). The impacts included in this study are evaluated with eight indicators; flood damage, hydro power production, navigation, impacts on recreational use and four different ecological indicators.

Climate change impacts on water resources have been researched widely, but climate change effects on the regulation of complex watersheds have been studied to a much lesser extent (Fowler et al. 2007). Studies incorporating hydrological climate change simulations and impact assessment in regulated lakes or reservoirs have been performed for example in an Alpine basins in Switzerland (Hingray et al. 2007), in a water supply systems in England and in the upper Danube catchment in Germany and Austria (Barthel et al. 2010; Fowler et al. 2007) and in the USA from a system performance perspective on a regional scale (Lettenmaier et al. 1999) and in the extensively developed and regulated Colorado River (e.g. Christensen and Lettenmaier 2007; Payne et al. 2004). Adaptation to climate change in management and operation of a water resources system has been evaluated in Canada (Minville et al. 2009a). These studies were carried out in modified watersheds in which either water supply or water power production had a major role. In natural lakes with similar hydrology to Finland there has been research for example in the Great Lakes in USA and Canada (Hartmann 1990; Lee et al. 1997) and in the large lakes of Sweden (Bergström et al. 2006).

The aim of the study was to estimate climate change impacts on hydrology and lake regulation in the Vuoksi watershed in Finland and to assess the possibilities to adapt the lake regulation to these changes. The differences to previous studies are the properties and regulation permits of the study watershed and the focus on adaptation. The study differs from previous studies due to the combination of hundreds of connected natural lakes, calendar-based regulation limits, major recreational importance and Nordic hydrologic conditions. Besides assessing climate change impacts on hydrology, this study aims at testing adaptation possibilities through examples of altered lake regulations and on one lake estimating the impacts of these changes on different uses of the lake.

2 Study Lakes

The study area is the Vuoksi watershed in eastern Finland. It is the largest watershed in Finland with a total area of 61,000 km^2, including some areas in Russia. One fifth of the watershed is covered by hundreds of lakes, which are important for recreational use. Many of the lakes are regulated, including all the largest lakes in the watershed. Three lakes, Lakes Saimaa, Lake Pielinen and Lake Syväri (Fig. 1), were chosen for the hydrological analysis. The largest study lake is Lake Saimaa, the largest lake in Finland with an area of 4,380 km^2, while Lake Pielinen has a lake area of 890 km^2 and Lake Syväri of 81 km^2. The basin areas are 61,000, 20,820 and 2,430 km^2, respectively. The study lakes were chosen to represent different types of lakes in the watershed. The smallest lake, Lake Syväri, in representative of a small to medium size upstream regulated lake and several similar lakes exist in the watershed. Lake Saimaa and Lake Pielinen were chosen as large central lakes, which are rare, but important lakes in the region and even nationally.

For all these three lakes the largest floods have generally been snowmelt floods. For the smaller lakes Lake Syväri and Lake Pielinen these floods occur during late spring or early summer. Due to long lake routes causing long time delays, the highest water levels in Lake Saimaa typically occur in late summer, although high water levels have also taken place in autumn and winter after prolonged heavy precipitation. The outflows of Lakes Pielinen and Saimaa mostly follow the natural rating curve, where the outflow at a certain water level is always the same. With natural rating curve the outflow from the lake is the same as it would be if the lake would be unregulated. However, a dam exists in the outlets of both lakes providing the technical possibility to change the outflow, and this option is used during floods and droughts.

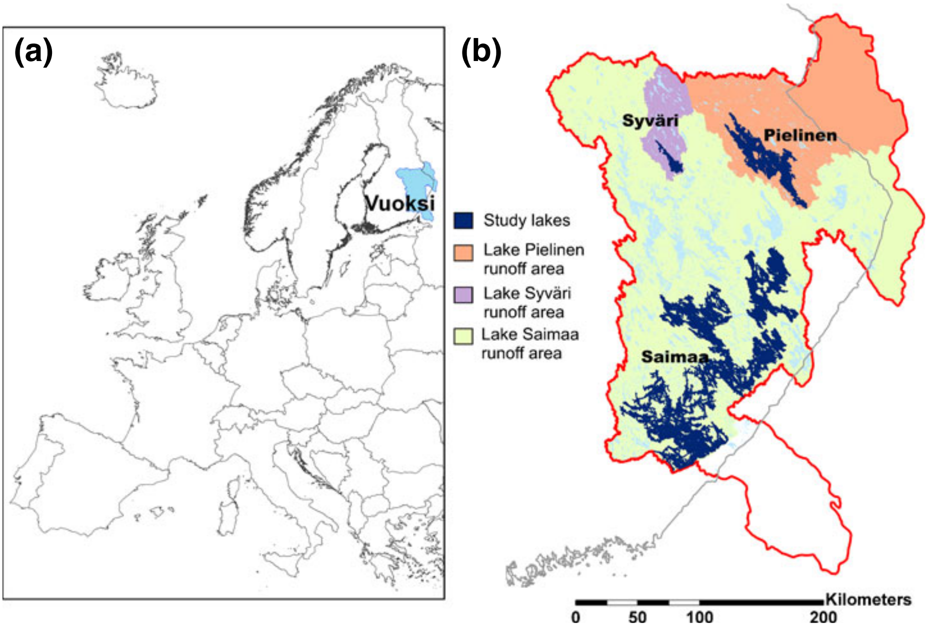


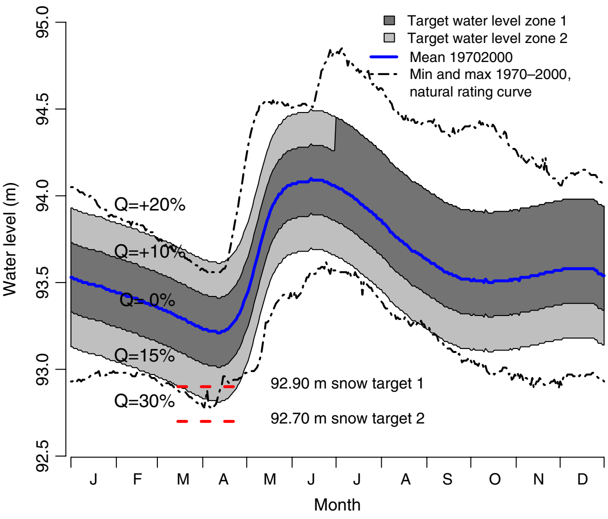
Fig. 1 The location of **a** the Vuoksi watershed in e Finland and **b** the study lakes and the boundaries of their runoff areas

According to Lake Pielinen's release rule the outflow from the dam normally follows the natural rating curve that was applicable before the dam was built in the outflow river. In a threatening flood or drought situation in Lake Pielinen it is however possible to apply an exemption permit subject to the Water Act to change the outflow and thus avoid or reduce damages. Exemption permits have been used since 1980 on average once in three years for several weeks at a time.

In Lake Pielinen an ongoing study examines the possibilities to change the regulation of the lake. Currently the lake is regulated only in flood or drought situations, but more intense regulation scheme has been proposed. In a study by Verta et al. (2007) a new operating scheme, in which the discharges can be increased or decreased in a more flexible way, has been developed. In the regulation scheme the outflow follows the natural rating curve when the water level is within certain limits from the average water levels called the target water level zone 1 (see Fig. 2), but can be decreased or increased if the water level deviates from the target zone or if the amount of snow is large. The first advantage of this new regulation scheme is the possibility to decrease damage caused by flood or drought by preparing in advance. The second advantage is the faster and more flexible way to handle the operation of the lake compared to the current laborious application process for the exemption permit. The impacts of this regulation scheme in changing climate were evaluated and are presented in the section Impacts of water level changes on Lake Pielinen.

