Master's thesis

NTNU
Norwegian University of Science and Technology
Faculty of Engineering
Department of Civil and Environmental Engineering

Delaram Kazemian

Modelling ice using the River1D ice model

Master's thesis in Hydropower Development
Supervisor: Knut Tore Alfredsen
February 2024

NTNU
Norwegian University of
Science and Technology

Delaram Kazemian

Modelling ice using the River1D ice model

Master's thesis in Hydropower Development
Supervisor: Knut Tore Alfredsen
February 2024

Norwegian University of Science and Technology
Faculty of Engineering
Department of Civil and Environmental Engineering

NTNU
Norwegian University of Science and Technology

DECLARATION OF AUTHORSHIP

I, Delaram Kazemian, declare that this thesis titled " Modelling ice using the River1D ice model" and the work presented in it are my own. I confirm that:

- This work was done wholly or mainly while in candidature for MSc. research degree at Norwegian University of Science and Technology (NTNU)
- Where I have consulted the published work of others, this is always clearly stated.
- Where I have quoted from the work of others, the source is always given.
- Where the thesis is based on work done by myself jointly with my supervisor Knut Alfredsen (Professor), I have made clear what was done by others and what I have contributed myself.
- I have acknowledged all main sources of help.

Singed: Delarm Kazemian

Date: 19.02.2024

ACKNOWLEDGEMENTS

I would like to express my sincere gratitude to my supervisor, Professor Knut Alfredsen at the Department of civil and Environmental Engineering, NTNU. I appreciate the commitment throughout the semester and your availability to arrange meetings for related discussions, I want to express my gratitude to my parents, who have supported me through everything and will continue to do so. I would like to say thank you to my brother. I want to express my gratitude to my spouse for supporting me during the entire master's program. This is for you. I love you all. Delaram Kazemian

Abstract

Ice formation on rivers is a dynamic process that eventually leads to the complete and continuous ice cover with which the people of northern, and not-so northern regions of the globe are familiar. As water temperatures decrease in the Fall and attain slightly subfreezing levels, different ice forms begin to appear in the water. Interacting with each other, and driven by the turbulent river flow, these ice forms evolve into accumulations that cause many socioeconomic and ecological problems, while sometimes having beneficial impacts. Transportation and energy generation are two sectors that are particularly affected by ice formation, while infrastructure, private property and human safety can be imperilled by extreme freeze up events.

The accelerating pace of climate change has pronounced effects on the cryosphere components of our planet, particularly in polar and subpolar regions. Among these, river ice dynamics play a crucial role in shaping hydrological systems, influencing infrastructure, and impacting ecosystems (Beltaos 2013).

The primary objective of this research is to comprehensively characterize the River1D ice model, developed by Alberta University, by elucidating its fundamental principles, mathematical foundations, and underlying assumptions. Through an extensive literature review, we contextualize the significance of understanding river ice dynamics in the face of global climate change and its consequential impact on water resources and infrastructure.

This master's thesis delves into the realm of river ice modelling, focusing on the utilization and exploration of the River1D ice model.

The thesis employs a systematic approach, beginning with the validation and verification of the River1D ice model through a comparison of its simulations with observed field data from diverse case studies. By rigorously assessing the model's accuracy and reliability, we aim to establish its credibility as a tool for simulating and predicting river ice dynamics.

The research extends beyond the technical intricacies of the River1D ice model to explore its practical applications. Through case studies and simulations, we investigate the model's potential in predicting future river ice conditions, managing water resources, and informing decision-making processes for climate change adaptation.

In conclusion, this master's thesis offers a comprehensive investigation of the River1D ice model, shedding light on its capabilities, limitations, and potential contributions to the field of river ice modelling. By enhancing our understanding of the complex interplay between climate, hydrology, and river ice dynamics, this research seeks to provide valuable insights for researchers, policymakers, and practitioners engaged in the sustainable management of cold-region water resources.

Main questions for the thesis

1. Perform a literature review on previous studies of using River1D modelling for river Orkla. The study should both review results and findings from the studies and the methods used for the assessment.

2. Data for the current situations should be checked for quality and calibration and validation periods should be selected for the modelling.

3. Calibrate the model for a period and run validation for a different period.

Supervision, data, and information input

Professor Knut Alfredsen will be the supervisor of the thesis work.

Discussion with and input from colleagues and other research or engineering staff at NTNU. Significant inputs from others shall, however, be referenced in a convenient manner. The research and engineering work carried out by the candidate in connection with this thesis shall remain within an educational context. The candidate and the supervisors are therefore free to introduce assumptions and limitations, which may be considered unrealistic or inappropriate in contract research or a professional engineering context.

Report format and reference statement

The thesis report shall be in the format A4. It shall be typed by a word processor and figures, tables, photos etc. shall be of good report quality. The report shall include a summary, a table of content, lists of figures and tables, a list of literature and other relevant references and a signed statement where the candidate states that the presented work is his own and that significant outside input is identified. The report shall have a professional structure, assuming professional senior engineers (not in teaching or research) and decision makers as the main target group

Table of Contents

Contends **Page**

List of figures

List of Tables

Chapter 1

Introduction

1.1 Background

Rivers, as dynamic and intricate components of Earth's hydrological systems, undergo profound seasonal changes that are particularly pronounced in colder climates. One of the most visually striking and impactful phenomena in these regions is the formation and movement of river ice. The presence of ice significantly alters the hydrodynamics of rivers, affecting water flow, sediment transport, and ecological processes. Understanding and predicting the behaviour of river ice is paramount for effective water resource management, environmental conservation, and infrastructure resilience.

The challenges associated with river ice are becoming increasingly pertinent in the context of climate change. Global temperature variations are causing shifts in precipitation patterns, altering freeze-thaw cycles, and influencing the frequency and intensity of river ice events. These changes pose a threat to both natural ecosystems and human infrastructure, requiring sophisticated tools and models to comprehend the complex interactions between flowing water and ice cover. In response to this pressing need for advanced modelling techniques, the River1D ice model has emerged as a powerful computational tool for simulating river ice dynamics. Developed as an extension of the River2D hydrodynamic model, River1D is specifically designed to capture the intricate processes associated with ice formation, growth, decay, and movement in river channels. Its versatility and robust numerical methods make it well-suited for addressing the complexities of river ice, offering a platform for researchers to explore and analyse the various facets of ice dynamics.

Numerous numerical models for ice formation and/or ice jams are available as public domain software and for a fee. A few of them are Mike-Ice (Thériault, Saucet, and Taha 2010), RICEN(Shen, Wang, and Lal 1995), DYNARICE (Shen, Liu, and Chen 2001), River 1D (She et al. 2009), JTT (Huokuna 1990)and RIVICE (Lindenschmidt, Sydor, and Carson 2012). Since many of the models are created with the intention of resolving site-specific issues, they do have limits when it comes to accurately representing all facets of river ice (Shen 2010).

