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Frazil ice problems in changing climate conditions

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In the future, an increased precipitation together with higher temperatures in the winter will most likely cause higher discharges in European rivers in high latitudes. As the cold periods will nonetheless remain, the occurrence of a rapid cooling directly after the flood event may cause frazil ice problems in increasing quantity and frequency.

This study utilized the results of the WaterAdapt project, where climate change scenarios for different future time periods were simulated with the Watershed Simulation and Forecasting System (WSFS) of the Finnish Environment Institute. The main component of WSFS is a HBV-type conceptual watershed model. The climate scenarios used in the hydrological simulation were from different global climate models simulated with IPCC SRES emission scenarios. The time period used in this study was 2040-2069 along with the reference period of 1971-2000 and four different climate scenarios were used.

On the basis of climate change scenario results including for example the average daily discharges and air temperatures, a simple spreadsheet application was composed. The spreadsheet was used to parse the days where certain conditions such as adequate temperature below zero and high discharge were fulfilled and to roughly estimate the conditions for frazil ice formation. The results of this processing enabled a direct comparison of the number of days favorable to frazil ice production between the control time period and estimated future climate. The spreadsheet application was used to estimate frazil ice conditions in the Kokemäenjoki River, which is known for harmful frazil ice floods. This paper presents some first results of those studies.

1. Introduction

During this decade there have been several very warm and rainy winters in Finland. During the winter 2004-2005 frazil ice caused harm in the Kokemäenjoki River but because of successful river discharge regulation there were no large flood damages (Huokuna 2007). The winter 2005-2006 was also warm and rainy. During the winter 2007-2008 the discharges in rivers were very high in the Southern Finland and many rivers were without ice cover until the middle of February. Short cold periods in January and in February caused frazil and anchor ice problems in rivers which normally do not face those problems

Climate change scenarios project that by 2070-2099 average yearly temperature in Finland would increase 3-7 °C and yearly average precipitation would increase 13-26 % with largest increases during winter. (Ruosteenoja and Jylhä 2007, IPCC 2007). By 2040-69, which is the time horizon of this study, the temperature changes are about 1-3.7 °C and precipitation changes 5-15 %. In high latitudes the temperature is projected to increase more than the global average warming.

WaterAdapt project is a national project financed by the Finnish Ministry of Agriculture and Forestry as part of a Climate Change Adaptation Research Programme ISTO. The projects aim is to estimate changes in Finland's hydrology, water resources and floods due to climate change and to evaluate possibilities to adapt to these changes through changes in lake regulation. According to the results of the WaterAdapt project and previous studies climate change will alter especially the seasonal distribution of runoff in Finland. Winter runoff and winter time floods are expected to increase due to wetter and warmer winters with increased snowmelt and precipitation. Spring snowmelt runoff and floods on the other hand decrease since there is less accumulated snow and longer and warmer summers cause summer runoff to decrease as well. (Silander et al. 2006)

The Kokemäenjoki River was used as an example river in the climate change studies which are presented in the chapters 2, 3 and 4. The river is known for harmful frazil ice floods especially in Pori which is located at the mount of the river (Huokuna 2007). The location of the Kokemäenjoki River and Pori are represented in the Figure 1. The watershed of the river covers an area of about 27000 km^2 and the length of the main Kokemäenjoki River is about 110 km

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2. Climate change simulations

The climate scenarios used in this study were obtained from the Finnish Meteorological Institute (FMI) (Ruosteenoja 2007) and from the ENSEMBLES project. In the simulations four climate scenarios for the period 2040-69 were used. One of the scenarios is an ensemble mean scenario, which is an average of 19 global models with A1B emission scenario calculated by FMI (Table 1). In the A1B emission scenario the estimated future emissions of greenhouse gases are quite intermediate compared with the other SRES emission scenarios. The other three scenarios (Table 1) are one from global climate model (so called warm scenario), and two from one regional climate model with two different global climate models as boundary conditions (so called wet and cold scenarios). These four scenarios were chosen from a total of 14 climate scenarios so that they cover different kinds of temperature and precipitation changes. The climate change signal was transferred to the offline hydrological model with a so called delta change approach. In this approach the monthly average changes of temperature and precipitation in the scenarios are added to the observed temperatures and precipitations of the reference period

Table 1. Climate scenarios used in this study and projected changes in temperatures and precipitations in the Kokemäenjoki River catchment area by 2040-69 compared to 1971-2000.

