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Article

Some Aspects of Ice-Hydropower Interaction in a Changing Climate

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Abstract: Ice formation and related processes in rivers and lakes/reservoirs influence the operation of hydropower plants in cold regions. It is a matter of interest to the scientific community and hydropower operators alike how existing ice effects and problems will manifest themselves in a future changed climate. In this paper, we use different modeling results to investigate future freshwater ice conditions. The modeling approaches include using temperature derived winter indices, using one-dimensional (1D) hydrodynamic and ice cover model on three case study reservoirs, and using a 1D river hydrodynamic and ice cover model for a river reach. The analysis shows that changes in river and reservoir ice regimes due to climate change scenarios may have both positive and negative consequences for hydropower operation. Positive consequences emerge from reduction in ice season and reduced static ice loads. Negative consequences or challenges are attributed to unstable winters that may lead to increased frequency of freeze-thaw episodes with a shortened winter season. These aspects are discussed in more detail in the paper.

Keywords: ice formation; hydropower; climate change; ice effects

1. Introduction

Globally, hydropower is the largest renewable energy source [1], and it produced (in 2009) around 16.5% of the world's total electricity and around 85% of the world's renewable electricity [2].

Hydropower is a major source of energy in cold region countries too. Some of the countries in cold regions that have a large share of hydro in their energy mix include Norway (99%), Canada (59%), and Sweden (49%), the statistics showing values for the year of 2010 [2]. Future projections of inflow under a changed climate imply a wetter hydrology for most of the cold regions and hence a probable increase in hydropower potential [3]. A further important issue that makes hydropower even more valuable in the future is the increasing shift to greener energy sources such as wind power. As wind power is an intermittent resource, hydropower, with its quick start-stop functions and energy reserve in reservoirs, will be ideally suited for load balancing [4].

In northern regions where winters are severe with a prolonged period of freezing temperatures, river and reservoirs freeze over forming various types of ice. Ice formation poses some special problems for hydropower systems [5,6]. Hence, the design and operation of hydropower structures must consider ice effects both for the associated project structures and environmental and socio-economic effects. The major ice effects/problems on hydropower systems include [5,7]:

- Intake blockages with frazil ice and anchor ice causing head losses and even complete shutdowns;
- Flow reductions to the intakes in case of run-of-river intakes causing reduced output and even complete shutdowns;
- Upstream and downstream flooding caused by ice jamming;
- Icing of structures specially gates (intake gates and spillway gates) that causes operational and safety concerns in case of spillway gates;
- Creating open water reaches downstream of power plant outlets which may lead to extensive frazil ice formation and jamming affecting downstream facilities;
- Operational restrictions on hydro-electric operators to avoid ice problems.

While hydro-climatic factors are mainly responsible for the problems posed by ice, human actions such as reservoir operation strategies employed during the ice season will have important contributions in either alleviating or aggravating the problems. For example, regulation for hydropower production leads to an increase in discharge at freeze-up, resulting in a more dynamic [8], and prolonged [9] freeze-up period than would occur naturally. The prolonged freeze-up period leads to severely constrained flow-peaking operations on many regulated rivers resulting in lost revenues in general and inability to balance intermittent sources. On the other hand, hydro peaking also results in shorter periods with ice cover on reservoirs, especially near the intakes [10]. Hence, continued monitoring and mitigation of ice-related effects will be an issue of particular importance for hydropower producers, especially those with remote facilities [11].

Warming of the climate system in recent decades is unequivocal [12]. This is evident from observations of increases in global average air and ocean temperatures, widespread melting of snow and ice, and rising global sea levels [13]. Climate has a key influence in winter hydrology including the ice regime. Factors that control the ice regime such as river flow and the heat exchange between water and the atmosphere are climate-controlled [14]. In the higher latitudes of the Northern Hemisphere, significant temperature trends have been observed in recent decades, with most pronounced changes occurring during winter and spring [15,16]. The changes in Fennoscandia averaged a decadal warming trend between 1961 and 2010 of 0.20 °C (autumn), 0.53 °C (winter) and 0.38 °C (spring) [15]. Concurrently, a number of other studies using historical observations of ice phenology (for lakes and rivers) have shown consistent evidence of later freezing and earlier breakup in the Northern Hemisphere [17–19]. Projections of future climate indicate that ice regimes (duration, extent and composition) will gradually change [15,20]. More frequent occurrence of mid-winter breakups and associated ice runs and jamming are changes that can be predicted as a result of warming of the climate system [20]. Mid-winter breakup events as a result of amplified winter warming may increase in the more temperate and maritime environments and also in the colder interior regions. Increased trends of mid-winter thaws (MWTs, >+1 °C) have also been observed in the Fennoscandia region [15]. Most studies relating to climate change impact have focussed on changes in water balance components such as precipitation, river flow and evapotranspiration [12,21]. Very limited studies exist that have used process based models to investigate changes in the ice regime of water systems (rivers, lakes and reservoirs). There is especially sparse literature on river studies. Large scale studies conducted on lakes project a general decrease in the ice cover duration and ice thickness due to changes in climate [22–25]. Few studies using detailed numerical modeling conducted on rivers also depicted reduction in the duration and extent of ice cover [26,27].