As we delve into the modelling of river ice using the River1D ice model, it is crucial to acknowledge the existing gaps in understanding and the limitations of current models. Previous studies have made significant contributions to the field, but challenges remain in accurately representing the interactions between ice, water, and sediments. This thesis builds upon the existing body of knowledge by employing the River1D ice model to enhance our understanding of these complex dynamics. By combining theoretical insights, numerical simulations, and validation with observational data, this study aims to contribute valuable knowledge to the field of river ice modelling. The results obtained will not only advance our understanding of ice dynamics but also provide practical implications for water resource management, flood forecasting, and ecosystem conservation in the face of a changing climate.

1.2 Literature review

Large seasonal fluctuations in the cold areas' climate lead to large variations in the demand for the energy produced by hydropower producers as well as in the resource that is accessible to them. The fact that these two crucial inputs for their production's schedule are entirely out of sync presents one of the biggest obstacles. When water resources are stored as snow in the mountains and inflow is at its lowest, demand is at its highest, and when inflow is at its maximum, demand is at its lowest. Furthermore, during the cold season, frost and ice make it difficult to operate hydroelectric facilities. In order to meet demand, water must be kept in reservoirs throughout the year. Carefully managing water resources is also necessary to maximize producer benefits in addition to preventing shortages. Additionally, when other unregulated energy sources run out of control or are not accessible, the rivers must be kept free of ice and open to quick upregulation. Snow can store a lot of water. A large amount of precipitation falls as snow at northern latitudes. This storage is a crucial source of water for irrigation, the public water supply, and—not to mention—the hydropower sector in these areas. More than half of the yearly runoff in colder climates can come from the spring flood caused by ablation of the snow cover (Barnett, Adam, and Lettenmaier 2005). To be able to plan long-term hydropower scheduling in cold places, one must have a thorough understanding of the snow process, the distribution and amount of the snow storage, and how and when this will melt. This has been a major motivator for creating snow ablation models and techniques for assessing snow storage. Planning hydroelectric structures requires consideration of snowmelt as well, since the design flood is frequently correlated with the melt time. When producing hydropower in cold climates, ice will build and disintegrate in reservoirs and on rivers. Ice presents technical difficulties for the generation of hydropower by putting weights on structures, obstructing spillways and intakes, and limiting operation throughout the winter.

When producing hydropower in cold climates, ice will build and disintegrate in reservoirs and on rivers. The natural environment and how rivers and lakes are used in the winter will be impacted by the establishment of hydropower, which will also have an impact on the ice regime (Alfredsen and Bruland 2022). River ice dynamics have been the subject of extensive research due to their profound implications for water resource management, ecological health, and infrastructure resilience. using numerical model simulations is among the most effective and economical methods of studying river ice processes and evaluating ice effects on river's regime. The application of numerical models in studying river ice has significantly advanced our understanding of these complex phenomena. In this literature review, we explore key studies that have paved the way for the modelling of river ice, focusing on the evolution of numerical tools and methodologies. Central to this exploration is the River1D ice model, which has emerged as a sophisticated computational framework for simulating ice dynamics in river systems. Ninety-nine percent of Norway's electricity comes from hydropower, and the continuous functioning of hydropower facilities over the winter months is critical to meeting demand and Most of Hydropower in Norway are high head with large capacity, Development of hydropower will have impact on temperature and ice conditions in the river downstream of the outlet from the hydropower station (Gebre et al. 2013) Several regulated rivers in Norway and elsewhere have populations of Atlantic salmon which is an important species for recreational fishing and for local economy (Stensland, Dugstad, and Navrud 2021). Due to releases from deep reservoir intakes, the water temperature in the area downstream of the power plant's outlet will rise in the winter (Heggenes et al. 2021). This will also change the winter ice regime (Heggenes et al. 2018). The thermal and ice regime of regulated rivers can be significantly impacted by water releases from reservoirs and interbasin transfer schemes; (Alfredsen and Tesaker 2002). River ice problems frequently prevent operations during the winter (Morse and Hicks 2005; Billfalk 1992; Alfredsen and Tesaker 2002; Prowse et al. 2011).

Early Approaches to River Ice Modelling:

Early efforts in river ice modelling predominantly relied on simplified analytical models and empirical approaches. These models often treated ice as a rigid body, neglecting the dynamic interactions between ice cover and flowing water(Hibler III 1986). While these approaches provided initial insights, they were limited in capturing the intricate processes governing ice formation, movement, and decay.

Advancements in Numerical Modelling:

Research on river ice has advanced significantly with the development of numerical techniques. Two-dimensional hydrodynamic models, such as River2D, laid the foundation for simulating river flow and sediment transport. But initially, these models were not well-suited to deal with the intricacies of ice dynamics. Researchers began integrating ice modules into existing hydrodynamic models, and the River1D ice model emerged as a dedicated tool for capturing the unique challenges posed by river ice.

River1D Ice Model Theoretical Foundations:

Developed as an extension of the River2D model, the River1D ice model introduced a comprehensive framework for simulating the thermal and mechanical interactions between river water and ice cover. The theoretical foundations of the model include equations governing heat transfer, ice growth and decay, and interactions with riverbed sediments. Its one-dimensional nature allows for efficient representation of longitudinal variations in ice processes.

Validation and Applications:

However, earlier iterations of the model were restricted to rectangular channel shape and omitted several significant river ice processes, including the creation of border ice, the growth of anchor ice, and the movement of frazil beneath ice covers (Blackburn 2022). Researchers have increasingly turned to the River1D ice model to simulate real-world ice events and validate model outputs against field observations. These applications have ranged from small streams to large rivers, demonstrates the model's versatility across different scales and environments. Validated simulations have provided valuable insights into ice jam formation, ice cover dynamics, and the influence of climate change on river ice regimes.

Current Challenges and Future Directions:

Currently, an implicit finite difference solution to the Saint-Venant equations serves as the foundation for the majority of one-dimensional (1D) river ice models that exist (Blackburn 2022). Despite the progress made with the River1D ice model, challenges persist in accurately representing all aspects of river ice dynamics. Current research focuses on improving the model's ability to simulate ice processes under varying environmental conditions, incorporating ice-sediment interactions, and addressing the uncertainties associated with climate change impacts.

In summary, the literature reviewed highlights the evolution of river ice modelling from simplistic approaches to sophisticated numerical tools. The River1D ice model, with its theoretical foundations and practical applications, stands at the forefront of this evolution, offering a promising avenue for advancing our understanding of the intricate dynamics of ice in river systems. The subsequent chapters of this thesis will build upon this foundation by employing the River1D ice model to further explore and contribute to the growing body of knowledge in river ice dynamics.

