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Simulation of the ice regime in a Norwegian regulated river

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ABSTRACT

River ice models are commonly used to study ice conditions in wide and low-gradient rivers in cold regions. However, examples of applications of these tools in shallow and fast-flowing rivers are rarely reported. In this study, the one-dimensional model MIKE-Ice was applied to study the ice regime of the regulated river Orkla in Norway. The river Orkla is characterized as a steep and shallow river with sequences of pools and riffles throughout its length. The model was calibrated and validated for the winters, 2010–2011 and 2011–2012 respectively. The study shows that the model is applicable in a steep river with transects of both subcritical and supercritical flow conditions, which is a different environment than most previously reported applications of river ice models. The simulated hydrodynamics and water temperature show good agreement with observations. The model was further tested on its ability to simulate the presence/absence of frazil ice and the development of an ice cover at observation points in the river using continuous monitoring with cameras. The ability to correctly simulate the ice cover extent of the entire model domain was also tested based on a number of field campaigns. The ice simulation results correspond well with observations both spatially and temporally. Further, two discharge scenarios were simulated: a) No hydropower regulation, and b) reduced hydropower operation: to assess the impact of the regulation and to explore the sensitivity of the model. The simulation results demonstrate how hydropower regulation has altered the thermal and ice regimes. The study concludes that Mike-Ice is a useful tool for predicting the river regime in the river Orkla, where dynamic ice formation is a dominant process.

1. Introduction

Hydropower covers 99% of Norway's need for electricity, and continuous operation of hydropower plants during winter is highly important for the demand coverage. Most Norwegian hydropower plants are high-head systems with large storage capacities, thereby having considerable effect on the hydrological regime of regulated rivers. Water releases from reservoirs and inter-basin transfer schemes can have a significant consequence on the thermal and ice regime of regulated rivers (Alfredsen and Tesaker, 2002; Tesaker, 1990), and river ice problem is often a constraint for operation during winter (Billfalk, 1992; Morse and Hicks, 2005; Prowse et al., 2011). Typical problems are blocking of intakes (Andersson and Andersson, 1992), premature ice-breakups due to warm water releases from reservoirs (Hicks, 2009) and effects on flow and water level due to excessive frazil and anchor ice formation in reaches that do not freeze over during winter (Stickler and Alfredsen, 2009). Modeling ice regime changes due to hydropower operations is not a common practice in Norway, and as ice conditions are expected to be important during the relicensing of regulation permits (Asvall, 1990) methods for analyzing regulation effects on ice are needed. In addition, an operational change towards utilizing the high regulation potential of hydropower to cover peak demands in a load balancing scenario would lead to a more variable flow regime and a potential for more severe ice problems. This further strengthens the need for establishing tools for ice prediction in Norwegian regulated rivers.

There are a number of numerical models for ice formation and/or ice jams available both commercially and as public domain software. Some examples are JTT (Huokuna, 1990), RICEN (Shen et al., 1995), DYNARICE (Shen et al., 2001), River 1D (She et al., 2009), CRISSP (Shen, 2002), Mike-Ice (Thériault et al., 2010) and RIVICE (Lindenschmidt et al., 2012). Many of the models do have limitations in capturing all aspects of river ice as they often are developed with the goal of solving site-specific problems (Shen, 2010). However, some numerical models have been formulated to consider the full dynamic ice regime of the river e.g. RICEN, CRISSP and Mike-Ice. Much of the ice modeling researches so far have mainly focused on large and low-gradient rivers. With few exceptions (Bjerke and Kvambekk, 1994), very few attempts have been made to develop or test a numerical model for the relatively small, steep and shallow rivers common in Norway, which often have complex dynamic ice formation (Stickler et al., 2010). The current practice for ice condition assessment e.g. due to river regulations is descriptive based mostly on observations and experience with little or no application of predictive tools (Asvall, 1992, 1994, 2008). Bjerke and Kvambekk (1994) applied the RICE model to the Orkla river and found that the

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numerical tool is applicable in a steep river with simplification, i.e. constant flows. They found that the simulated water temperature corresponded reasonably well with observed temperature. The model showed that frazil production at Bjørset decreased with increased ice cover upstream of Bjørset intake. However, they observed simulation discrepancies on border ice, ice cover extent and jam thickness.

In this study, the one-dimensional model Mike-Ice (Ice Generation and Accumulation Module) has been applied to a reach of the regulated Orkla river in Norway. There are two main purposes of the study. First we investigated the applicability of the MIKE-Ice model in a regulated river which is steeper and smaller than the Romaine and Péribonka Rivers in Canada where the model was previously tested (Thériault, 2011; Thériault et al., 2010). The model was verified against measured water flow and temperature, and further tested against observations of frazil and ice cover formation for the current situation. Secondly, we ran the model for the same reach for estimated unregulated flow conditions and for a scenario with reduced hydropower production to evaluate the impact of the regulation and to evaluate the sensitivity of the model to regulated flow.