Considerable warming and change in precipitation patterns are predicted by General Circulation Models (GCMs) as a result of increased greenhouse gas concentrations in the atmosphere. Warming is projected to be greatest over land and at most high northern latitudes [12,13] and stronger during the winter time [28]. The pronounced warming during winter may imply shorter winter duration and hence shorter snow and ice season. In addition, there may also be changes in the seasonality of the river flow with more flow in winter and less in summer and spring. This is especially apparent as climate projections generally predict a trend towards higher precipitation in northern latitudes [21]. Due to the economic and ecological importance of freshwater ice, there is a growing need to forecast how global warming will influence the freshwater ice dynamics in cold regions [29,30]. The general impact of climate warming in the future is to delay freeze-up, advance break-up and thereby have a shorter ice season [31]. But, the detailed effects of a changed ice dynamics within a shortened ice season is less clear. A shorter ice season may imply economic savings to hydropower facilities, whereas more frequent mid-winter break-ups may lead to increased frazil production [31], and hence more frequent problems in a shorter season. Detailed quantitative predictions using process-based numerical models will provide better insight into future ice conditions under a changed climate.

This paper addresses the evaluation of ice effects on hydropower systems in a future climate. We accomplish this by making use of two approaches: (1) we evaluate expected ice problems under climate change in general using large scale climatology indices; and (2) we make detailed investigations using numerical models with case studies. The climatology indices constructed from daily mean air temperature data are valuable proxies to freshwater ice phenology (freeze-up and break-up) as well as ice thickness and provide a region-wide perspective of future conditions. The case studies, on the other hand, are attempts for a detailed evaluation of the sensitivity of river and lake/reservoir ice regimes to expected changes in climate. The analyses provide valuable information in assessing climate change impacts on existing hydropower infrastructure as well as in the planning of new ones in cold regions.

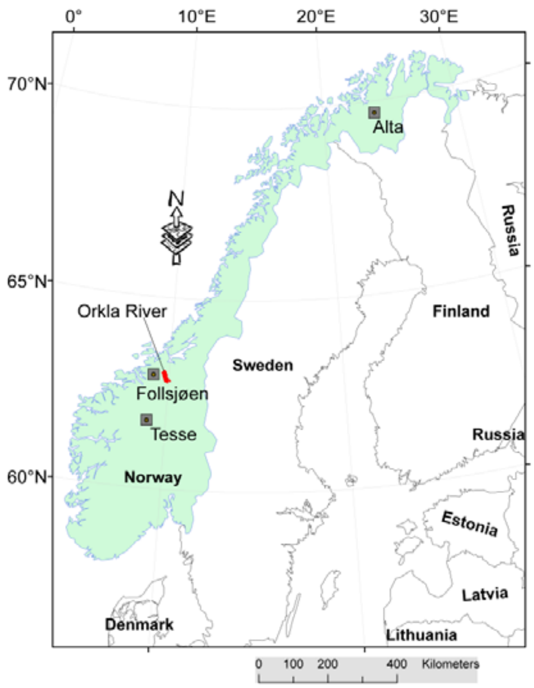
2. Data and Methods

2.1. Data

We use temperature and precipitation data from the high resolution 1 km × 1 km gridded data set from the Norwegian Meteorological Institute (DNMI) for the river ice and reservoir ice case studies. For studying the large scale winter climatology using temperature indices the data comes from a regional study carried out by Gebre and Alfredsen [15]. The principal tools for investigating potential future climate changes are GCMs. Because of the relatively coarse spatial resolution of GCM output, applications of GCM climate projections require processing of the GCM output to bring the effective spatial scale of the data to a local level. One such method is to dynamically downscale the GCM outputs to a higher spatial resolution using Regional Climate Models (RCMs) with more enhanced physics and driven by GCM forcing as boundary conditions.

For the future climate analysis in this study, the data used comes from multiple sources. For the winter (climatology) indices and reservoir ice cover studies, future scenarios corresponding to the Intergovernmental Panel on Climate Change (IPCC) A1B emissions scenario from two GCMs (HadCM3Q3 and ECHAM5) downscaled by the RCA RCM from the Swedish Hydrological and Meteorological Institute are used. For the river ice case study in the Orkla basin, we used data from two GCMs (HadAm3H, A2 and B2 emissions scenario; and ECHAM4, B2 emissions scenario) downscaled to a 25 km resolution by HIRHAM RCM maintained at DNMI, and bias-adjusted and interpolated to a 1 km × 1 km grid covering the whole of mainland Norway [32]. As noted above, the future scenario data used are not the same for the different studies because the studies were conducted in different project settings. Figure 1 shows the locations of the study areas (mainland Norway, and the three reservoir sites as well as one river site used as case studies).