1.3 Description of the Study Area

1.3.1 Geographical overview

The focus of this study is the River Orkla, located in the stunning landscapes of Norway. Originating in the mountainous terrain of Trøndelag county, the Orkla River meanders its way through diverse ecosystems, shaping the region's hydrology and offering a unique setting for the investigation of river ice dynamics. Covering a catchment area that spans both altitue and lowland regions, the river Orkla is characterized by its dynamic flow regimes, influenced by seasonal variations, topography, and climatic conditions. The River Orkla is known for its salmon and trout populations, making it a popular destination for anglers.

Conservation efforts are often in place to protect and sustain the river's fish species, contributing to the overall biodiversity of the region.

1.3.2 Hydrological Characteristics:

The River Orkla is a significant watercourse with a length of approximately 180 kilometers. Its basin covers an area of approximately 3,460 square kilometers. It derives its flow from the surrounding mountains and experiences variations in discharge throughout the year, with notable contributions from snowmelt during the spring and summer months. The river plays a crucial role in supporting local ecosystems, providing habitats for diverse flora and fauna, and serving as a valuable resource for both recreational and industrial activities. The river's flow and discharge vary seasonally, with higher volumes during the spring and early summer due to snowmelt. Monitoring and managing the discharge are crucial for both hydroelectric power generation and environmental conservation.

1.3.3 Climatic Conditions:

The climate in the River Orkla basin is characterized by the maritime influence of the Norwegian Sea. Winters are cold, with temperatures often dropping below freezing, leading to the formation of ice on the river surface. The study area experiences distinct seasons, with summer temperatures allowing for the melting of accumulated snow and ice. The interplay of these climatic conditions contributes to the complex dynamics of river ice in the Orkla River.

1.3.4 Topography and River Morphology:

The River Orkla flows through a varied landscape, starting from the mountainous regions with steep gradients and eventually transitioning into gentler slopes as it approaches the lowlands. This variation in topography influences the river's velocity, sediment transport, and the formation of ice features. The riverbed exhibits a mix of bedrock and alluvial deposits, adding to the heterogeneity of the study area.

1.3.5 Ecological Significance:

The Orkla River is home to a diverse range of aquatic and terrestrial ecosystems. Salmon and trout, among other fish species, inhabit its waters, contributing to the river's ecological richness. The seasonal ice cover plays a crucial role in shaping the habitat and life cycles of these aquatic species, making the study of river ice dynamics essential for understanding the broader ecological dynamics of the River Orkla.

1.3.6 Significance for the Study:

The River Orkla is one of the significant rivers in Norway, known for its rich history and diverse hydrological characteristics. The Orkla River is renowned for its utilization in hydroelectric power generation. It has several hydroelectric power plants along its course.

Dams and reservoirs have been constructed to regulate the flow of the river, ensuring a consistent and reliable source of energy. The unique characteristics of the River Orkla make it an ideal case study for investigating the complexities of river ice dynamics. The interaction between climatic conditions, topography, and ecological components provides a rich context for the application of the River1D ice model. Through this study, we aim to enhance our understanding of how the River1D model performs in capturing of ice processes in a real-world, diverse river system, with implications for both local management practices and broader climate change adaptation strategies.

1.4 Site and topography

The regulated river Orkla flows for approximately 200 km through a typical "V" shaped valley in the upper section and a large and flat valley in the lower half before draining into Orkdalsfjorden. The river is in mid-Norway (63° 17′ N, 9° 50′ E). This information was provided by Borsányi (2005). The river has an average yearly runoff of 70 m^3 /s and a drainage area of 3053 km^2. In the early 1980s, Orkla was managed with three large reservoirs and five hydroelectric facilities. The river is made up of series of riffles and pools with a wide range of hydraulic characteristics. almost 22-kilometer section between the Grana power plant's outflow and the Svorkmo power plant's intake in Bjørset has been chosen for the modelling work. The slope throughout this section is 2.3 m/km on average. The Grana power station draws its energy from the 139 million cubic meter Grana reservoir. Significant frazil and anchor ice formation at the research site has been documented because of the regulation (Stickler and Alfredsen 2009). This river has been the subject of several ice/winter investigations in the past(Bjerke and Kvambekk 1994);(Stickler and Alfredsen 2009), (Stickler et al. 2007)

The formation of ice on rivers can have significant effects on their regulation and hydropower generation. Here are some key considerations:

Water Flow and Regulation:

- Ice can obstruct the flow of water in rivers, leading to changes in the water levels and potentially causing flooding in upstream areas. This can affect the regulation of river flow and impact the ability to manage water levels for various purposes such as irrigation, municipal water supply, and flood control.

Hydropower Generation:

- Ice formation can pose challenges to hydropower generation. Ice accumulation on structures, such as dams and intakes, can reduce the efficiency of water intake and impact the operation of turbines. Ice can also lead to mechanical damage to turbines, which may require shutdowns for repairs.

Temperature Changes:

- Ice formation is closely related to water temperature. In cold climates, particularly during winter, the temperature drop can lead to the freezing of river surfaces. This can affect the operation of hydropower plants as water levels and flow rates may be altered due to ice-related blockages.

Operational Challenges:

- Hydropower plants may need to adjust their operations to deal with ice-related challenges. For instance, operators may need to reduce water intake during icy conditions to prevent damage to equipment. This can impact the overall efficiency and output of the hydropower plant.

Structural Integrity:

- Ice accumulation can exert additional forces on structures, such as dams and spillways. This can lead to concerns about structural integrity and may require additional engineering considerations to ensure the safe and reliable operation of these facilities.

Mitigation Measures:

- Various mitigation measures can be implemented to address ice-related issues. These may include the use of de-icing equipment, such as bubblers and heaters, to prevent ice formation on critical structures. Additionally, careful monitoring of weather conditions and river flow can help operators anticipate and respond to potential issues.

Environmental Impact:

- Ice formation can also have environmental impacts on river ecosystems. It may affect aquatic life, disrupt habitats, and influence water quality. Understanding and managing these environmental considerations are crucial for sustainable river management. In summary, ice formation on regulated rivers can have multifaceted effects on water flow regulation and hydropower generation. Managing these challenges requires a combination of engineering solutions, operational adjustments, and environmental considerations to ensure the reliable and sustainable use of river resources.

1.5 Objectives of the Thesis

This master's thesis seeks to achieve several interconnected objectives:

1. Model Characterization: Provide a detailed overview of the River1D ice model, outlining its theoretical foundations, numerical methods, and governing equations.

2. Validation and Verification: Assess the accuracy and reliability of the River1D model by comparing its simulations with observed field data from representative river systems.

3. Applications: Explore practical applications of the River1D model in predicting river ice dynamics, managing water resources, and informing climate change adaptation strategies.

Through a comprehensive exploration of the River1D ice model, this thesis aims to contribute valuable insights to the field of river ice modelling, advancing our understanding of the intricate interactions between climate, hydrology, and river ice dynamics

Chapter 2

Model and Input Data

2.1 Common types of river ice

Farzil ice: When water is supercooled, frazil ice forms, which is made up of tiny ice spicules or discoid floating in the water. The flocs and clusters rise to the surface because of greater buoyancy, where they combine to form ice pans. Frazil slush can form from flocs, clusters, and particles of ice that have been moved beneath an existing layer of ice.