Lake Syväri is regulated for hydropower and flood prevention purposes. Regulation permits define upper and lower limits for water levels which are broken only during floods or droughts. The regulation limits in this lake include a mandatory spring draw-down of at least one meter by the beginning of April. In addition to

Fig. 2 Schematic presentation of the new regulation scheme for Lake Pielinen. The outflow from the lake (Q) depends on the water level and time of year. The percentages give the deviation from outflow according to the natural rating curve. Based on a report by Verta et al. (2007)



the regulation limits Lake Syväri has target water level zones, which are not legally binding but are usually followed. These target water level zones aim for example at keeping the water level during the recreational season in summer near the upper limit within a relatively narrow range. The regulation permits and limits in Lake Syväri are similar to many other lakes in the region and in other parts of Finland as well.

The outflow of Lake Saimaa is based on the contract between Finland and Russia because the outflow river from Lake Saimaa, the Vuoksi, flows to Russia. When the water level in Lake Saimaa is within ±50 cm of the daily average, the outflow follows the natural rating curve, but when the water level threatens to vary above or below this range, the release rule allows increasing or decreasing the outflow in order to avoid damages (Ollila 1997). However, the possibilities to decrease the highest water levels are limited, because increasing the outflow from Lake Saimaa could cause flood damage on the Russian side in the outflow river, the Vuoksi. The current contract with Russia does not allow the discharges to increase above the natural rating curve without mutual agreement. To account for this, a maximum discharge of 1,100 m^3/s was used in the simulations. This maximum discharge was not exceeded in the simulations until the discharge according to the natural rating curve became larger than this limit.

3 Methods

3.1 Hydrological Modelling

The hydrological watershed model in the Watershed Simulation and Forecasting System (WSFS; Vehviläinen et al. 2005) was used to simulate the hydrological effects of climate change. It is a conceptual watershed model, which is based on the Swedish HBV-model structure (Bergström 1976) and simulates the hydrological cycle using standard meteorological data. Different versions of the HBV-model have been used in assessing hydrological effects of climate change in several countries, especially in Scandinavia (e.g. Andréasson et al. 2004; Beldring et al. 2006; Steele-Dunne et al. 2008; Vehviläinen and Huttunen 1997). The WSFS is used in the Finnish Environment Institute for operational hydrological forecasting in Finland.

The inputs of the WSFS are precipitation, temperature and optionally potential evaporation. In these simulations potential evaporation is calculated from temperature, precipitation and time of year used as an index for short wave radiation with empirical equations (Vehviläinen and Huttunen 1997). The equations for potential evaporation have been calibrated and validated based on measurements from Pan-A evaporation (Vehviläinen and Huttunen 1997). The actual evapotranspiration is calculated from potential evaporation and soil moisture deficit. Similar hydrological models with temperature and precipitation as inputs have been used in many studies of climate change impacts on hydrology (e.g. Andréasson et al. 2004; Steele-Dunne et al. 2008; Minville et al. 2009b). Even simpler temperature-index models using only temperature and monthly correction factors have been used to calculate potential evaporation (Andréasson et al. 2004; Steele-Dunne et al. 2008).

The model structure can be seen in Fig. 3. The simulated components of the hydrological cycle are spatial precipitation, snow accumulation and melt, soil moisture, soil and lake evaporation, subsurface storage and runoff, ground water storage

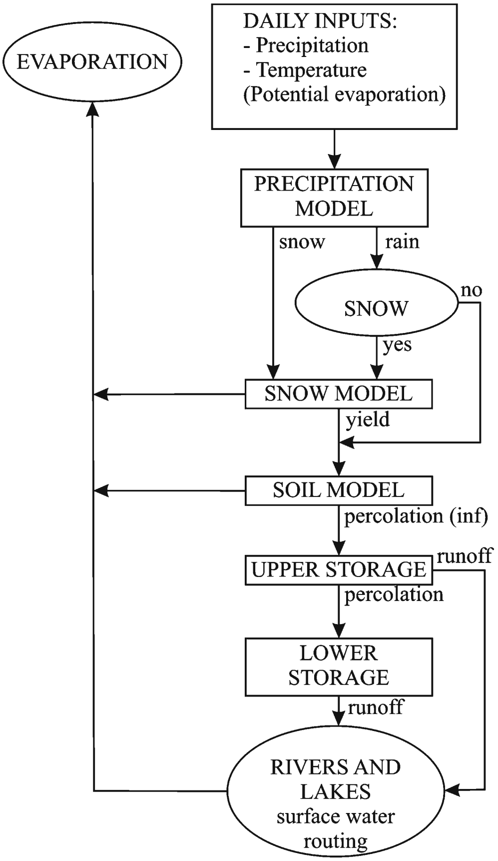


Fig. 3 Basic structure of the Finnish watershed model WSFS (adapted from Vehviläinen et al. 2005)

and runoff and discharges and water levels of rivers and lakes. The entire Vuoksi watershed is simulated, and therefore the upstream regulation choices affect the downstream lakes.

The hydrological model has been calibrated on the basis of water level, discharge and snow observations of 1981–2006. The Nash-Sutcliffe criteria R^2 for the model performance for daily water levels were in the calibration period 0.93 for Lake Pielinen, 0.86 for Lake Syväri and 0.93 for Lake Saimaa and for the validation period 0.88, 0.72 and 0.82, respectively. The validation period was 1971–1980 and 2007–2008, except for Lake Syväri only 2007–2008 since the regulation practices and limits in this lake changed in 1988.

The reference period in the study was 1971–2000. Observed temperature and precipitation of the reference period were changed using the delta change approach (also called perturbation or change factor approach), which is hitherto the most commonly used method for transferring the climate change signal to impact models (e.g. Fronzek and Carter 2007; Lettenmaier et al. 1999; Middelkoop et al. 2001; Prudhomme and Davies 2008). In this approach the average monthly temperature and precipitation changes from the climate scenarios are added to the observed temperatures and precipitations of the reference period.

Fourteen climate scenarios were used and three time periods 2010–2039, 2040–2069 and 2070–2099 were studied. This provides an opportunity to examine both short term and long term changes. Use of several climate scenarios when estimating climate change impacts is recommended in many studies (Prudhomme and Davies 2008; Steele-Dunne et al. 2008), since results from different climate scenarios can vary considerably. This also enables estimation of uncertainties related to climate change.

The climate scenarios were provided by the Finnish Meteorological Institute (FMI). The scenarios were chosen based on availability, past experiences and use in other studies in the Northern Hemisphere. Scenarios from three global climate models (GCM) and mean scenarios calculated by the Finnish Meteorological Institute (Ruosteenoja and Jylhä 2007) as an average of 19 GCMs (IPCC 2007) were used with three emission scenarios (Table 1). In addition two scenarios downscaled with the RCA3 regional climate model (RCM) (Rummukainen et al. 2001) from two GCMs were used (Table 1). Applying a mixture of both GCM and RCM results in impact studies is an approach recommended by Fronzek and Carter (2007). With these scenarios the annual temperature in the river Vuoksi watershed increased by 0.7–2.2°C by 2010–2039, 2.0–3.3°C by 2040–2069 and 2.7–5.2°C by 2070–2099 and the corresponding precipitation increases were 0.5–9%, 6–20% and 7–33%, respectively (Table 1).