Figure 1. Location of the three reservoir sites (boxes) and the Orkla River reach used as case study as well as the Fennoscandia region used for the index-based regional assessment.

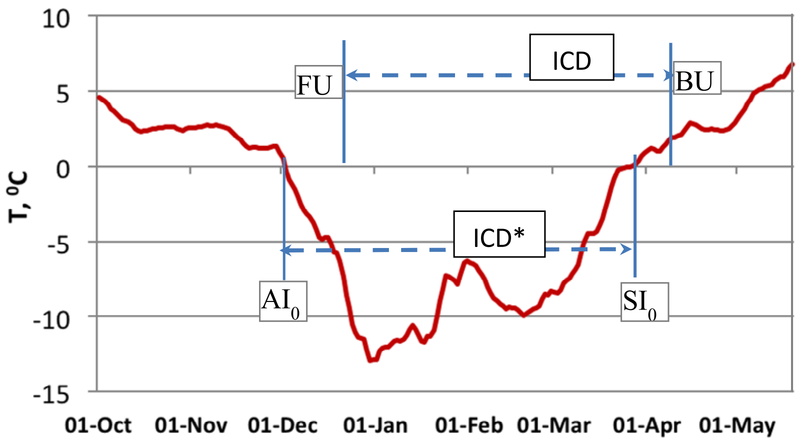


2.2. Assessment Methods

2.2.1. Using Climatology Indices

Air temperature is the single most important factor that influences the energy balance and ice cover regime in rivers and lakes. Changes in temperature derived indices, for example, autumn and spring 0 °C isotherm dates, annual accumulated freezing degree days (AFDD), and MWT can be used to infer the likely situation of the ice cover regime in the future. The advantage of using these indices is that they require only air temperature data that are readily available and are also reasonably predicted using GCMs and RCMs. Another advantage is that the indices provide useful proxy information for site-specific and regional studies that lack observational ice related data. Figure 2 provides a simplified illustration of the relationship between climatology indices and ice phenology dates.

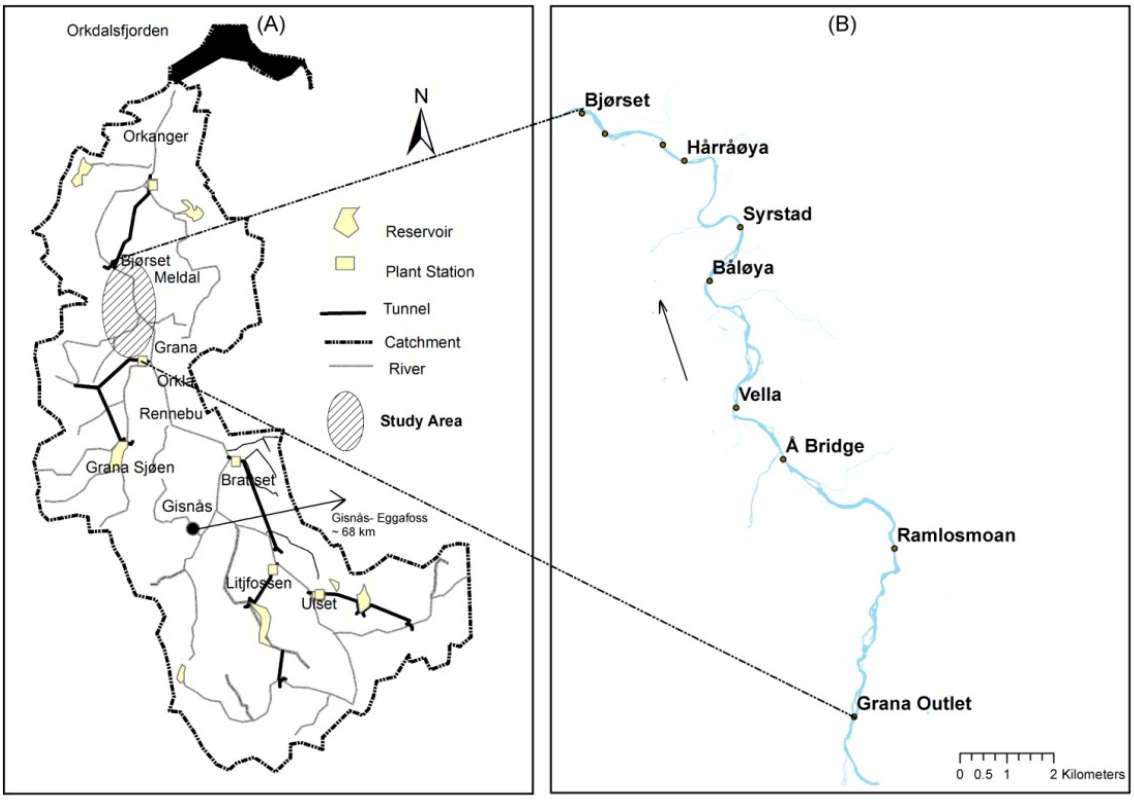
Figure 2. Figure showing a typical 31-day running mean temperature plot and the corresponding temperature indices (AI_0—Autumn 0 °C isotherm, SI_0—Spring 0 °C isotherm) and how they relate to ice phenology (FU—Freeze-up date, BU—Breakup date). ICD and ICD* refer respectively to the ice cover duration derived from ice phenology observations and the 0 °C isotherm dates.