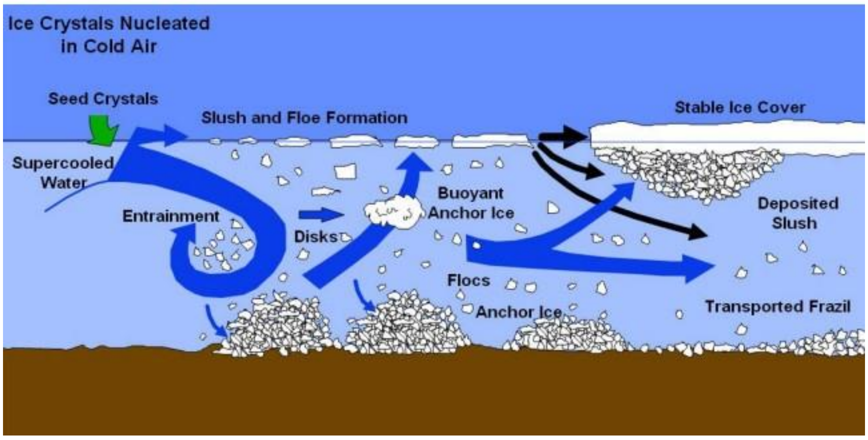


Figure 1. Simplified diagram of frazil ice evolution (Beltaos 2013)

Following their formation, the frazil ice crystals can undergo further evolution at the macro-scale through flocculation and floe formation, as well as at the micro-scale, which is the real crystal level itself. The anisotropic crystalline dynamics of the ice crystal itself, in conjunction with the formation and growth of frazil ice crystals under non-equilibrium, supercooled conditions, provide the main driving force for micro-scale evolution. This produces a disk-shaped crystal that is very different from an ice crystal in equilibrium, or when the surface energy of the contained volume is at its lowest. It appears that during the growth phase, the process that drives the crystal toward equilibrium shape and results in "equilibrium metamorphosis" is overwhelmed and has minimal effect on the crystal's form. It appears that during the growth phase, the process that drives the crystal toward equilibrium shape and results in "equilibrium metamorphosis" is overwhelmed and has minimal effect on the crystal's form (Colbeck 1992) . Little is known about the mechanisms governing the transformation of disk-shaped crystals into their equilibrium form in rivers, a process that has not been thoroughly explored.

- **Pancake ice**: Pancake ice consists of predominantly circular pieces of ice with raised rims due to the pieces colliding with each other(Beltaos 2013).

Figure 2. Frozen pancake ice cover (Nisters and Schröder 2021)

A sizable area of ice, in any shape or form, on the surface of a body of water is called an ice cover.

- **Brash ice:** is an accumulation of floating ice made up of fragments < 2 metres across.

- **Skim ice**: Skim ice, or thick, thin sheets of ice that are detached from the riverbanks, can be created by thermal ice growth at the water's surface. Low turbulence in the area near the water's surface in relation to the ice crystals' rising velocity is linked to the production of skim ice. Low air temperatures, along with reduced wind and water velocities, encourage the production of skim ice. Skim ice sheets that are moving can expand to very vast lateral dimensions—hundreds of meters, for example. Such sheets can quickly induce a freeze-over across the whole width of the channel when they are caught by a constriction, bend, or edge of an existing ice cover. in areas of low water velocity, the water surface may become supercooled to a sufficient level to promote the growth of small ice particles at the surface. If the turbulence intensity of the flow is insufficient to entrain these particles into the flow, they will continue to grow in the horizontal direction at the water surface and form skim ice (Beltaos 2013).

- **Border ice**: at the onset of below-freezing air temperatures, the net rate of heat loss from the channel banks will typically exceed that of the flowing water, causing the saturated bank material to freeze. The water depth very near to the bank is quite shallow, which helps to promote relatively low water velocities and therefore the existence of a thin, supercooled layer of surface water. The ice then extends from the edge of the bank into the water. If the water velocity is low, the border ice can often originate as long, thin ice needles that face into the flow. Hydraulic effects of border ice formation include an increase in the flow resistance and the wetted perimeter of the flow, which partially causes upstream staging. The channel will become completely covered as this effect intensifies(Beltaos 2013).

Figure 3. December 2011 border ice formation on Winnipeg's Assiniboine River. Border ice initially produced by frazil accretion and then by thermal growth after the frazil supply was blocked by an upstream frazil bridge. (Beltaos 2013)(Image credit: M. Cleveland).

- **Anchor ice:** Frazil ice may get "anchored" to the river's bed material when river water is supercooled. An essential type of river ice known as anchor ice can change the roughness of the channel, provide localized flow staging, operate as a transport mechanism for sediment, and influence aquatic life. Ice that sticks to the bottom of rivers, lakes, and seas is generally referred to as anchor ice, also known as bottom ice((Schaefer 1950);(Wigle 1970);(Tsang 1982)). There are two different ways that anchor ice might form: either by underwater nucleation or by active frazil particles accumulating on submerged objects. Anchor ice originates on the bottom substrate material of rivers and lakes and is invariably coupled with supercooled water Although it is occasionally associated with sandy bottoms, anchor ice is most frequently found in conjunction with gravel, cobble, and rock substrates(Hirayama et al. 1997);(Kerr, Shen, and Daly 2002);(Stickler and Alfredsen 2005); (Kempema, Ettema, and McGee 2008);(Bisaillon and Bergeron 2009). When seen through water, anchor ice usually has a milky white appearance. Sediment deposited within the ice block can darken the colour of the ice.

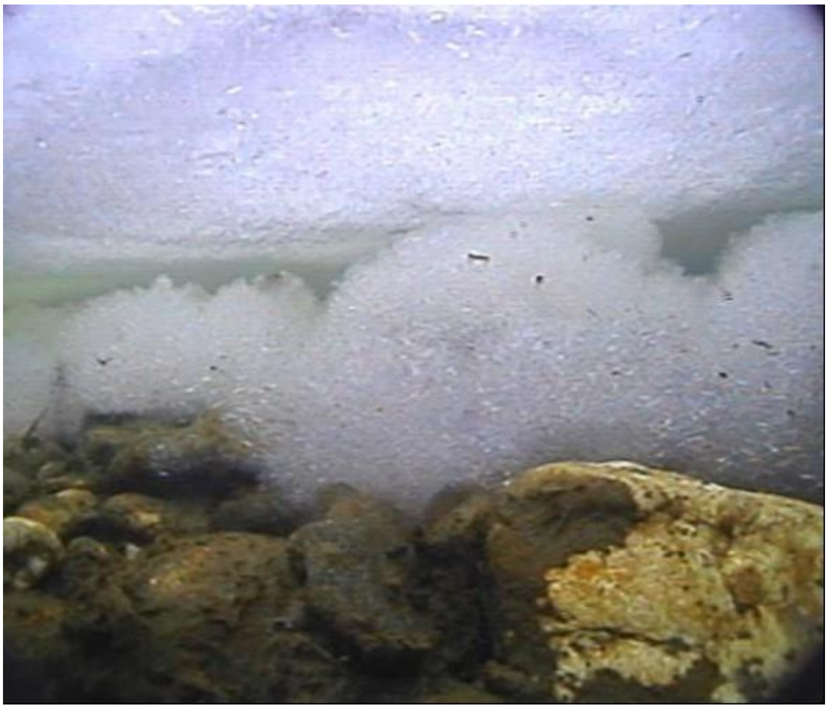


Figure 4. Anchor ice growth around gravel on the bed of a shallow river. Photo by E.W. Kempem (Beltaos 2013)