The hydrological scenarios were created by simulating 30 years of daily discharges and water levels with the WSFS in the reference and future time periods using the delta change approach and 14 climate scenarios. Average, minimum and maximum daily water levels of the 30 year periods were further examined. The properties of the reference period affect the return period of the maximum and minimum water levels, which are meant only to provide an overview of moderate flood and drought water levels.

The regulation in the model was defined with model operation rules in which the outflow was based on the water level and the time of year. In the reference period the model operation rules generally corresponded to the current regulation

Table 1 Climate scenarios used in the study (Finnish Meteorological Institute, ENSEMBLES data archive) and their projected annual changes in temperature and precipitation in the Vuoksi watershed by 2070–2099 compared with the reference period 1971–2000

No.	GCM (see IPCC 2007)	RCM	Emission scenario	Abbreviation	T change (°C)	P change (%)
1	19 GCM mean	–	A2	Mean-A2	4.91	18.4
2[a]	19 GCM mean	–	A1B	Mean-A1B	4.29	16.2
3	19 GCM mean	–	B1	Mean-B1	3.09	12.1
4	ECHAM5/MPI-OM	–	A2	Echam5-A2	4.34	18.7
5	ECHAM5/MPI-OM	–	A1B	Echam5-A1B	4.13	17.2
6	ECHAM5/MPI-OM	–	B1	Echam5-B1	3.17	12.9
7	UKMO-HadCM3	–	A2	HadCM3-A2	5.16	11.4
8	UKMO-HadCM3	–	A1B	HadCM3-A1B	*5.21*	15.7
9	UKMO-HadCM3	–	B1	HadCM3-B1	3.73	18.3
10	CCSM3	–	A2	CCSM3-A2	4.77	15.1
11	CCSM3	–	A1B	CCSM3-A1B	3.56	12.5
12	CCSM3	–	B1	CCSM3-B1	*2.70*	7.0
13	UKMO-HadCM3	RCA3	A1B	RCA3-H-A1B	4.44	*33.8*
14	ECHAM5/MPI-OM	RCA3	A1B	RCA3-E-A1B	3.41	18.1

The greatest and the smallest changes are italicized

[a] Scenario used for demonstration

practices. The climate change simulations for regulated lakes were performed with two regulations; unmodified regulations attempting to follow the current regulation limits and modified regulations. The operating rules were modified to take the changed climate with shorter and wetter winters better into account and thus had an earlier and smaller draw-down of water levels during winter and spring.

The same model operating rules were used for simulation of the entire 30 year period and thus they were not optimal for every year. In reality the regulation permits on many lakes in Finland are such that the holder of the permit can make subjective decisions about the outflows depending for example on electricity prices as long as the regulation limits and to some extent the target water level zones are followed. Thus the regulation is in reality somewhat more variable and flexible than modelled here, especially on Lake Syväri, which is more strongly regulated than the other study lakes.

In Lake Pielinen the new regulation scheme developed by Verta et al. (2007) was applied automatically using rules which increased the outflow by 10–20% from the natural rating curve or decreased it by 15–30% when water level deviated from the target water level zones 1 and 2 (see Fig. 2). The snow water equivalent (SWE) was also used in the regulation scheme. If the SWE was high the water level during spring was lowered to the specified target levels. In climate change simulations, situations with very little snow were also identified and in this case the outflow was only increased at a higher water level than otherwise.

3.2 Impact Assessment

The social, economic and ecological impacts of changes in water level fluctuations and discharges of Lake Pielinen were evaluated with eight indicators. Lake Pielinen was chosen for the impact analysis, because the change in regulation is considered on the lake and because of its regional importance. The estimated impacts include flood damages, disadvantages for recreational use and navigation, hydro power production and four indicators on ecological impacts of water level and ice cover changes. These eight indicators were calculated from the water levels and outflow of Lake Pielinen for the reference period 1971–2000 and the periods 2010–2039, 2040–2069 and 2070–2099 with 14 climate scenarios. The calculations were made for each period with two different outflow strategies; the natural rating curve and the new regulation scheme.

The indicators have been developed and used in the Finnish Environment Institute in several regulation development projects (Keto et al. 2008; Marttunen and Järvinen 1999; Tarvainen et al. 2006). The water level fluctuation analysis tool Regcel (Keto et al. 2008) was used to calculate the ecological indicators and the disadvantage for recreational use. The ecological indicators were fish spawning conditions, disturbance to littoral flora and fauna by freezing of the lake bottom, shoreline erosion and extension of the sedge zone. However, these indicators have not been used in climate change studies before and were not designed for this purpose. The ecological indicators only cover the impacts of changes in water level and ice cover. The evaluation of all climate change effects on ecology is beyond the scope of this study, since much more inputs about changes in water quality etc. would be required. Nonetheless the included indicators provide interesting results about one aspect of climate change impacts on ecology.

The flood damages were evaluated in Euros from water levels based on flood damage curves in Lake Pielinen. Impacts on navigation were evaluated by calculating the average yearly number of days when water level is too low for navigation during the current season May-November. The combined power production of the two hydro plants in the outflow river of Lake Pielinen was calculated. Impacts of water levels on recreational use were evaluated by calculating the average annual disadvantage for recreational use in Euros. The calculations were made using functions of disadvantage for recreational use based on questionnaires and land surveys (Verta et al. 2007). These functions describe the decrease of the value of the lakeside real estate when the water level deviates from the optimum water level for recreational use during the recreational season.

4 Results

The results summarised in Table 2 show the 90% range of water levels with 14 scenarios and Figs. 4 and 5 show the average daily water levels and discharges. The changes in mean water levels were rather small in most scenarios in Lake Pielinen and Lake Saimaa (Table 2), but the seasonal changes were significant (Fig. 4). The water levels increased during winter and decreased during summer months. Student t-tests for the average seasonal (winter [DJF], spring [MAM], summer [JJA], autumn [SON]) water levels showed that in 2040–2069 and 2070–2099 the changes in water levels from the reference period were on average statistically significant ($P < 0.05$), except in Lake Syväri during autumn. In 2010–2039 the differences in seasonal water levels were on average statistically significant except in Lake Syväri and Lake Pielinen during autumn and in Lake Saimaa during in winter and summer. The maximum water levels increased in Lake Saimaa and Lake Pielinen in 2040–2069 and onwards, but decreased in Lake Syväri.