2.2.2. River Ice Modelling

The Orkla River in central Norway (Figure 3) is the study site, and it is an example of a typical high-head hydropower system. The river system has been regulated with three reservoirs and five hydropower plants and a number of water transfers with secondary intakes. The Mike-Ice model was setup for the 40 km reach between the outlet of Brattset hydropower plant and the Bjørset dam. The analysis in this paper, however, is limited to the 20 km reach between the outlet of Grana power plant and Bjørset dam which by experience has the most severe ice. The outflow from Grana power plant enters the river in the middle of the study reach. The study reach has an average wetted width of 45 m, a mean slope of 0.23% and winter flows ranging from 15 m^3/s to 55 m^3/s (mean of ~35 m^3/s). Orkla has a long history of frazil production after the regulation, and intake clogging and frazil induced head losses are known to appear in the river.

Figure 3. Location map showing (**A**) the hydropower setting and (**B**) the modeling reach for river ice impact case study.



Frazil is a central issue in many hydropower schemes, and to study impacts on frazil formation in the current and future climate we used a one-dimensional (1D) process based river ice model, Mike-Ice [33]. The ice model is setup as an add-in module to the well-known Mike11 1D hydraulic software (Danish Hydraulic Institute, Hørsholm, Denmark). The model simulates water temperature with/without supercooling, border ice formation, frazil ice formation and its evolution, transport of surface ice, ice cover formation and thermal ice cover retreat. The Mike-Ice model was calibrated on the reach from the Grana outlet to the Svorkmo intake. The model was evaluated against observed flow at Syrstad gauge, observed water temperature at several locations and observed ice from field campaigns, time lapse video and aerial photography. The model was found to provide good results. Discharge showed a Nash-Sutchcliffe R^2 of 0.79 and water temperature showed an average R^2 of 0.71. Further, it was observed that the model managed to predict both the development of the ice cover and presence of drifting frazil with quite good accuracy. A more detailed description of the model and the setup in Orkla can be found in [27,34].

The Orkla model is used for two different purposes in this analysis. In the first scenario we simulated the Orkla hydropower system with the current climate and several future climate scenarios using the data setup presented earlier. In addition we also simulated a modified hydropower system consisting only of the Bjørset Dam and intake to evaluate the impacts on a typical run of the river system. In the latter case the upstream water temperature boundary conditions were derived from observations from an unregulated tributary at the Gisnås gauge. Unregulated flows were constructed by scaling from the unregulated gauge at Eggafoss (neighboring catchment) using catchment area and specific runoff ratio as the scaling factor.

2.2.3. Reservoir Modeling

Dams in cold regions are designed taking into account static/thermal and dynamic ice loads. These loads are traditionally computed using empirical formulae as a function of the maximum ice thickness in the reservoir. Changes in the energy balance in the future will cause changes in ice thickness thereby leading to changes in ice loads. Ice cover on reservoirs also influences hydropower operation by way of reducing the volume of water available during winter as water is converted to ice. Another is the effect of ice on rip-rap stability as well as bank erosion during draw-down. Releases from dams can also cause environmental problems since deep water intakes can change the natural temperature regime. We use results from reservoir modeling case studies for current and future climate to discuss the likely situation of reservoir related effects in a future climate. The model used is a modified version of the 1D lake thermal and ice cover simulation model, MyLake [35] which was adapted for reservoir application and calibrated with historical data prior to use for analysis with future climate scenarios. The model uses the following input data with daily time step: temperature, precipitation, wind speed, relative humidity, cloud cover and air pressure in addition to empirically computed solar radiation.

Future inflows for both the river ice and reservoir study applications were derived using the Hydrologiska Byråns Vattenbalansavdelning (HBV) hydrological model [36] which was well-calibrated using historical data. Pertinent weather data for the future climate were constructed by perturbing historical data with monthly climate change signals using the delta-change approach [37].

3. Results and Discussion

Based on the results from the climatological analysis and the detailed simulations of river and reservoir ice we have evaluated how currently reported problems might be influenced in the future. There are cases where the future changes pull in both directions with both positive and negative impacts on the ice, and in this case we have reported both and if possible made an assessment of which is the most important. Current issues where ice processes can interact negatively with hydropower structures or hydropower production are listed in Columns 1 and 2 in Table 1, based on the review by Gebre *et al.* [7]. The general evaluations outlined in the following sections are based on an average assessment of the changes in ice conditions. It is worth noting that the spatial variability is high (as seen in Figures 4 and 5), and the magnitude of the changes will vary with the location of the hydropower plant. In general, lower and more coastal plants will see the largest changes from the current conditions and therefore it is necessary to scale the impacts discussed to the location of the plant or reservoir.