Freeze up jamming and formation of ice cover

A body of water may experience the formation of an ice cover in a static or dynamic manner. Lakes and low-velocity river zones are popular places for the creation of static ice cover, which is mostly caused by thermal factors. The interaction of moving ice floes with moving water or wind is the primary factor governing the dynamic creation of an ice cover. The result of this interaction is the creation of a freezeup ice jam, which is an unconsolidated layer that finally turns into a sheet of solid ice, either entirely or partially. Thus, a crucial step in the creation of river ice coverings is freezeup jamming Furthermore, freezeup jams can cause flooding, interfere with the production of hydropower, damage property and infrastructure, and have a numerous additional negative effects on the environment (Eliasson and Gröndal 2008).

Ice formation in regulated rivers

A dam changes a river's temperature and flow patterns, which affects the kinds and stability of ice that form in the river and how long it takes for it to freeze. For example, flow augmentation from reservoir releases may result in greater water levels during freezeup. The formation of ice cover in river reaches downstream of the dam may be inhibited or eliminated by variations in flow brought on by greater power generation during periods of peak demand or by the release of warmer reservoir water. The period of ice cover formation is critical for hydropower operations (Wigle et al. 1990). Generally, the sooner an ice cover forms the better as it insulates river water from the cold air and restricts the quantity of ice produced. Depending upon the weather, a unit area of open water can produce 4-10 times the ice than the same area in an ice-covered river (Wigle et al. 1990). A few of the issues that may arise from this are hanging dam formation that obstructs the flow to the power plant, frazil ice deposition on trash intakes, static and dynamic loads on structures, and downstream floods brought on by freezeup jamming. Once an ice layer is in place, these freezeup issues become less problematic. The completion of Dickson Dam in 1983 resulted in significant changes to the ice regime of the Red Deer River at the City of Red Deer, Alberta, Canada, as reported by(Gerard 1992a). a comprehensive review of freshwater ice effects on hydropower systems was presented recently by (Gebre et al. 2013).

2.2 Model description

The public domain program River1D from the University of Alberta serves as the foundation for the new river ice process model. Initially, the model was created as an open water hydrodynamic model, employing the characteristic-dissipative-Galerkin (CDG) finite element technique to solve the Saint-Venant equation (Hicks and Steffler, 1990, 1992). This approach has been shown to be consistently more stable and accurate than other systems (finite element and implicit finite difference), especially when modelling extreme dynamic events. It also perfectly conserves both mass and momentum (Hicks and Steffler, 1992). Several thermal (water cooling, frazil production and rise, and ice cover generation) and dynamic (ice jam development and release) ice processes were added to earlier iterations of the model. The model's use for these earlier iterations, however, was restricted to site-specific ice components and rectangular cross section geometry. The River1D model was modified to take into account natural channel geometry in order to more accurately represent river ice processes in intricate natural river systems. With additions to the ice processes of the ice processes taken into account in this new version of the model with natural channel geometry include water supercooling, frazil accretion, frazil re-entrainment, anchor ice formation and release, border ice formation, and under-cover transport of frazil.

To further replicate the ice cover progression, leading edge stability parameters for ice cover creation were applied. This explains the empirically modelled dynamic factors (such as hydraulic and mechanical thickening) that lower the rate of ice cover advancement.

2.3 Hydrodynamic equations

The conservation equation for water flow beneath and through the ice considers the existence of a floating ice cover and anchor ice on the riverbed. It is as follows:

$$\frac{\partial Q_w}{\partial x} + \frac{\partial A}{\partial t} = \frac{\rho_i}{\rho_w}\frac{\partial A_i}{\partial t} + (1 - p_a)\frac{\partial A_{an}}{\partial t} \tag{1}$$

The cross sectional area to the water's surface is denoted by A in this case; the discharge of water through and under the ice is denoted by Q_w; the cross sectional area of the surface ice, including border ice and under-cover moving flotilla, is represented by A_i; the cross sectional area of the anchor ice is denoted by A_{an}; the porosity of the anchor ice is indicated by pa; time is represented by t; and the river's streamwise path is represented by x. The water movement under and through the ice can be described using the momentum equation:

$$\frac{\partial \boldsymbol{Q_w}}{\partial \boldsymbol{t}} + \frac{\partial(\boldsymbol{\beta Q_w U_w})}{\partial \boldsymbol{x}} + gA_w\frac{\partial H}{\partial x} + gS_f A_w = 0 \tag{2}$$

where H is the water surface elevation above a given datum, β is the momentum flux correction coefficient determined using Fread (1988), S_f is the boundary friction slope, and U_w and A_w are the average velocity and cross-sectional area of the water flowing under and through the ice, respectively. The relationship between the water's cross-sectional areas and its surface is established by:

$$A = A_w + \frac{\rho_i}{\rho_w} A_i + (1 - p_a) A_{an} \tag{3}$$

The friction slope is evaluated using Manning's equation. When a stationary ice cover is present, the composite Manning's roughness coefficient, n_c, is calculated from the general form of the Sabaneev equation (Secil Uzuner 1975):

$$n_c = n_b \left(\frac{1 + \frac{P_i}{P_b} \left(\frac{n_i}{n_b} \right)^{\frac{3}{2}}}{1 + \frac{P_i}{P_b}} \right)^{\frac{2}{3}} \tag{4}$$

where P_b and P_i are the channel's wetted perimeters impacted by the bed and the ice, respectively, and n_b and n_i are the Manning's roughness coefficients for the bed and surface ice layer, respectively. Nezhikhovskiy's coefficients of Manning's roughness of the under surface of frozen slush ice (1964) can be used to compute the coefficient of roughness for the surface ice layer, or it can be given by the user as a function of thickness. In order to compute ice roughness, the user must first identify the kind of ice. Roughness is then interpolated using the simulated ice thickness and Nezhikovskiy's roughness coefficients for slush-ice covers that are primarily made "from ice," "from dense (frozen) slush," or "from loose slush."