Table 2 Summary of mean, highest and lowest water levels (m) in the study lakes in the reference period and in 2010–2039, 2040–2069 and 2070–2099

	Lake Pielinen nat. rating curve	Lake Pielinen new reg. scheme	Lake Saimaa[a]	Lake Syväri[a]
Mean water level (m)				
Reference period	93.64	93.62	75.80	95.55
2010–2039 range 90%	93.61–93.72	93.66–94.73	75.75–75.88	95.60–95.62
2040–2069 range 90%	93.63–93.81	93.70–93.81	75.77–75.94	95.57–95.65
2070–2099 range 90%	93.63–93.93	9370–93.91	75.76–76.10	95.50–95.65
Mean annual highest water level (m)				
Reference period	94.22	94.12	76.08	96.20
2010–2039 range 90%	94.10–94.25	94.08–94.20	76.06–76.22	96.05–96.21
2040–2069 range 90%	94.16–94.40	94.13–94.31	76.15–76.38	95.99–96.09
2070–2099 range 90%	94.25–94.64	94.21–94.49	76.20–76.66	95.97–96.03
Highest water level (in the 30 year period) (m)				
Reference period	94.76	94.53	76.50	96.43
2010–2039 range 90%	94.55–94.79	94.41–94.61	76.72–77.21	96.30–96.48
2040–2069 range 90%	94.65–95.04	94.44–94.80	76.97–77.44	96.17–96.30
2070–2099 range 90%	94.79–95.35	94.57–95.05	77.01–77.81	96.09–96.22
Mean annual lowest water level (m)				
Reference period	93.15	93.09	75.53	94.42
2010–2039 range 90%	93.15–93.29	93.27–93.36	75.43–75.56	94.59–94.71
2040–2069 range 90%	93.09–93.31	93.28–93.40	75.41–75.56	94.72–94.83
2070–2099 range 90%	93.02–93.32	93.24–93.43	75.38–75.61	94.79–94.91
Lowest water level (in the 30 year period) (m)				
Reference period	92.86	92.72	75.20	94.27
2010–2039 range 90%	92.62–92.91	92.96–93.13	75.24–75.33	94.47–94.59
2040–2069 range 90%	92.55–92.82	92.88–93.12	75.19–75.33	94.52–94.64
2070–2099 range 90%	92.49–92.77	92.82–93.10	75.14–75.34	94.61–95.75

In future time periods the results are 90% range from 14 climate scenarios

[a] With the unmodified model operation rules in the future time periods

The variation between the different climate scenarios was rather large; for example the change of total inflow to Lake Saimaa by 2040–2069 varied from 5% decrease to 21% increase. The precipitation increases were larger than the increase in runoff, because part of the increase in precipitation was lost as evapotranspiration and lake evaporation increased.

It is interesting to note that regional climate model results differ significantly from the results of the GCMs from which they have been downscaled (Figs. 4 and 5). Scenario RCA3–H-A1B (see Table 1 for acronyms) provided by far the greatest increases in precipitation, water levels and runoff of all the scenarios, whereas scenario RCA3–E-A1B gave smaller than average temperature increases especially in 2010–2039. The scenario producing the smallest runoffs was CCSM3-B1, where precipitation increases were smallest.

4.1 Effects of Climate Change to Water Levels and Regulation

The effects of different regulation schemes are demonstrated with figures from just one climate scenario in 2040–2069 (Figs. 6, 7 and 8) since showing all the scenarios would make the figures unreadable. The chosen scenario was the Mean-

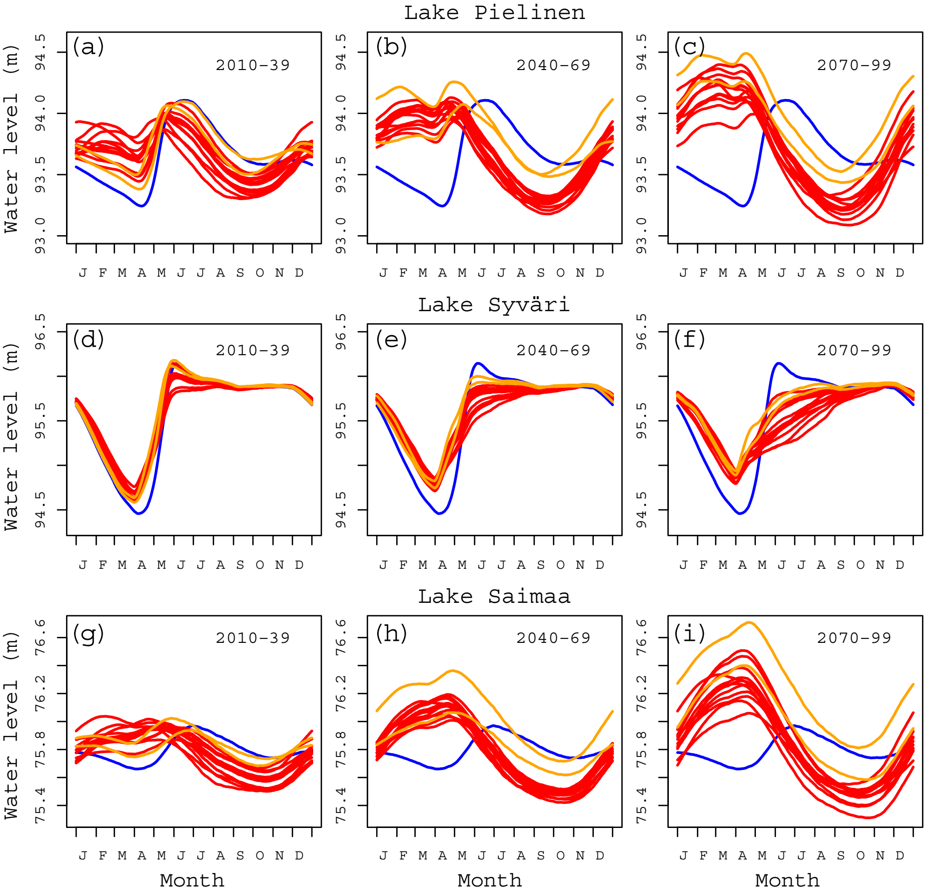


Fig. 4 Average daily water level (m) in Lake Pielinen (**a–c**), Lake Syväri (**d–f**) and Lake Saimaa (**g–i**) in the reference period (*blue*) and in 2010–2039 (*left*), 2040–2069 (*middle*) and 2070–2099 (*right*). The results are with unmodified regulations and 12 GCM climate scenarios (red) and two RCM climate scenarios (*orange*)

A1B scenario, which is the average of 19 GCMs for temperature and precipitation with the intermediate A1B emission scenario. It was chosen, because it produced average changes in temperature and precipitation, although it was not necessarily an average for the water level and discharge changes. However, it was not among the scenarios that produced either largest or smallest changes in runoff out of the 14 scenarios and thus can be used as an example.

In Lake Pielinen the simulations were first made using the natural rating curve. This is how the lake is operated at present, except that the exemption permits used to the decrease or increase exceptionally high and low water levels are not included in the simulations. In these simulations the average water levels in Lake Pielinen increased during winter and decreased during summer due to climate change (Fig. 4a–c, Table 2) and both flood and drought problems increased with most scenarios during the periods 2040–2069 and 2070–2099. In these periods the maximum water levels occurred during winter and early spring (Fig. 6, Table 2)