Regional climate model	Global climate model	Emission scenario	Temperature change year	Precipitation change year	Referred here as
None	19 model mean	A1B	2.3 ºC	10 %	mean scenario
None	CCCM3	A2	2.9 ºC	9 %	warm scenario
RCA3	HadCM3-e1	A1B	2.6 ºC	17 %	wet scenario
RCA3	ECHAM5	A1B	1.8 ºC	7 %	cold scenario

The hydrological scenarios about the effects of climate change to discharges were simulated with the Finnish Environment Institutes Watershed Simulation and Forecasting System (WSFS) (Vehviläinen et al. 2005). The WSFS is a conceptual hydrological model, used for operational flood forecasting and for research purposes. The system is based on watershed model, which has HVB-model structure and simulates the hydrological cycle using standard meteorological data. The model simulates the whole land area of Finland, including cross-boundary watersheds, total of 390 000 km^2. The inputs of the model are precipitation and temperature and the simulated components of hydrological cycle are snow accumulation and melt, soil moisture, evaporation, ground water, runoff and discharges and water levels of main rivers and lakes. (Vehviläinen et al. 2005)

The hydrological scenarios for the Kokemäenjoki River were evaluated by simulating 30 years of daily discharges with the WSFS in the reference period 1971-2000 and in the future 2040-69. In the reference period the input data were observed temperatures and precipitations. In the simulations of future time periods the reference period precipitations and temperatures were changed according to the monthly changes of the climate scenarios. Discharges and water levels in lakes were then simulated with the changed temperatures and precipitations as input and new discharges for the 30 year period are obtained.

The regulation of the upstream lakes affects the simulated discharges in the Kokemäenjoki River. In the simulations the lakes are regulated with an operating rule where outflow from lake depends on water level and date. When simulating the reference period the operating rules corresponded on average to present regulation practices. When simulating the climate change situation the operating rules were modified only slightly from the present practices to take the expected changes in regulation rules and practices into account.

Results from the Kokemäenjoki River show that the discharges increase between November and March and decrease in May-September (Figure 2). The winter discharge and floods increases because in a warmer climate a larger portion of the increasing precipitation falls as rain and snowmelt occurs increasingly in the winter time. Due to this there is much less snow and the spring snowmelt runoff decreases. The summer runoff decreases due to longer summer with higher evaporation, especially from lakes.

3. The “frazil ice risk day” analysis

As it is known that cold air temperature together with high discharge connive the formation of frazil ice, it could be useful to be able to estimate the future frazil ice formation conditions. Because the climate change simulations are calculated with daily values the results are very easily transferable to a standard spreadsheet program, like Microsoft Excel used in this study. By defining an equal sized matrix over the each desired quantity and giving them critical values it is possible to calculate for example the monthly sum of the "frazil ice risk days" for each climate change scenario. In here, the “frazil ice risk day” means a day where both air temperature and discharge are suitable for frazil ice formation.

To describe a continuous cold weather needed to cool down the water temperature for frazil ice formation and hereby to avoid erroneous late autumn and early winter frazil ice risk days where the critical discharge and daily average temperature are reached, but where the water is not necessarily cooled down enough, an additional parameter of 7-day air temperature was added. A -1 °C weekly average temperature was considered to fulfill the sufficient water cooling at the lower part of the Kokemäenjoki River.

Before applying the method in the climate change simulations it was first tested on observed data from 1971-2007. Koskinen et al. (2006) have reported the previous floods in the city of Pori and on the observation period there have been frazil ice related floods timed during winters 1974-75, 1981-82, 1982-83 and 2004-05. In the winter 2006-2007 there were a potential flood. These were taken as calibration values in defining the critical discharge and air temperature values for frazil ice formation. The ice cover thickness was ignored as this was considered to require further development and as there were no observations available. The objective of the calibration was to catch those four winters and as few other winters as possible. The objective was reached with a discharge of 400 m³/s and air temperature of -4 °C. In addition of the four reported frazil ice winters six other winters were pointed out by this method. The same critical discharge value was also and in separate of this study estimated by the responsible regional water authority of the Kokemäenjoki River basin, Southwest Finland Regional Environment Centre.