3.1. Hydropower Operation and General Winter Conditions

During the winter several hydropower companies will experience operational constraints to prevent negative ice conditions in rivers. This can be restrictions on magnitude and variability of turbine flow to keep stable ice covers and to prevent accidental ice releases (particularly evident in hydro peaking rivers), and it can be demands for stable production during early winter freeze-up to develop a stable ice cover.

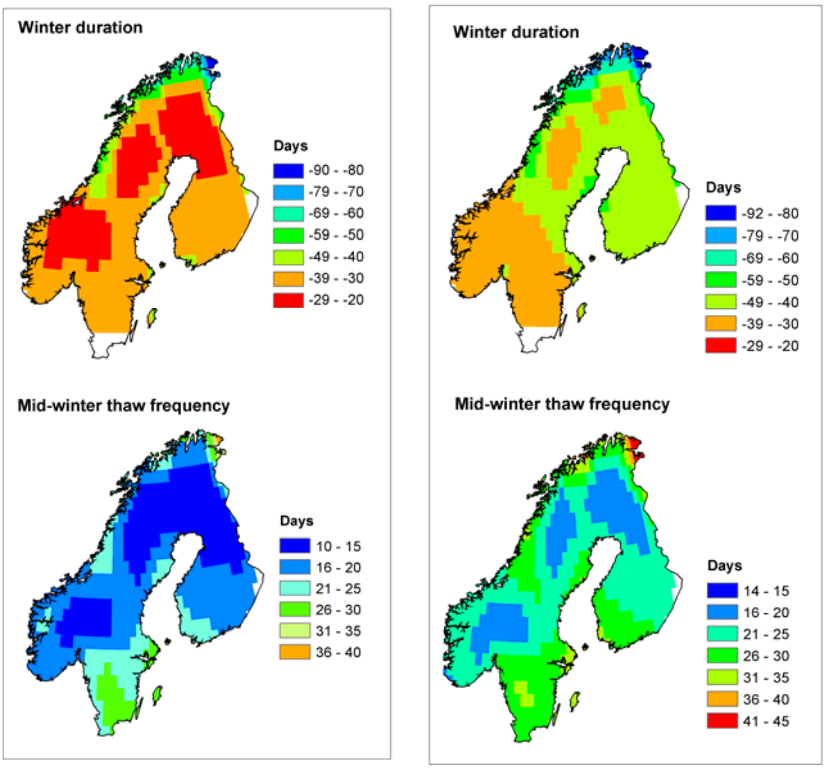
Table 1. Evaluation of climate impacts on hydropower production, table summarizes discussion above. The items and current effects are adapted from Gebre *et al.* [7]: (+) effects denote situations where current ice effects are relieved or removed; and (−) effects where current ice negative impacts are getting stronger or where new ice related impacts may appear.

Hydropower component	Current effects	Climate impact (+)	Climate impact (−)
Dams	Ice loads on dams and dam faces.	Reduced ice loads on dams. Reduced floe size.	More frequent river breakups—more dynamic load on river constructions.
Spillways	Frozen gates, ice formation in spillway tunnels.	Shorter winter season.	-
Reservoirs	Ice forces on banks. Transport.	Reduced ice thickness.	Reduced transport potential.
Trash racks	Clogging by frazil and drifting ice.	Reduced winter season and reduced frazil production—less need for operational constraints and ice removal.	Potential for more ice runs, clogging of intakes. More frazil in rivers with run of the river plants—potential intake problems.
Intake gates	Frost and ice loads on gate.	Shorter season and less ice reduce load.	More mechanical breakups—increased dynamic load.
Water outlets	Stability in reservoirs. Accumulation in river outlets.	Less ice in river outlets.	Further decrease of stability due to lessened ice thickness.
Rivers	Unstable winter ice conditions downstream of outlets.	Reduced length of winter season. Reduced ice formation.	More unstable regime.
Operational	Limits flow variability during ice season.	Reduced ice season—more unrestricted production.	More unstable conditions, blocking by breakups and restraints on operation.

The ice cover/winter duration as designated by the number of days between the autumn and spring 0 °C isotherm dates (see Figure 2) shows a marked reduction in the future climate. At the same time the ice cover season will be unstable due to the significant increase in MWT frequency (defined here as number of days with mean daily temperature greater than +1 °C) (Figure 4). Whereas the shorter ice covered season generally implies a reduced period where hydropower operators have to deal with ice related problems and therefore a reduced need to observe ice related restrictions, a more unstable ice cover season may result in a more dynamic ice regime with mid-winter breakups and freeze-ups. This can indicate a less stable ice cover, which could lead to even stricter restrictions on flow changes due to break-up risk [20] and the increased number of thaws may lead to more breakups and potential blocking of intakes and reduced production [11]. This could particularly be a problematic issue for brook intakes, which are often located in mountainous areas, which in winter can be difficult to access. Removal ice from such events can therefore be a challenge and periods with water loss can be prolonged.