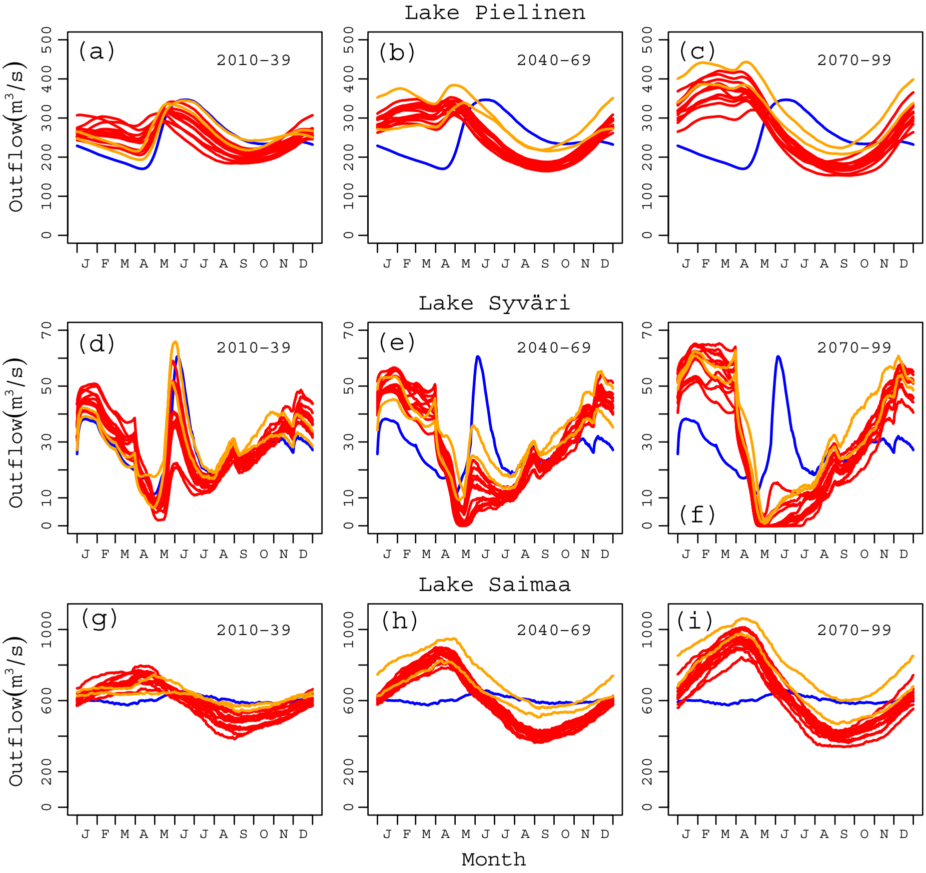


Fig. 5 Average daily outflow (m^3/s) from Lake Pielinen (**a–c**), Lake Syväri (**d–f**) and Lake Saimaa (**g–i**) in the reference period (*blue*) and in 2010–2039 (*left*), 2040–2069 (*middle*) and 2070–2099 (*right*). The results are with unmodified regulations and 12 GCM climate scenarios (*red*) and two RCM climate scenarios (*orange*)

and increased from the reference period with most of the scenarios. On the other hand, minimum water levels during summer and autumn decreased. Low water levels during this recreational period are much more disadvantageous than low water levels during winter and spring. At present, the water level fluctuation in Lake Pielinen is already considered by many lake users to be harmfully high (Verta et al. 2007). The results indicate that climate change will further increase this fluctuation.

The simulations for Lake Pielinen were also made with the new regulation scheme (Fig. 2), in which discharges can be increased or decreased from the natural outflow when water levels deviate from the target zones. With this new regulation scheme the highest water levels can be decreased and the lowest water levels increased (Fig. 6). Thus the negative effects of climate change could be alleviated by changing the regulation of the lake.

In Lake Syväri current regulation limits require that the lake level be lowered by the beginning of April in order to provide storage capacity for the spring flood. If

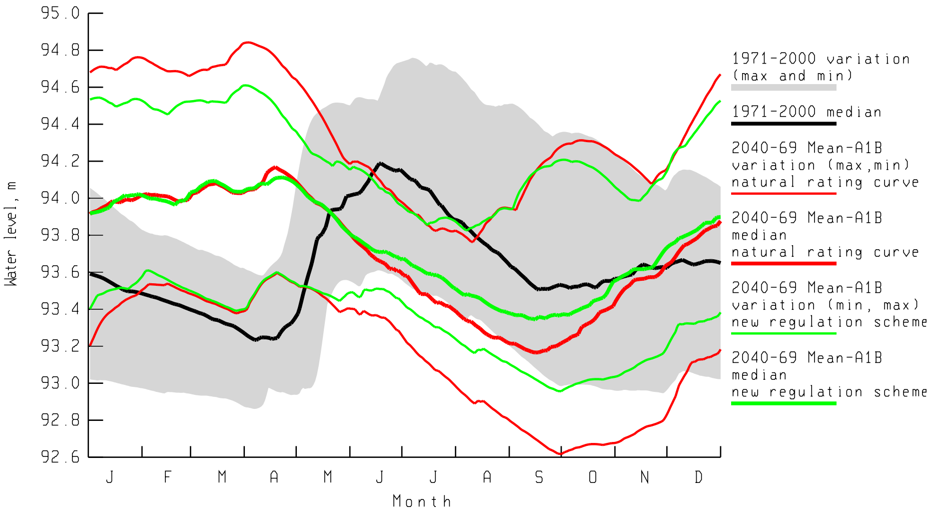


Fig. 6 Daily water levels in Lake Pielinen in the reference period with the natural rating curve and in 2040–2069 with the natural rating curve (*red*) and a new regulation scheme (*green*). *Thick lines* show the average daily water levels and the gray zone (for the reference period) or the *thin lines* (for 2040–2069) show the maximum and minimum daily water levels of the 30 year period

these regulation limits and similar limits in upstream lakes were followed in 2040–2069, the lake surface remained in some years low throughout the entire summer, since spring floods decreased dramatically and occurred earlier (Fig. 7). It was

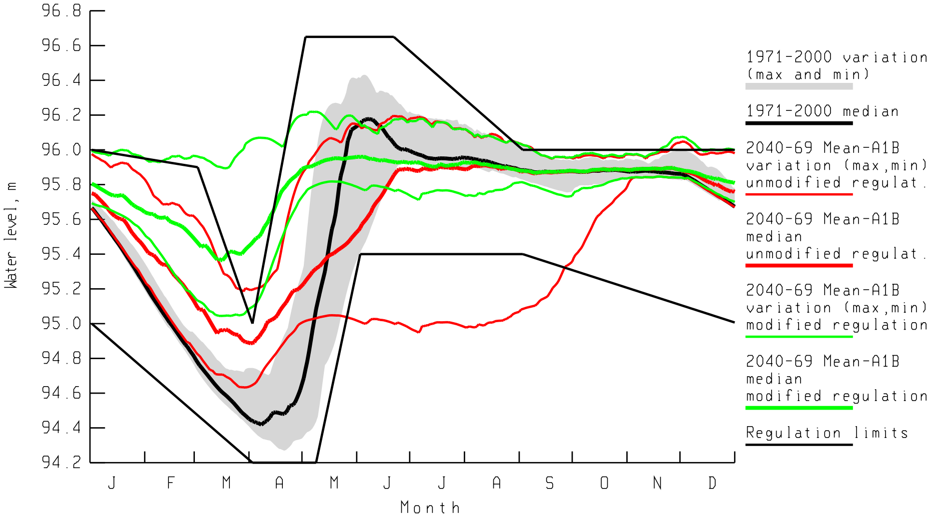


Fig. 7 Average, minimum and maximum daily water levels in the Lake Syväri in reference period (*black and gray*) and in 2040–2069 with unmodified regulation (*red*) and modified regulation (*green*). *Thick lines* show the average daily water levels and the gray zone (for the reference period) or the *thin lines* (for 2040–2069) show the maximum and minimum daily water levels of the 30 year period

necessary to modify the regulation so that the draw-down was smaller and ended earlier in order to reach the preferred summer water levels for recreational and other uses (Fig. 7, Table 2). With the modified regulation the current regulation limits were breached during spring, but the optimal water levels during summer were reached. Change of the regulation limits will therefore in all likelihood become necessary for Lake Syväri by 2040–2069. The problems seen in 2040–2069 (Fig. 7) with the unmodified regulation only increased in 2070–2099, but the same modified regulation schemes performed well during both periods. To further improve the modified regulation schemes in 2070–2099 the draw-down of water levels in early spring could be decreased and water levels in autumn could be lowered.