2.4 Ice equations

Water cooling and supercooling, frazil ice formation, frazil rise and re-entrainment, border ice growth and decay, surface ice transport, thermal ice growth and decay, anchor ice evolution, under-cover frazil transport, and ice cover progression based on leading edge stability criteria are all considered in the recently improved River1D model. Using the Streamline Upwind Petrov-Galerkin finite element method, all transport equations are solved (Brooks and Hughes 1982). Fig. 6 illustrates the vertical ice processes considered in the model.

2.4.1 Water cooling and supercooling

The conservation of thermal energy in the water and suspended frazil ice (ice-water mixture) is considered when simulating water temperature, as stated by (Shen 2010)

$$\frac{\partial(e_{wi}A_w)}{\partial t}+\frac{\partial(e_{wi}Q_w)}{\partial x} = -\underbrace{\frac{B_o(1-C_i)}{\rho_w}\emptyset_{wa}}_{net\ heat\ exchange\ between\ water\ and\ air} - \underbrace{\frac{(B_oC_i+f_bB_{ws})}{\rho_w}\emptyset_{ia}}_{\substack{net\ heat\ exchange\ between\ water\ and\ air\ through\ the\ ice\ cover\ air \\ when T_w>0°C\ and\ T_a<0°C}} - \underbrace{\frac{(B_oC_i+P_bC_{an}+f_bB_{ws})}{\rho_w}\emptyset_{wi}}_{net\ heat\ exchange\ between\ water\ and\ ice} + \underbrace{B_o\frac{\rho_i}{\rho_w}L_i\eta C_f}_{frazil\ rise\ when\ T_{w<0°C}} + \underbrace{C_{an}P_b\frac{\rho_i}{\rho_w}L_i\gamma C_f}_{frazil\ accelaration\ to\ bed\ when\ T_{w<0°C}} - \underbrace{B_oC_i\frac{\rho_i}{\rho_w}L_i\beta_{re}\left(t_{si}+t_{sf}(1-P_f)\right)}_{\substack{re-entrainment\ of\ surface\ ice\ to\ suspended\ frazil\ layer\ when \\ U_i>U_{i-re} and\ U_i>0}} - \underbrace{C_iB_o\frac{\rho_i}{\rho_w}L_iB_{re}\left(t_{ui}-(1-P_f)\right)}_{\substack{re-entrainment\ of\ surface\ ice\ to\ suspended\ frazil\ layer\ when \\ U_i>U_{i-re} and\ U_i=0}} \quad (5)$$

The thermal energy of the ice-water mixture per unit mass is denoted by e_{wi}, which is equal to $C_p(1-C_f)T_w - \rho_i C_fL_i/\rho_w$; T_w is the temperature of the water; C_p is its specific heat. The volumetric concentration of suspended frazil ice is denoted by C_f. L_i, the latent heat of ice, has a value of 334 KJ/kg. B_{ws} is the overall width of the main channel at the water's surface, excluding any overbank flow; Where B_o is the breadth of the water surface not covered by border ice and f_b is the proportion of the main channel covered by border ice, $B_o = (1-f_b)B_{ws}$; Surface ice concentration is denoted by C_i. C_{an} is the portion of the bed (as indicated by the user) that is covered in anchor ice; The net rates of heat exchange are υ_{wa}, υ_{ia}, and ϕ_{wi} per unit surface area between water and air, through the floating ice layer, and between ice and water, correspondingly, all measured in accordance with (Andrishak and Hicks 2008); The user specifies η as the rate of frazil ascent and γ as the rate of frazil ice accretion to the bed. When U_i exceeds the ice velocity threshold for re-entrainment, U_{i_re}, β_{re}, the user-specified rate of surface ice re-entrainment, will take place. The thicknesses of the solid ice layer are denoted by t_{si}, the frazil slush layer by t_{fs}, the frazil slush porosity by p_f, and the under-cover moving frazil layer by t_{ui}. The linear heat transfer approach is used to estimate the energy budget equation for heat exchange between water and air (Andrishak and Hicks 2008):

$$\emptyset_{wa} = \emptyset_s + h_{wa}(T_w - T_a) - j_{wa}T_a + K_{wa} \quad (6)$$

where ϕ_s is the net incoming solar radiation; h_{wa}, j_{wa}, k_{wa} are heat transfer coefficients; and T_a is the air temperature.

2.4.2 Suspended frazil production and transport

once the water becomes supercooled, frazil ice will form in the water column. The thermal growth and decay of frazil ice in the water column, as well as mass transfer between the surface ice, under-cover moving frazil, and anchor ice layers, affect the concentration of suspended frazil ice:

$$\begin{aligned} &\frac{\partial(A_w C_f)}{\partial t} + \frac{\partial(Q_w C_f)}{\partial x} \qquad (7) \\ &= \underbrace{\frac{\emptyset_{fw}}{\rho_i L_i}}_{growth\ and\ decay} - \underbrace{B_o \eta C_f}_{frazil\ rise} - \underbrace{C_{an} P_b \gamma C_f}_{frazil\ accertion\ to\ bed} \\ &+ \underbrace{B_o C_i B_{re}\left(t_{si} + t_{fs}(1 - P_f)\right)}_{re-entainment\ of\ surface\ ice\ to\ suspended\ farzil\ layer\ when\ U_{i-re}<U_i\ and\ U_i>0} \\ &+ \underbrace{B_o C_i B_{re}\left(t_{ui} - (1 - P_f)\right)}_{re-entrainment\ of\ under-cover\ moving\ farzil\ to\ suspended\ farzil\ layer\ when\ U_i=0\ and\ U_w>U_{i-re}} \end{aligned}$$

where ϕ_{fw}, which is evaluated similarly to (Shen and Wang 1995), is the net rate of heat exchange per unit surface area between suspended frazil particles and water.

$$\emptyset_{fw} = -\frac{2K_w N_u^f}{r_o d_e}(C_f + C_{fo})A_w T_w \tag{8}$$

where K_w is the thermal conductivity of water, de is the typical thickness of a frazil particle, r_o is the typical radius of a frazil particle, and C_{fo} is the frazil seeding concentration. N_f^u f is the Nusselt number of a suspended frazil particle. All parameters are user-specified, with the exception of K_w, which is fixed at 0.566 W/m/°C (Shen 2016).