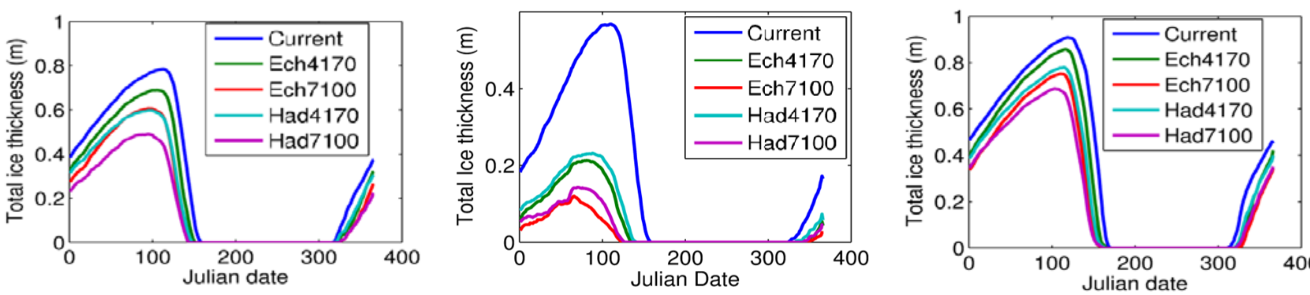
Reduced duration of winter will also generally reduce concerns in river reaches downstream of the hydropower system, and reduce the length of season when ice is an environmental concern for the operator. But on the other hand unstable ice conditions during the shortened winter will still provide challenges and risk of hydropower induced ice problems in receiving waters.

Figure 4. Mean changes in winter duration and mid-winter thaw (MWT) frequency (in the three months of December, January and February) in the two future time periods: (**A**) 2041–2070; and (**B**) 2071–2100 compared to the control period of 1961–1990. The climate change signals used were the average of the two General Circulation Models (GCMs) (ECHAM5 and HadCM3Q3) downscaled using the Swedish RCA Regional Climate Model (RCM). Reproduced from [15] with permission from IWA Publishing.



(**A**) (**B**)

Figure 5. Mean changes in ice thickness of three hydropower reservoirs between the current period and four future scenarios: (**A**) Tesse reservoir; (**B**) Follsjoe reservoir; and (**C**) Alta reservoir. Ech and Had refer to the GCMs ECHAM5, respectively; and HadCM3Q3 whereas 4170 and 7100 refer to the future time periods 2041–2070 and 2071–2100, respectively. Reproduced from [38] with permission from Elsevier.



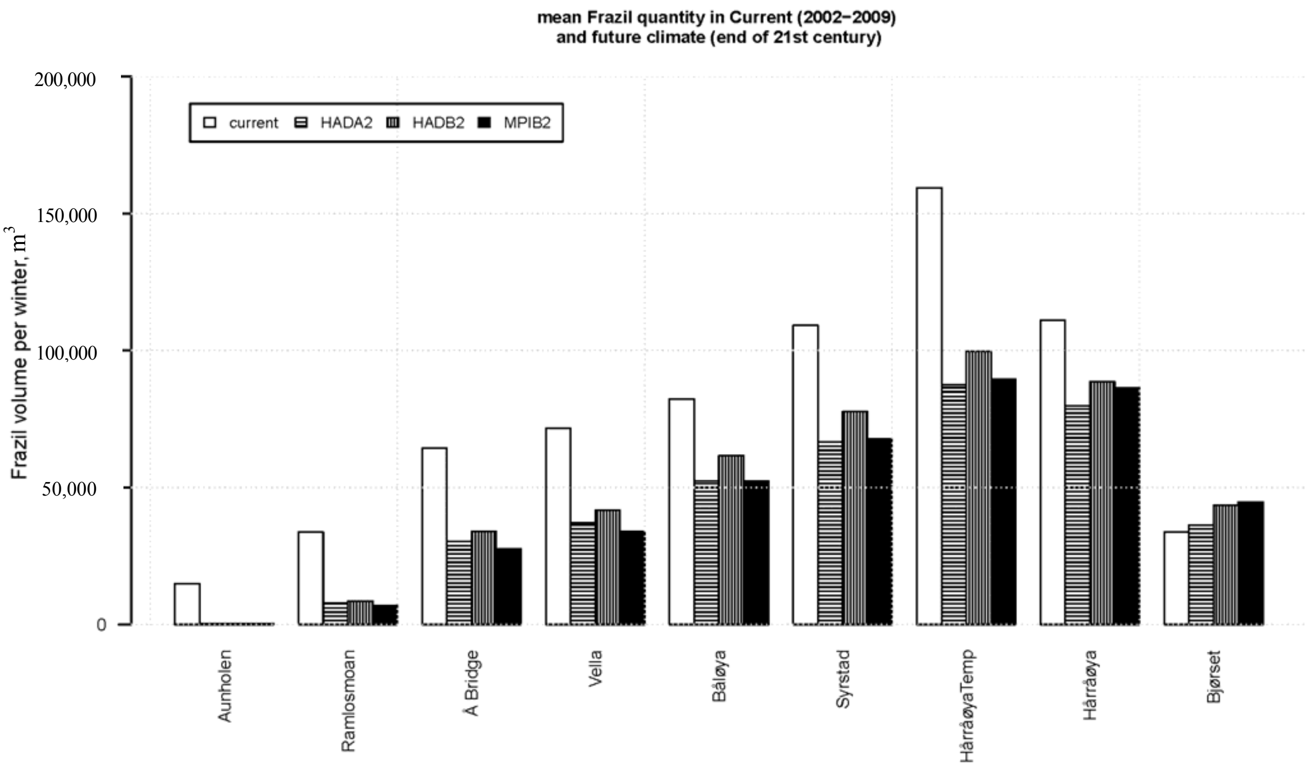
(**A**) (**B**) (**C**)