Since currently the largest floods in Lake Syväri are spring floods, their decrease means that the highest water levels and outflows and thus flood risk decreased. This occurs in many smaller upstream lakes in eastern Finland, where spring floods are currently by far the largest floods. Autumn and winter floods increased, but not enough to become as large as the current spring floods.

According to the results, the seasonal rhythm of Lake Saimaa in future time periods changed considerably from the present situation (Fig. 4g–i, Table 2). In the simulations of 2040–2069 the highest water levels in Lake Saimaa occurred during winter and early spring and the lowest during late summer and autumn (Fig. 8). Floods increased due to increased precipitation. The inflow to Lake Saimaa was highest during late autumn and winter because of warmer winters with increased snow melt, very low winter evaporation and the long time delays of the autumn rains from the farthest parts of the watersheds due to long lake routes.

A large winter flood occurred in the reference period in 1974–1975, and this flood was the largest flood in the climate change simulations. The flood was caused by a mild and wet autumn and winter, which became even milder and wetter with the

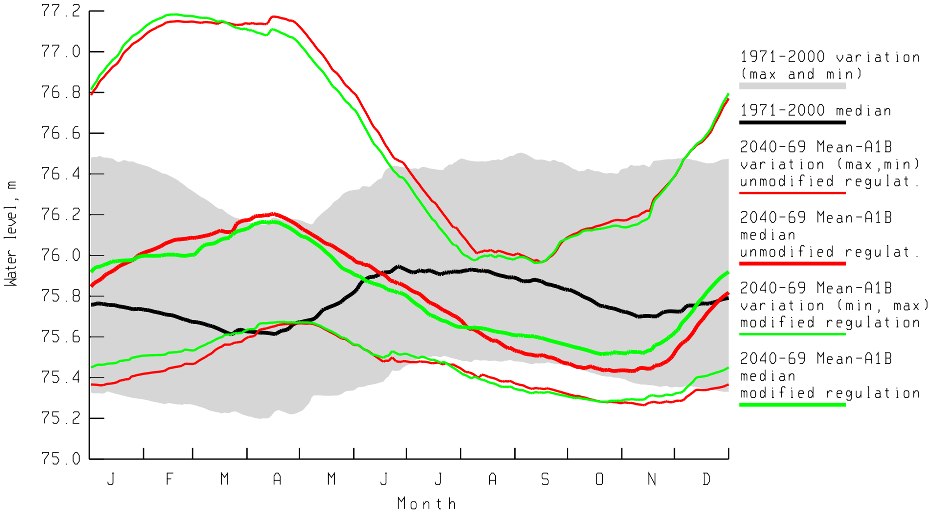


Fig. 8 Average, minimum and maximum daily water levels in Lake Saimaa in the reference period (*black and gray*) and in 2040–2069 with unmodified regulation (*red*) and modified regulation (*green*). *Thick lines* show the average daily water levels and the gray zone (for the reference period) or the *thin lines* (for 2040–2069) show the maximum and minimum daily water levels of the 30 year period

climate change scenarios. This rare winter flood in the reference period was one reason why the maximum values increased so dramatically. Another reason was the limit value for increasing the outflow from the natural outflow, which limited the possibilities to decrease the large floods. After this limit was exceeded, the water level increased rapidly.

The regulation storage of the upstream lakes is not large compared to the inflow of Lake Saimaa and therefore upstream regulations did not have a major effect on Lake Saimaa. The new regulation scheme for Lake Pielinen decreased its storage in severe flood and drought situation, which affects the water level of Lake Saimaa. Lake Saimaa regulation was modified only within the current contract with Russia and thus the possibilities to affect the water level were limited (Fig. 8), since possible modifications were rather small and the limit value of outflow was not increased.

4.2 Impact Assessment of Water Level Changes in Lake Pielinen

Impacts of water level fluctuation on flood damages, recreational use, hydro power production, navigation and ecology were assessed for Lake Pielinen. These evaluations were made with the natural rating curve and the new regulation scheme for the reference period 1971–2000 and for 2010–2039, 2040–2069 and 2070–2099 with the 14 climate scenarios (see Table 1). The results are presented as an average and 90% range from these scenarios. A summary of the results of the impact indicators with the average of the 14 scenarios is shown in Table 3.

Table 3 Summary of the impacts of water level change in Lake Pielinen according to the average of 14 climate scenarios

	Natural rating curve			New regulation scheme vs. Natural rating curve			
	2010–2039	2040–2069	2070–2099	1971–2000	2010–2039	2040–2069	2070–2099
Freezing of the lake bottom	+	+	+	0	0	0	0
Extension of the sedge zone	+	+	+	0	–	–	–
Spawning conditions of pike	0	+	+	–	0	–	–
Shoreline erosion	0	–	–	0	0	+	+
Floods	+	–	–	+	+	+	++
Recreational use	0	–	–	+	+	+	+
Navigation	–	–	–	+	+	+	+
Hydro power production	+	+	+	0	0	0	0

For the natural rating curve the results are compared with the reference period 1971–2000 with the natural rating curve and for the new regulation scheme the comparison is made with the natural rating curve for the same period. Plus sign indicates a change towards a better direction, a minus sign a change for the worse, two signs indicate a stronger change, 0 indicates no change

4.2.1 Ecological Impacts of Water Level and Ice Cover Changes

The indicators that depict effects of water level change on lake ecosystems were calculated from water levels, water colour, maximum ice thickness (meters) and ice-off and ice-on days. Water colour was given as a constant based on observations. The timings of ice-off and ice-on days were estimated from the surface water temperatures simulated with the WSFS model and ice thickness changes were estimated on the basis of observations. For more accurate estimates for the ice-on and ice-off days, a specific ice model would be needed. The ice model in WSFS is currently under development, and will be taken into use in future studies.

Changes in the water level fluctuation regime in Lake Pielinen caused by climate change may increase the extension of the sedge (*Carex* sp.) zone and benefit reproduction of northern pike (*Esox lucius*) due to more suitable water levels during spawning (Table 4). The disadvantage for the littoral flora and fauna by freezing of the lake bottom may decrease due to thinner ice and less draw-down in winter. On the other hand, the higher water levels during autumn and winter and shortening of the period with ice cover may increase the erosion of the shoreline and thus make it a harsher living environment. The calculated indicators showed both positive and negative effects from water level fluctuations caused by climate change. Compared with the natural rating curve, the new regulation scheme had a small negative effect on other indicators except a positive impact for shoreline erosion. With most indicators the differences between the two outflow strategies were however smaller than the effect of climate change.

4.2.2 Flood Damages

On average the flood damages in Lake Pielinen first decreased in the period 2010–2039 as the largest spring floods decreased. By 2040–2069 winter floods increased due to mild and wet autumns and winters and with most climate scenarios the overall flood damages increased from the reference period. The increase of flood damages was very large by 2070–2099, although the range of damages also became large. With the new regulation scheme the highest water levels and thus flood damages could be decreased significantly by increasing the outflow (Fig. 9).