2.4.3 Border ice formation

The border ice growth is simulated by the model using both static and dynamic mechanisms. According to (Matousek 1984), static border ice is presumed to form as skim ice when the subsequent conditions are met: $T_a < 0$ °C, $T_w < 0$ °C, and $U_{wl}/U_{cr} < 0.167$, where U_{cr} is the maximum water velocity for border ice accretion and U_{wl} is the local water velocity in the open water next to the border ice edge. The following equation is included in the model to account for the lateral accretion of border ice:

$$\frac{dB_b}{dt} = aC_i^b \left(\frac{U_{wl}}{U_{cr}}\right)^d \frac{\emptyset_{wa}}{\rho_i L_i} + e\frac{\emptyset_{DDF}}{\rho_i L_i} \tag{9}$$

where a, b, d, and e are user-defined coefficients; $\emptyset_{DDF}$ is the rate of heat loss depending on the degree days of freezing; and B_b is the border ice width from a given bank. The first term is derived from Michel et al.'s (1982) empirical dynamic border ice model. Only when $0.167 < \frac{U_{wl}}{U_{cr}} < 1.0$ and $C_i > 0.1$ is this term active. The second component, which is based on the straightforward degree-day equation for border ice growth created by (Haresign, Toews, and Clark 2011), was added to account for border ice growth that is not explained by dynamic border ice creation (first term) and skim ice formation. The second term also provides the user with a more straightforward model for border ice formation that only needs the calibration of one parameter (e), since the first term requires the calibration of three parameters (a, b, and d), which may not be feasible. For a particular cross section, the total border ice width (B_{btotal}) is obtained by evaluating Eq. (9) at both the left (B_{bl}) and right (B_{br}) banks. The following relationship is used to estimate the local water velocity, or U_{wl}:

$$U_{wl} = U_w \left(\frac{D_{wl}}{D_w}\right)^{\frac{2}{3}} \tag{10}$$

where T is the channel's entire width, D_w (=A_w/T) is the mean hydraulic depth of the water, and D_{wl} is the local water depth at the border ice's edge. "A wedge-shaped ice sheet extending from the shoreline, with the thickest portion closest to the shore and the thinnest portion actively growing laterally" is how (Haresign, Toews, and Clark 2011; Clark 2013)defines border ice, as illustrated in Fig. 6. The method used to simulate the border ice thickness (t_b) and cross sectional area (A_b) in the model has been guided by this description. Equation: This model describes the growth and decay rate of border ice thickness, t_b:

$$\frac{dt_b}{dt} = \underbrace{\frac{-T_a h_{wa} - \emptyset_s}{L_i \rho_i \left(1 + \frac{h_{wa} h_{wa}}{K_i}\right)}}_{growth\ and\ decay} - \underbrace{\frac{\emptyset_{wi}}{L_i \rho_i}}_{decay} \tag{11}$$

where K_i represents ice's thermal conductivity. As soon as the border ice begins to grow laterally, the thickness of the border ice at each bank is represented by a border ice thickness calculation. It is expected that where the border ice edge extends into the channel, the thickness zeroes out. The cross-sectional area of the border ice is estimated using the mean of these two thicknesses (t_b/2).

$$A_b = \frac{t_b B_{btotal}}{2} \tag{12}$$

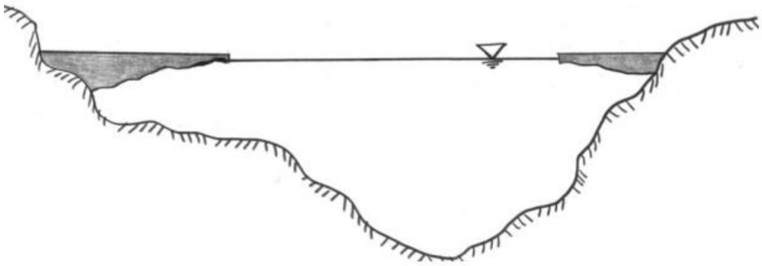


Figure 5.Schematic of border ice formation showing decreasing ice thickness with distance from the channel bank (Beltaos 2013)

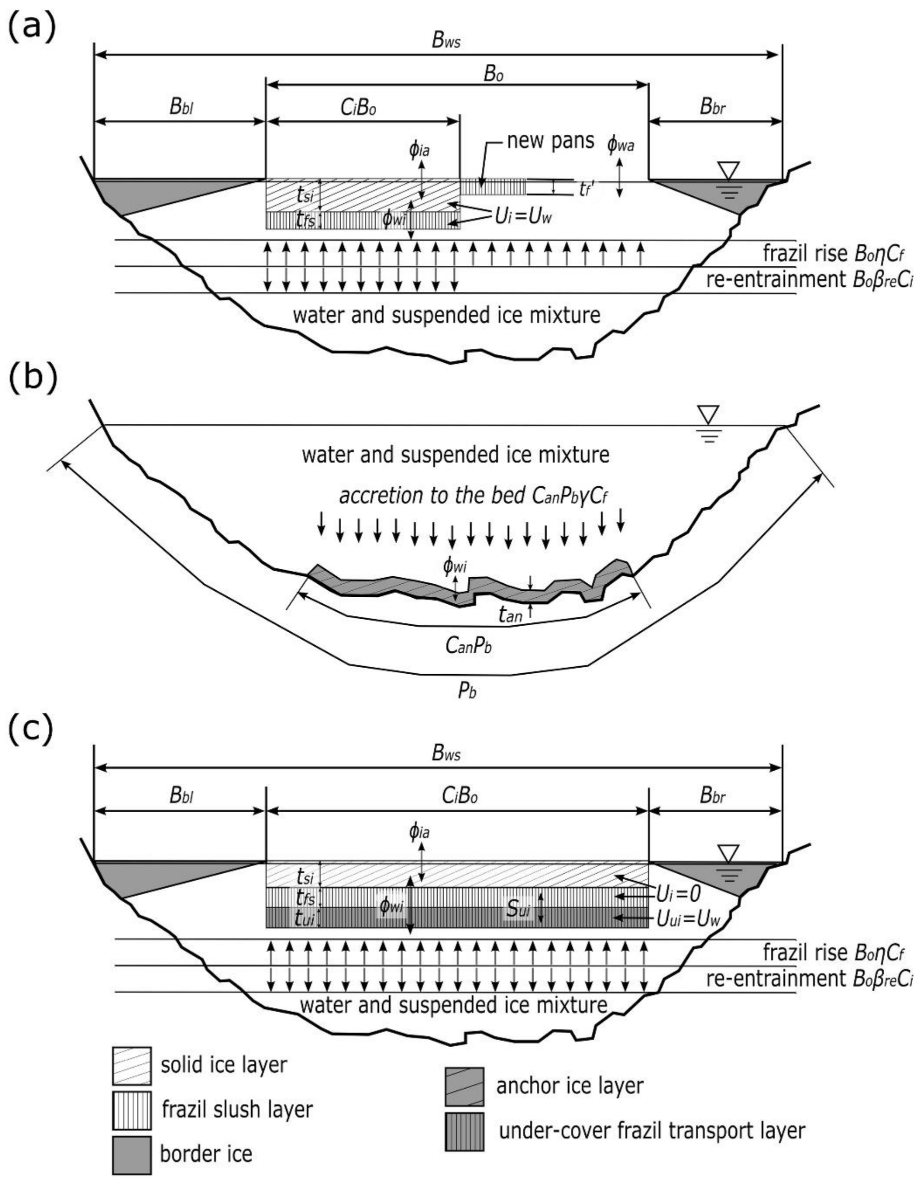


Figure 6.Cross section definition sketch of the vertical processes considered in the model for (a) moving surface ice layers, (b) anchor ice, and (c) stationary surface ice layers with moving under-cover frazil layer adapted from (Andrishak and Hicks 2008)