1.1. Study site and methods

1.1.1. Study site

The regulated river Orkla is located in mid-Norway (63° 17′ N, 9° 50′ E) and flows nearly 200 km through a typical “V” shaped valley in the upper region to a wide and flat valley in the lower part (Borsányi, 2005) before it drains into Orkdalsfjorden (Fig. 1 A). The river has a drainage area of 3053 km^2 and an average annual runoff of 70 m^3/s. Orkla was regulated with five hydropower plants and 3 big reservoirs in the early 80's. The river consists of sequences of pools and riffles with large hydraulic diversity. A nearly 22 km long stretch (Fig. 1 B) between the outlet of the Grana power plant and the intake to Svorkmo power plant at Bjørset has been selected for the modeling work. The stretch has an average slope of 2.3 m/km. The Grana reservoir with a volume of 139 Mm^3 is the source of the Grana power plant. Massive frazil and anchor ice formation due to the regulation has been reported at the study site (Stickler and Alfredsen, 2009). A number of ice/winter studies have previously been conducted on this river, (Bjerke and Kvambekk, 1994; Dahl, 1986; Stickler and Alfredsen, 2009; Stickler et al., 2007).

1.1.2. Hydro and climate data

River geometry for the model is based on cross-sections collected for flood mapping described in a Norwegian Water Resources and Energy Directorate (NVE) flood mapping report by Fjellanger Widerøe Kart (2001). In addition, extra cross sections were collected in the steep reaches in the downstream part of the model domain to better capture the river characteristic at locations known for frazil production. These transects were measured using a SONTEK M9 ADCP and a Leica RTK-GPS system.

The discharge at the upstream boundary consists of the flow from Brattset hydropower plant, lateral inflow in the upstream reach and production discharge from the Grana power plant. The water level at Bjørset intake has been used as the downstream boundary. All production data and water levels were obtained from the Orkla hydropower company. Discharge data at Syrstad gauge is used to calibrate the hydrodynamic model; these are obtained from NVE (Norwegian Water Resources and Energy Directorate). All input data are collected with an hourly time resolution. There are a few tributaries contributing to lateral flow between Grana and Bjørset, with a total contributing area of 260 km^2. However, in the ice simulation lateral flow has been excluded since winter flow is very low. During the scenario simulations, the unregulated flow at Brattset has been scaled based on area and specific runoff ratio from a neighboring catchment. We

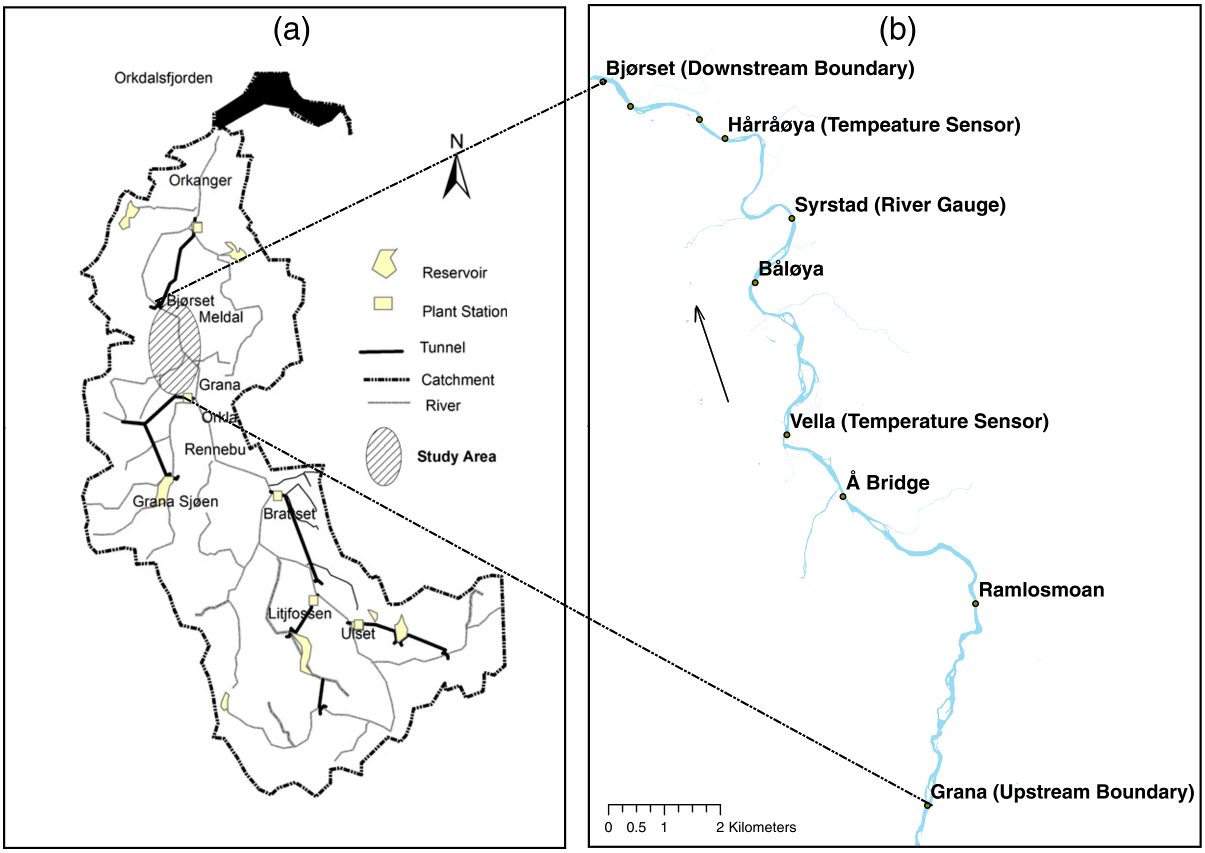

Fig. 1. A: Orkla river basin showing the hydropower system, Fig. 1 B: Modeled river reach between Grana outlet and Bjørset intake.