Winters where frazil ice days existed with calibrated critical discharge and air temperature values are presented in table 2. On average each winter with frazil ice days had 3,3 days of frazil ice. The median of the frazil ice days presented in table 2 is 2 days.

Table 2. Number of frazil ice days on winters 1971-2007 using observed discharge and temperature data and reported frazil ice winters.

Winter	**1974-1975**[*]	**1980-1981**	**1981-1982**[*]	**1982-1983**[*]	**1989-1990**	**1992-1993**	**2001-2002**	**2004-2005**[*]	**2006-2007**
Number of frazil ice days	9	4	2	4	1	1	1	6	2

*) Reported frazil ice winter

4. Results

The critical 400 m³/s discharge and -4 °C air temperature were applied in four climate change scenarios for period 2040-2069. The annual amounts of frazil ice risk days for warm and cold scenarios are presented in Figures 3 and 4. On the past period there were 30 frazil ice risk days in 9 winters. On period 2040-2069, depending on the climate change scenario, there would be 102-230 risk days on 15-22 winters. The variation is rather great especially on the amount of days, but the trend is clearly towards more days on more winters. The mildest frazil ice risk day amounts were obtained with the cold scenario (102 days in 15 winters) and the largest with the wet scenario (230 days in 22 winters).

Figure 5 illustrates the monthly distribution of the frazil ice risk days in climate change scenarios and observed data with a critical discharge of 400 m^3/s and air temperature of -4 °C. The 7-day average for air temperature was set to -1 °C. The monthly values in graphs are summed over the whole scenario or observation period. The observation period is adjusted to 30 years for better comparison. In the future (2040-2069) the frazil ice risk days occur in greater amount and in addition the present peak month January there are considerable more days in December and February as well. It is also noticeable that on the observation period only 3 percent of frazil ice risk days occurred before December and 26 percent before January. The corresponding percents for the 2040-2069 scenarios are between 4-15 % before December and 24-54 % before January. Except the cold scenario the results in later scenarios are very similar with each other.

The main factor enhancing the amount of the days seems to be increasing discharges (Fig. 6 a) where some significant changes may be seen in some months. The change in mean temperatures around the city of Pori (Fig.6 b) is more constant throughout the winter months and between the different scenarios.

5. Conclusions

Climate change may have a great impact on river ice conditions. This has been presented in several papers (Beltaos & Burrell 2003, Andrishak and Hicks 2005, Magnuson et al. 2000). In this paper the impacts of climate change on frazil ice formation in Kokemäenjoki River are studied by using a simple spreadsheet application to study climate change scenarios which have been produced by climate and watershed models. According to the results the number of days during which the conditions for frazil ice formation are favorable are increasing significantly in the Kokemäenjoki River because of climate chance. A more sophisticated approach is needed to take the ice cover formation into account and the effect of it on frazil ice formation. The selected years should be simulated with a hydrodynamic model capable to simulate ice cover formation. By this way the effects of discharge regulation could be better estimated.

During the last five years there have been several rainy and warm winters with a lot of frazil ice problems in Finland. It is too early to say if these weather and frazil conditions are marks of the effects of climate change. However, it seems evident that we are going to have that kind of winters more frequently in the future.