Over the latest years a large number of small hydro plants have been built in Norway, and ice is reported as a significant source of operational problems. These are typically run-of-the river type plants with low storage capacity and also very often located in steep streams and rivers. Vaskinn [39] reported that ice problems exceeded flood damages, and that reduced production capacity due to frazil accumulation at trash racks and ice runs blocking intakes were the dominating issues. In addition, total shutdown due to frost blocking inflow or intakes are reported. As for all other issues related to ice, small hydro operators will also experience a shorter ice season in the future. On the other hand, a more unstable winter will probably exacerbate frazil problems in steep streams due to a lack of ice cover. The current scenarios for winter stability also points in the direction of more winter ice runs which also will increase potential problems for small hydropower plants.

3.2. Effects of Frazil Ice

For the high head system (the existing Orkla setup), the simulated number of days with frazil ice in the reach from Grana outlet to Bjørset Dam (Figure 6) is considered. This is the section which is known as the main frazil generator in the river. Results in Figure 6 show that frazil production generally increases going downstream from the outlet, and also a high production in steeper areas of the river. We also observe reduced production at the Bjørset intake, which is due to a stable ice cover formed on the intake pond. The hydropower operator will run stable production during freeze-up to establish the ice cover to prevent super-cooled water and frazil mix to reach the Bjørset intake.

Figure 6. Change in frazil production in the 2080s compared to the current period (2002–2009) for the Grana outlet–Bjørset reach for three different climate scenarios.