Table 4 Summary of the ecological impacts of water levels in Lake Pielinen in the reference period and in 2010–2039, 2040–2069 and 2070–2099 with two outflow strategies

Period	Natural				New regulation			
	1971–2000	2010–2039	2040–2069	2070–2099	1971–2000	2010–2039	2040–2069	2070–2099
Freezing of the lake bottom[a] (m)	1.25	0.67	0.31	0.14	1.30	0.71	0.33	0.14
Sedge zone[b] (m)	0.49	0.55	0.70	0.88	0.47	0.44	0.53	0.64
Spawning conditions of pike[c] (m)	0.30	0.28	0.36	0.53	0.22	0.26	0.32	0.46
Shoreline erosion[d] (m)	0.75	0.79	1.04	1.21	0.70	0.66	0.82	0.94

Average from 14 climate scenarios

[a] Water level decrease during the ice cover period (m)

[b] Maximum vertical extension of the sedge zone (m)

[c] Minimum water level in the sedge zone during the spawning of northern pike (m)

[d] Water level variation during the ice free period (m)

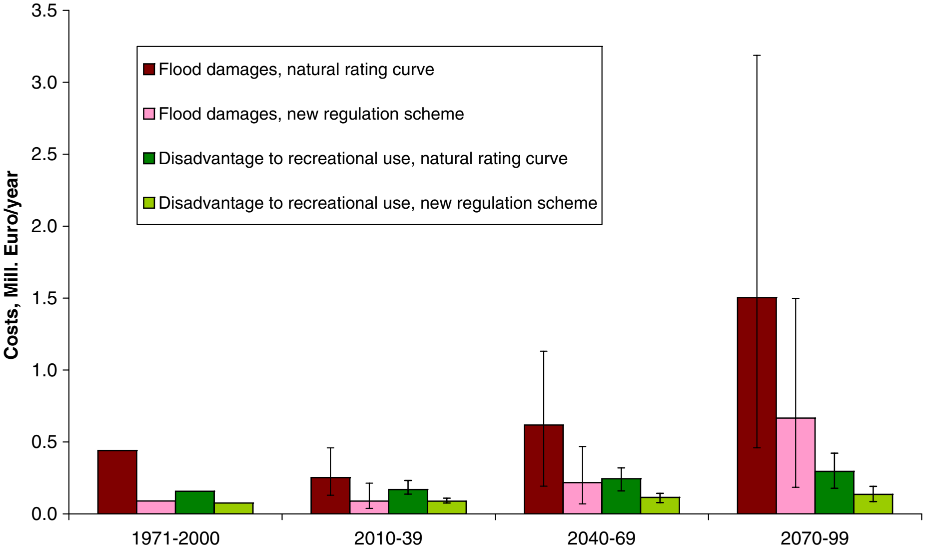


Fig. 9 Average annual flood damages and disadvantage to recreational use (M €/a) in the reference period 1971–2000 and in 2010–2039, 2040–2069 and 2070–2099. *Bars* show average values with two alternative outflow strategies (natural rating curve and new regulation scheme), and *error bars* the 90% range from 14 scenarios

Frazil ice floods can occur when river discharges are high, the river has no ice cover and the temperature drops well below zero, when ice forming on river bed and dam structures raises the water levels to flood heights. In a another river in central Finland, frazil ice floods have been estimated to become more common due to climate change (Huokuna et al. 2009) and those results apply in the outflow river of Lake Pielinen as well.

4.2.3 Recreational Use and Navigation

The disadvantage to recreational use increased in Lake Pielinen during 2040–2069 and 2070–2099 because water levels decreased during the summer and early autumn. The water levels too low for navigation also increased. During the period 2010–2039 this change was not yet significantly seen in the disadvantage to recreational use. The new regulation scheme increased the lowest water levels in summer and autumn and thus had a positive effect on recreational use and navigation (Fig. 9).

4.2.4 Hydro Power Production

The average annual hydro power production in the two power plants in the outflow river from Lake Pielinen were in the reference period 293 MWh and the average unproductive spills were 7 MWh with the natural rating curve. The water power production increased on average by 4% from the reference period by 2010–2039, 4% by 2040–2069 and 7% by 2070–2099 with the natural rating curve (Fig. 10). The 90% range of change was from −2% to +6% in 2010–2039, from 0 to +11% in 2040–2069 and from −1% to +16% in 2070–2099. With the new regulation scheme the water

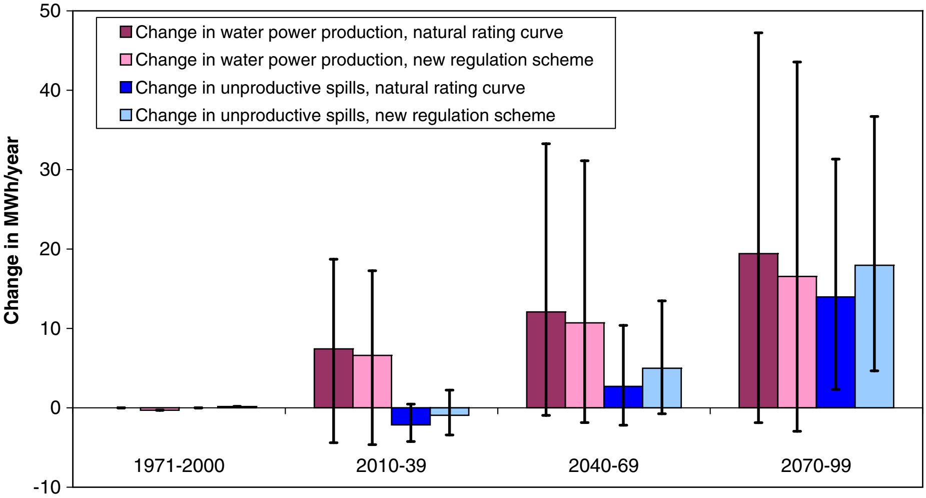


Fig. 10 Changes in water power production (MWh) and unproductive spills from the reference period (natural rating curve). Average changes in 2010–2039, 2040–2069 and 2070–2099 using two alternative outflows (natural rating curve and new regulation scheme) and the 90% range from 14 scenarios in *error bars*

power production was smaller than with the natural rating curve, but the differences between the two outflow strategies were rather small. In addition, the unproductive spills increased from the reference period in 2040–2069 and 2070–2099 (Fig. 10) and therefore the hydro power production could be increased more by increasing the capacity of the power plants. On the other hand, problems with frazil ice (Huokuna et al. 2009) may decrease production and cause interruptions in operation.

5 Discussion

According to the results of the climate change simulations, runoff and water levels will change significantly during different seasons. The results are in line with the results from previous studies in Finland (Vehviläinen and Huttunen 1997) and in other Nordic regions (Andréasson et al. 2004; Beldring et al. 2006; Minville et al. 2009a). In Lake Vänern, a large lake in southern Sweden, an increase caused by climate change in the flood risk and especially in autumn and winter floods has been reported (Bergström et al. 2006). Those results were similar to the increasing floods in Lake Saimaa and Lake Pielinen found in this study.

Two recent studies (Minville et al. 2009a, b) have evaluated changes in hydro-power production in a Canadian river system due to climate change. As in this study, they found increases in hydro-power production in 2040–2069 and 2070–2099 and a considerable increase in unproductive spills (Minville et al. 2009a). Adaptation of operation rules was found to be important for the hydro power production.