Acknowledgments

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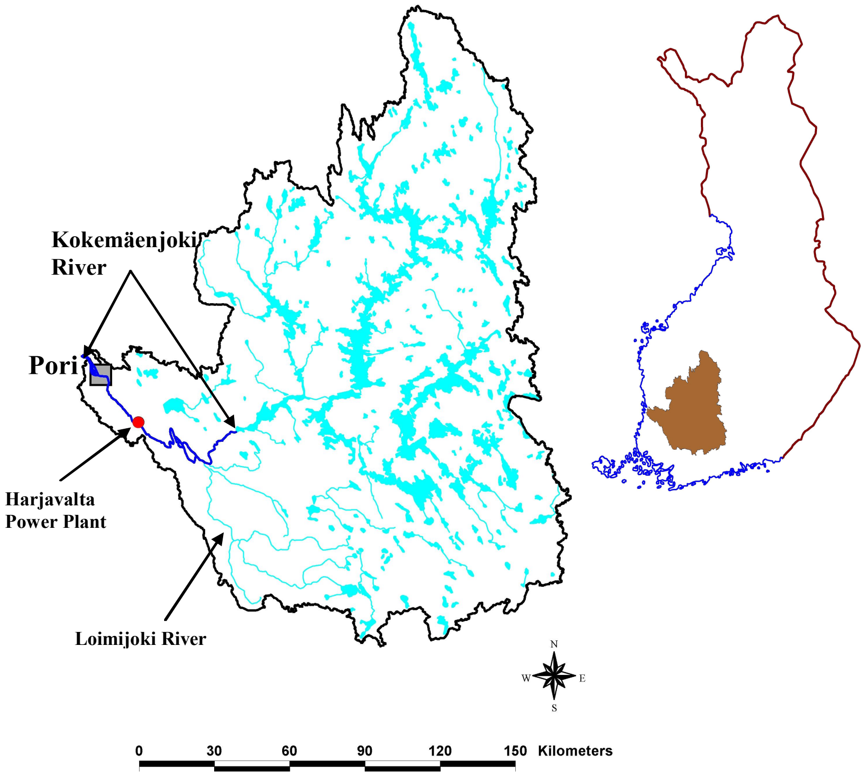

Figure 1. The Kokemäenjoki River watershed.

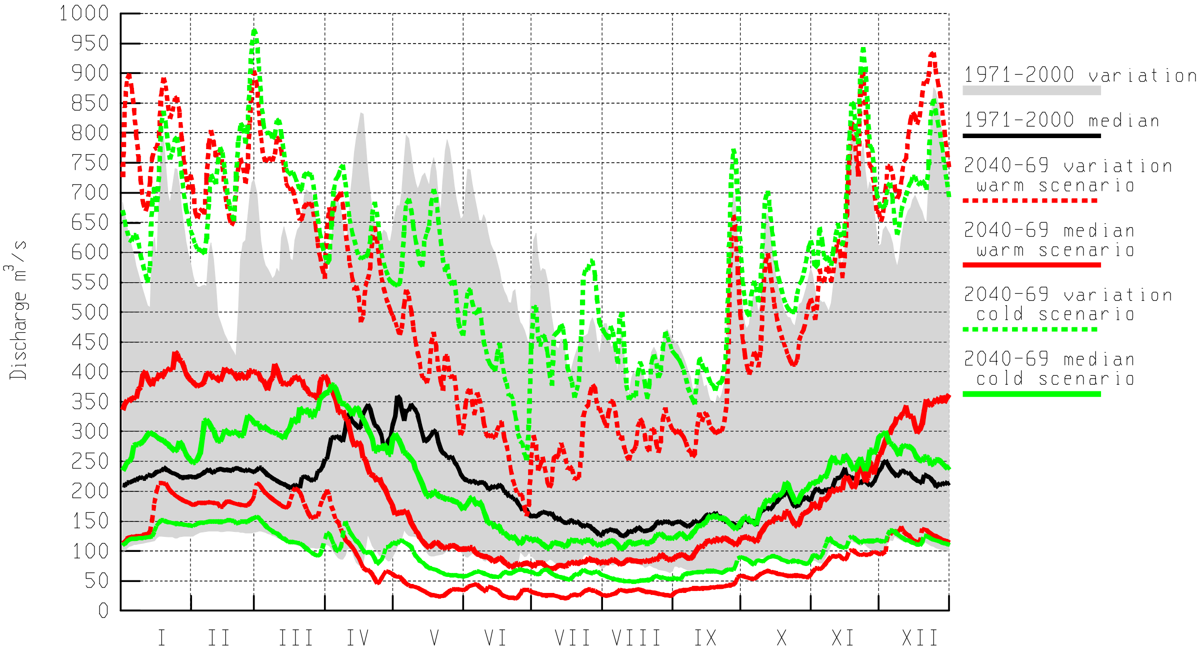

Figure 2. Simulated median, maximum and minimum discharges in Pori in the Kokemäenjoki River in the reference period 1971-2000 and in 20240-69 with two scenarios (warm and cold scenarios).