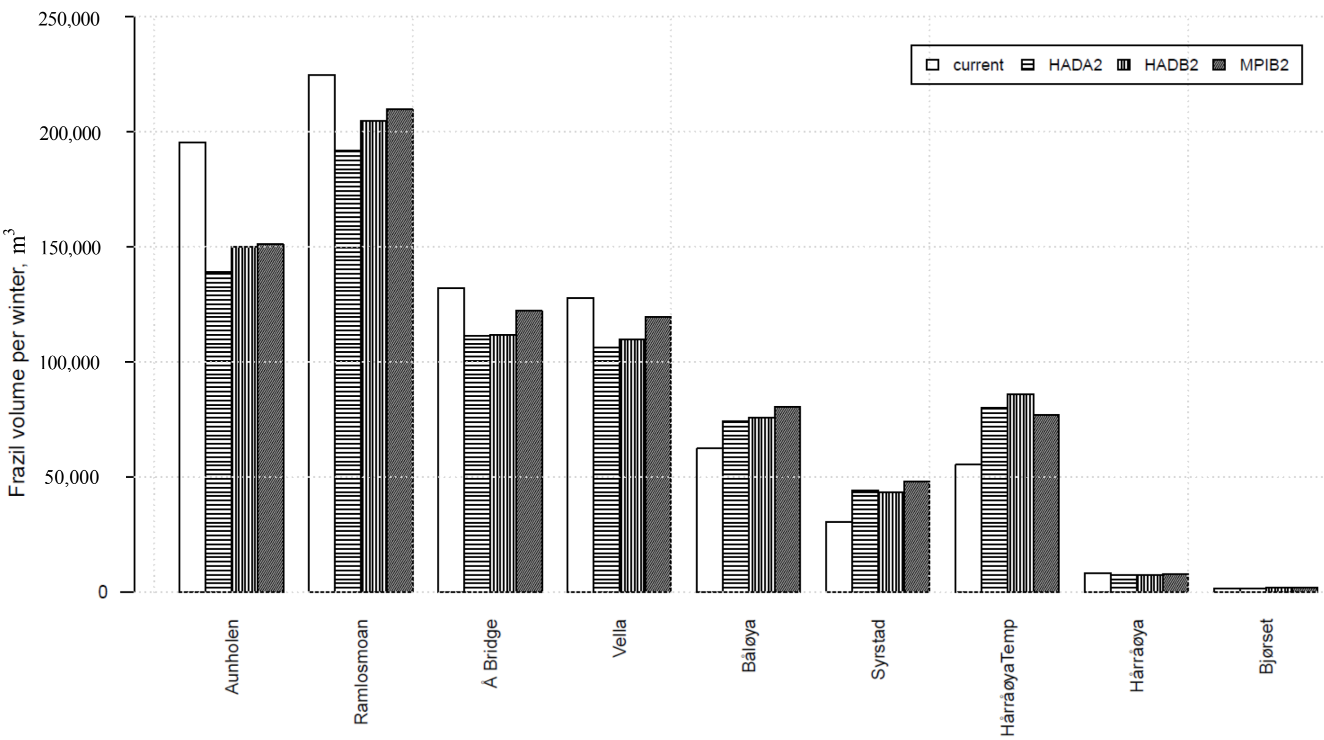


In all three future climate scenarios, the volume of frazil production is considerably reduced in all cross sections except the intake pond at Bjørset where we see a slight increase in the future. This reduction may be attributed to an increase in winter flow and increased water temperature in the future climate. The increased frazil production at Bjørset intake can be explained by a reduced duration of ice cover and hence a higher chance for generation and transport of frazil. A minimal variability between scenarios is observed.

These results indicate a reduced frazil load in the river, which will relieve the need for measures to prevent intake clogging and frazil induced head loss. On the other hand, a reduced ice cover at the intake pond might reduce the collection of frazil in the pool. This could potentially increase the load on the intake, but since surface ice removal from the pond is not expected to happen during cold periods it might not be a serious problem. Currently in Orkla a combination of operational constraints (flow restrictions) and mechanical removal of frazil from the gate area is employed, and based on the climatological and simulated results it is reasonable to believe that the need for such measures will be reduced in the future.

In the second scenario, the ice model is run without the upper reservoirs to investigate the impacts on a run-of-river hydropower system. The portion of the reach covered by ice is significantly increased compared to the regulated case, and an ice cover of 50% is observed in the reach compared to a maximum of about 12% in the fully regulated case. In the future scenarios, the ice cover extent is reduced (with minimal inter-scenario variability) a scenario average of 35%. This reduction in ice cover translates into an increase in frazil production due to more open water areas in the middle locations in the study reach (Figure 7). In this case we observe an increased frazil production due to a more unstable ice regime (as the climatological study also indicates), which could increase the potential frazil problems at the intake site. The simulated variability of complete ice cover also supports the notion of a more unstable ice regime in the future, which could further exacerbate intake problems such as clogging and dynamic load on gates.

Figure 7. Change in frazil quantity in the 2080s compared to the current period (2002–2009) for a run-of-river scheme with intake at Bjørset for three different climate scenarios.



3.3. Ice Conditions in Reservoirs

Climate change also impacts the ice regime on regulated reservoirs. Case study on three reservoirs located in different geographic/climatic regions in Norway (subarctic-mountainous, subarctic-coastal, and arctic) using a 1D process-based reservoir model shows a marked reduction in the seasonal ice thickness progression (Figure 5). The simulated reduction is much higher in the coastal reservoir compared to the other two reservoirs, signaling that coastal environments might be more sensitive to climate change. The reduction in ice thickness due to overall warming in the future climate may compromise the use of reservoir ice cover as a means of winter transportation. Operational strategies such as peaking operations also influence the ice strength on regulated reservoirs. Another effect of reservoir ice is the loss of storage due to grounded ice. Reductions in ice thickness generally imply reductions in the loss of storage due to grounded ice. The consistent trends of reduced ice thickness found in all the studied reservoirs in the future scenarios would decrease the ice loads on rigid structures such as concrete dams and spillways and thereby reduce the potential damages and future design requirements. Thinner ice cover could, on the other hand, lead to more frequent ice break-ups and contribute to a higher dynamic load on structures. It is also worth looking into the potential effect of several break-ups and refreezes of the ice cover over the winter.

An issue that is raised in some reservoirs is the local reduction in ice strength in the vicinity of outlets in reservoirs that receive discharge from upstream power plants. With decreased ice thickness and a potential for increased winter production due to increases in winter discharge, this is expected to be of larger importance in the future.

4. Conclusions

Among climate change effects pertinent to hydropower operation is the expected change in the ice regime due to changes in climate forcings. This paper has analysed possible future consequences to the ice-hydropower interaction in a future climate using regional climatological indices as well as case studies using process based models for a river system and three reservoirs on a detailed level.

Our analysis has shown that changes in river and reservoir ice regimes may have both positive and negative consequences for the operation of hydroelectric stations. All indicators show that the season where ice is an issue will be shortened in the future, thereby reducing the period with a need for operational constraints and ice mitigation. The detailed simulations show a similar pattern with a reduced ice load in the future compared with the current situations. On the other hand, the results show that for the winter period ice will still be a factor to consider, and the predicted instability in winter conditions could create new challenges in the future climate.

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Conflicts of Interest

The authors declare no conflict of interest.

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