The results show that in some lakes the current regulation permits and limits with a winter and spring draw-down of water levels will not be suitable in the changed climate and need to be changed. The new regulation permits should be flexible enough to function properly in a variety of conditions and adopt the ‘no-regret and flexibility’ principle as suggested by Middelkoop et al. (2001). Winters with large amounts of snow will still occur especially during 2010–2039 and in these years storage for the spring melt waters will still be needed. On the other hand winters with very low accumulated snow and high winter runoffs will become more common and the modified regulations should take this into account. Results showed that minimum water levels during summer and early autumn decreased because of longer and warmer summers and decreasing and earlier spring runoff peaks. Since summer is the prime time for recreational use and navigation, it is important to ensure that the water levels of regulated lakes will be high enough during early summer. Real time hydrologic forecasts could be utilized more in the future regulations. Hydrological forecast used together with long term weather forecasts with their improving accuracy can offer potential for improved regulation planning.

For some lakes such as Lake Pielinen, more effective regulation of the lake may be the best way to counterbalance the estimated negative effects of climate change. In Lake Pielinen the results of this study are already being used in an ongoing investigation of the possibilities to change the current regulation permit (Verta et al. 2007). Together with the recent mild winters, the results have already had some influence on this process and the proposed new regulation scheme includes modifications to take the possibility of mild winters better into account.

The winters of 2006–2008 were mild in Finland and the water levels of Lakes Saimaa and Pielinen were exceptional. The water level of Lake Saimaa increased during autumn and part of the winter and was very high compared to the average water level (Fig. 11). In Lake Pielinen the water level higher during January to April 2007 and in April 2008 than it had been in 1959–2006. The water level fluctuations in 2007 and 2008 were already similar to that of the scenarios for 2010–2039 and even

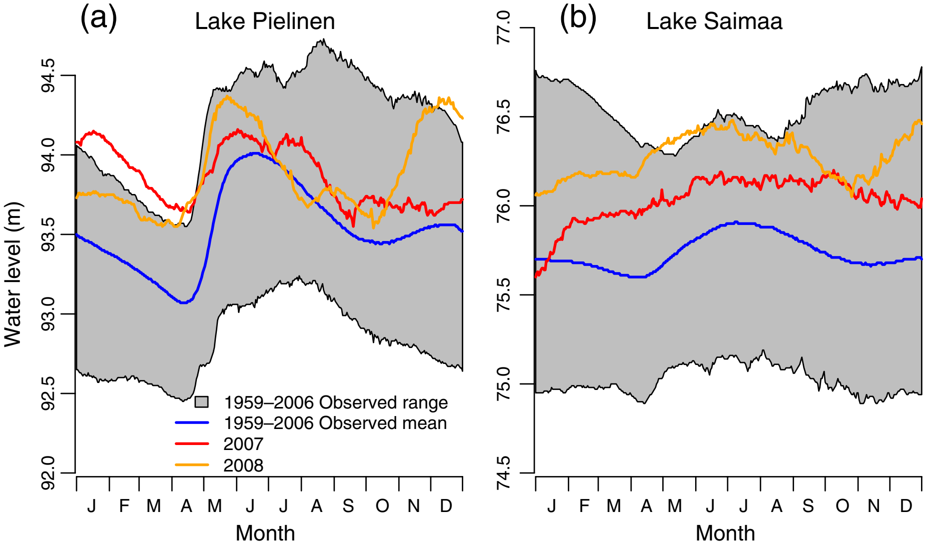


Fig. 11 Observed water level **a** in Lake Pielinen and **b** in Lake Saimaa in 1959–2006 and in 2007 and 2008. Same legend applies for both **a** and **b**

2040–2069. Whereas these warm years are at least partly due to natural variability, and the weather from only a few years does not offer proof of climate change, they nonetheless show that the major changes estimated here are not unrealistic.

5.1 Uncertainties of the Study

Climate change studies always contain uncertainties due to the unknown development of future climate and the limited number of climate scenarios used. In addition uncertainties arise from the hydrological modelling, but since only one conceptual hydrological model with one optimal set of parameters was used the modelling uncertainty was not estimated. GCMs have been reported as being the greatest source of uncertainty in climate change studies (e.g. Déqué et al. 2007; Prudhomme and Davies 2008), but the hydrological model and the method of applying the climate scenarios also affect the results significantly. The delta change approach used here does not take into account the changes in distribution of precipitation and temperature and only modifies the climate of the reference period. In Scandinavia very low winter temperatures are estimated to increase more than higher temperatures (IPCC 2007), which would affect the accumulation and melt of snow. The numbers of wet days and extreme precipitations in northern Europe are also estimated to increase (Christensen and Christensen 2004; IPCC 2007). The study lakes are relatively large, their runoff areas have high lake percentages and water level fluctuations are rather slow. Therefore, the changes in distribution of temperature and precipitation would not affect these lakes as much as for example small river catchments.

The regulation practices were simulated using the same model operation rules for all years, but in reality the regulation practices are more flexible. However, the results provide an overview of the challenges and possibilities of regulation on average. This study is a preliminary study on the adaptation needs in lake regulation. More detailed studies are needed before new regulation limits and practices can be recommended.

It should be kept in mind that the indicators used to estimate the social, ecological and economic impacts have been developed to estimate the effects of water level fluctuations in current conditions. For example, recreational and navigation seasons may change, and the behaviour of plant and animal species may change as they try to adapt to the climate change. For ecology, the impacts of climate change induced changes in water level and to some extent ice cover were estimated, but the estimation of overall effects of climate change on ecology is beyond the scope of this study. This would require much more information on changes of water temperature and water quality, such as changes in nutrient and oxygen concentrations. These can be even more important for the overall ecological impacts than the effects of water levels.

6 Conclusions

The results presented here show clear change in the seasonality of runoff and water levels, with decreases in late spring and summer runoff and water levels and increases in late autumn and winter. These changes were mostly caused by changes in snow accumulation and melt, but also changes in precipitation and evapotranspiration had an effect. The snow accumulation and spring snowmelt floods decreased by 2040–2069, but autumn and winter runoff peaks increased. The impacts of climate change on floods were different in different parts of the large watershed. In small upstream lakes (Lake Syväri), where largest floods at present are snowmelt floods, floods decreased due to decrease in snow accumulation. On the other hand, in large central lakes (Lake Saimaa), where floods are long-lasting volume floods, the floods increased by 2040–2069 during winter and early spring because of wetter and warmer autumns and winters. Minimum water levels decreased during summer and early autumn, the prime time for recreational use and navigation.

Climate change will cause the current regulation permits and limits to be unsuited for the new hydrological conditions on many lakes. Instead of snowmelt floods during spring and summer, the largest future challenges in eastern Finland will in many lakes be autumn and winter floods and occasional summer dryness. To adapt to these changes and to decrease the negative effects of climate change, many of the regulation permits must be changed. The need to change the regulation permits depends greatly on how they are defined at present. The stricter the current regulation limits are about putting into effect a deep winter and early spring draw-down of water levels at a specific time of year, the more likely they are to require revision. Changing the regulation permits and limits is a cost-effective adaptation measure, since it uses the existing dams and does not require any new large investments.

Water level fluctuations affect many social, ecological and economic objectives. These effects should be taken into account when establishing new operating rules in a changing climate. The indicators calculated from the simulated water level fluctuations of Lake Pielinen show both positive and negative changes due to climate change and the examined regulation schemes.

During the mild winters of 2006–2008 it has already become clear in southern Finland that some regulation permits are not suitable for these conditions. Changing the legally binding regulation permits and limits or changing the Water Act is necessary to adapt to the observed and expected changes. This is a laborious and time consuming process. Therefore, analysis of the suitability of the current regulation rules in changing climate should be continued in more detail in order to avoid a situation where the unsuitable regulation aggravates problems caused by climate change.

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