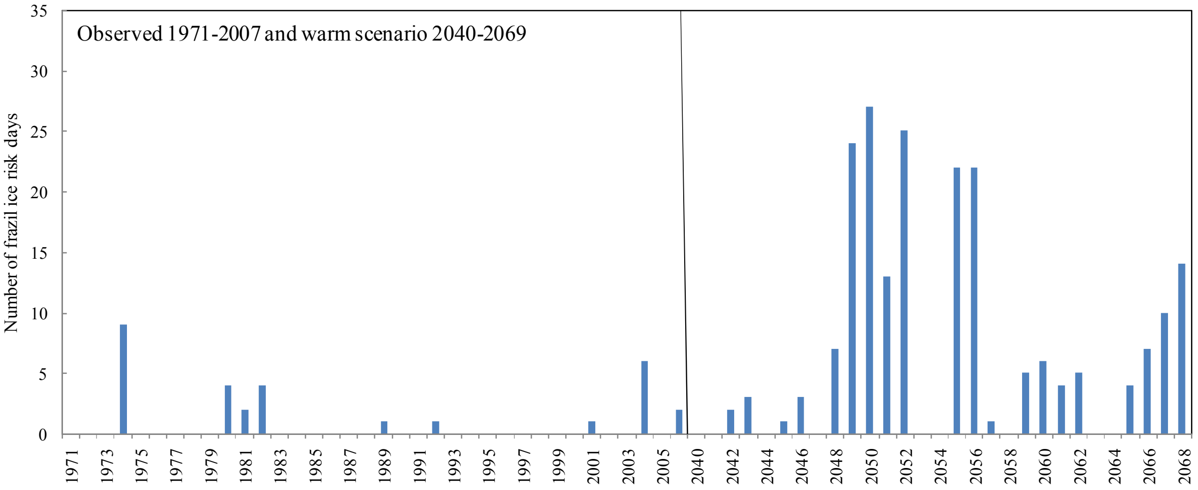

Figure 3: The number of annual frazil ice risk days based on observed data (1971-2007) and on warm climate change scenario 2040-2069.

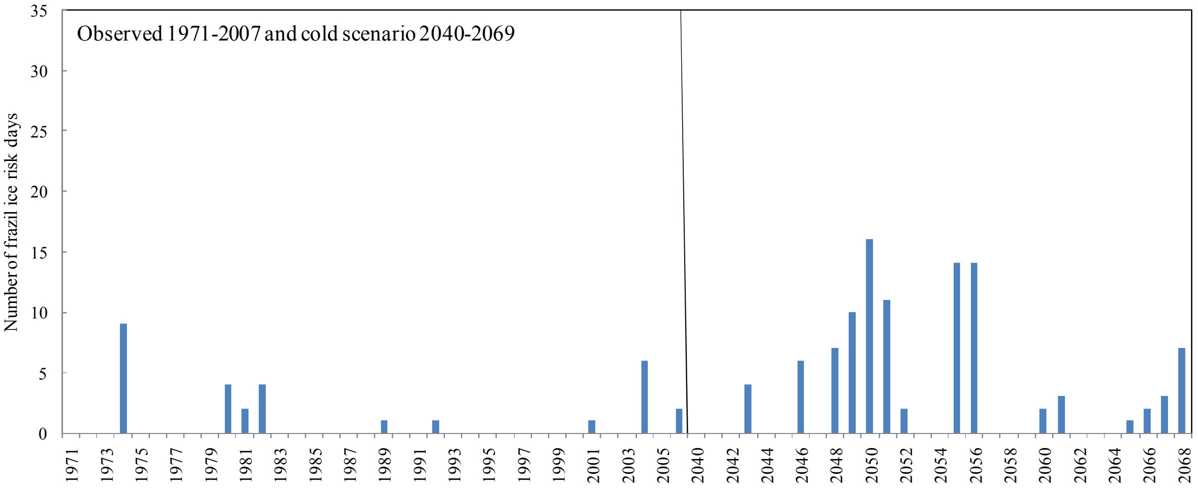

Figure 4: The number of annual frazil ice risk days based on observed data (1971-2007) and on cold climate change scenario 2040-2069.

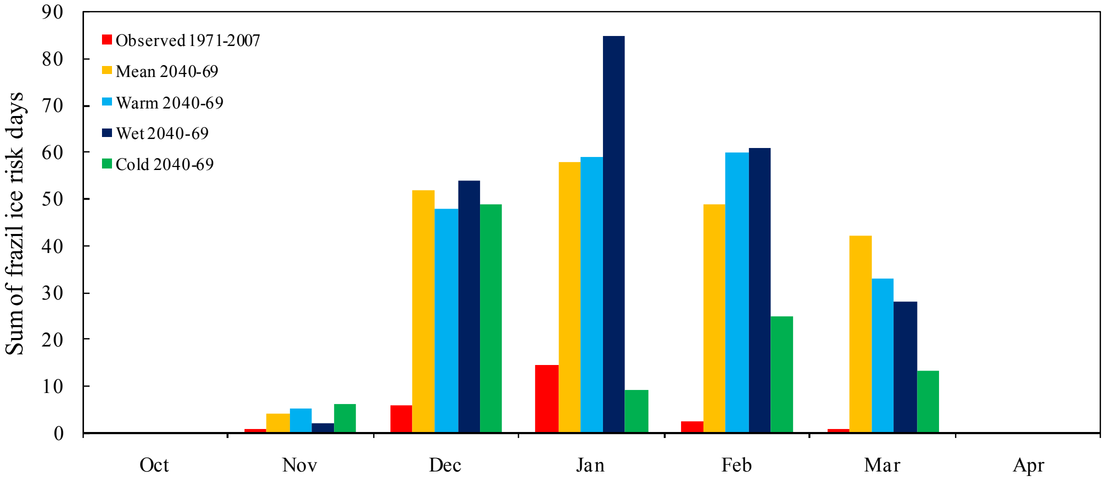

Figure 5: Monthly sum of frazil ice risk days in different 2040-2069 climate change scenarios with a critical discharge of 400 m³/s, air temperature of -4 °C and weekly mean air temperature of -1 °C. The sums of observed period 1971-2007 are scaled to correspond the 30-year period of the climate change scenarios.

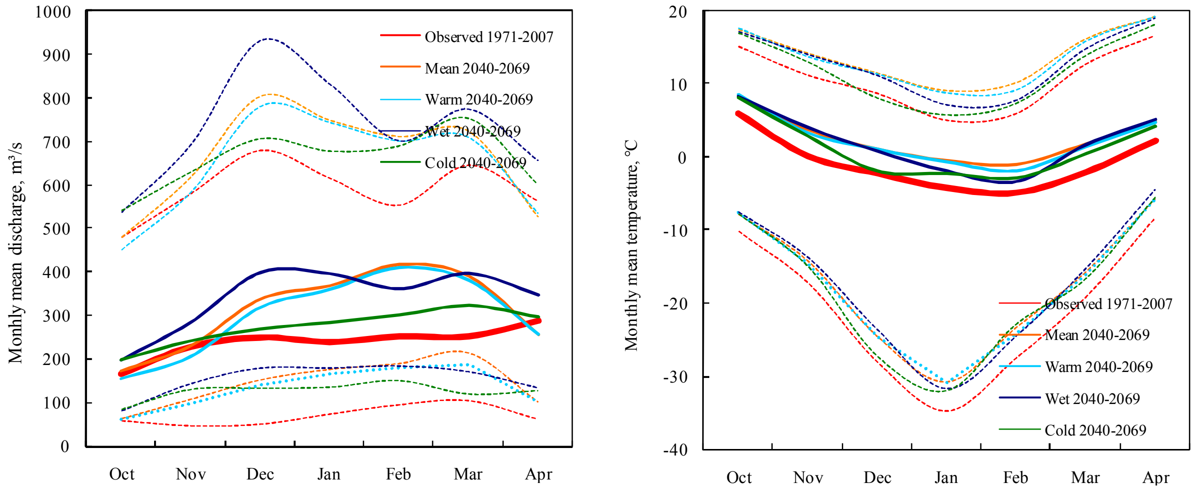

Figure 6. a) Median, maximum and minimum of monthly mean discharge and b) mean temperatures.