2.4.4 Anchor ice formation and release

(Shen, 2010) defines the rate of change of anchor ice thickness due to thermal growth and decay and frazil accretion at a particular cross section as follows:

$$\frac{dt_{an}}{dt} = \underbrace{\frac{\gamma C_f}{(1-P_a)}}_{growth\ due\ to\ the\ accretion\ when\ T_w<0°C} - \underbrace{\frac{\emptyset_{wi}}{\rho_i(1-P_a)L_i}}_{thermal\ growth\ and\ decay} \tag{13}$$

The cross-sectional area occupied by the anchor ice is defined by:

$$A_{an} = C_{an}P_b t_{an} \tag{14}$$

A crucial but challenging process that might result from mechanical and thermal processes is anchor ice release (Malenchak 2012). Anchor ice release happens in the improved River1D model when either the water temperature goes above zero (condition (1)) or the buoyancy forces of the anchor ice are greater than the gravity forces acting upon it (condition (2)). Condition (2) can be stated as follows, assuming that the bed material is densely packed based on a hexagonal close packing arrangement and that there is little anchor ice growth down into the bed material pore space.

$$t_{an} > \frac{\pi}{3\sqrt{3}} \frac{d_s(\rho_s - \rho_w)}{(1-P_a)(\rho_a - \rho_i)} \tag{15}$$

Here, the user-specified average diameter and density of the bed material are denoted by ds and ρ_s, respectively.

2.4.5 Surface ice evolution and transport

Solid and frazil slush layers, which are thought to move at a speed U_i until they settle and create a stationary ice layer or accumulation, describe the surface ice in the model. The fluctuation in the concentration of surface ice along the channel is explained by:

$$\frac{\partial(B_o C_i)}{\partial t} + \frac{\partial(U_i B_o C_i)}{\partial x} = \underbrace{\frac{B_o(1-C_i)\eta C_f}{t'_f(1-p_f)}}_{frazil\ rise} + \underbrace{\frac{B_o(1-C_i)\emptyset_{wa}}{t'_{si}\rho_i L_i}}_{\text{freezing between ice pans once ice has } stopped\ when\ U=_i=0, T_a<o} + \underbrace{\frac{(1-C_i)S_{ui}}{(1-P_f)t_{ui}}}_{transfer\ from\ under\ cover\ moving\ frazil\ layer} - \underbrace{B_o\beta_{re}C_i}_{\text{re entrainment of surface ice when } U_{i-re}<U_i} \qquad (16)$$

The thickness of fresh frazil pans is denoted by t'_f, the initial thickness of newly produced solid ice between the ice pans after the ice stops moving is represented by t'_{si}, and the source term S_{ui} represents the exchange between the stationary (A_{fs}) and under-cover moving (A_{ui}) frazil layers. The following describes the frazil slush layer's conservation of mass equation:

$$\frac{\partial A_{fs}}{\partial t}+\frac{\partial U_i A_{fs}}{\partial x} = \underbrace{\frac{B_o \eta C_f}{(1-\acute{P}_f)}}_{frazil\ rise\ 0<U_i} - \underbrace{\frac{B_o \emptyset_{ia} C_i}{L_i \rho_w P_f}}_{pore\ water\ freezing\ when\ A_{fs}>0\ and\ T_a<T_w\ll 0℃} - \underbrace{\frac{B_o C_i \emptyset_{wi}}{\rho_i (1-P_f) L_i}}_{decay\ at\ water-ice\ interface\ A_{sf}>0\ and\ T_w>0℃} - \underbrace{(B_o \beta_{re} C_i t_{fs})+}_{re-entrainment\ of\ surface\ ice\ when\ U_{i-re}<U_i\ and\ when\ 0<U_i} \underbrace{\frac{s_{ui}}{(1-P_f)}}_{transfer\ from\ under\ cover\ moving\ frazil\ layer} \tag{17}$$

where $A_{sf} = t_{fs} C_i B_0$ is the frazil slush layer's cross-sectional area. The mass conservation equation is as follows for the solid ice layer:

$$\frac{\partial A_{si}}{\partial t}+\frac{\partial A_{si} U_i}{\partial x} = \underbrace{f_1 \frac{B_O C_i \emptyset_{ia}}{\rho_i L_i}}_{growth\ and\ decay} - \underbrace{\frac{B_O C_i \emptyset_{iw}}{\rho_i L_i}}_{growth\ and\ decay\ at\ water\ ice\ interface\ when\ A_{fs}=0} + \underbrace{\frac{B_O (1-C_i) \emptyset_{wa}}{\rho_i L_i}}_{freezing\ between\ ice\ pans\ once\ ice\ has\ stopped\ when\ U_i=0\ and\ \mathrm{T_a}<0} - \underbrace{(B_o \beta_{re} C_i t_{si})}_{\text{re−entrainment of surface ice when and when } U_i>U_{i-re} \text{ and when } U_i>0} \tag{18}$$

where A_{si} is the solid ice layer's cross-sectional area $(A_{si} = B_o C_i t_{si})$ and f_1 is a conditional constant that is defined as follows.

$$f_1 = \begin{cases} 1 & when\ \emptyset_{ia} < 0, A_{si} > 0\ and\ T_a > o°\text{C}(melting\ of\ solid\ ice) \\ 1 & when\ \emptyset_{ia} > 0, A_{sf} = 0\ and\ T_w \ll 0°\text{C}\ (freezing\ of\ water\ colum) \\ \rho_i(1 - P_f)/\rho_w P_f + 1 & when\ \emptyset_{ia} > 0, A_{sf} > 0\ and\ T_w \ll 0°\text{C}\ (freezing\ of\ pore\ water) \\ 0 & otherwise \end{cases} \quad (19)$$

The surface ice, moving frazil ice under cover, and border ice are connected by:

$$A_i = A_{si} + (1 - P_f)(A_{fs} + A_{ui}) + A_b \quad (20)$$

2.4.6 Ice cover progression

Based on a single user-specified bridging position, ice cover creation is presumed to happen. After bridging, inbound ice will build up to create a stationary ice cover upstream through floe juxtaposition, mechanical thickening, or hydraulic thickening depending on the Froude number $\left(\text{defined as } {U_w}/{\sqrt{gD}}\right)$immediately upstream of the leading edge. The following formula is used to track the location of the ice front, X_i (Uzuner and Kennedy 1976):

$$X_i^{t+\Delta t} = X_i^t - \frac{C_i(t_{si} + (1 - P_f)t_{fs})U_i\Delta t}{t_{le}(1 - P_j) - C_i(t_{si} + (1 - P_f)t_{fs})} \quad (21)$$

Here, the model dates t and t + Δt correspond to the location of the ice front; Δt is the simulation time step; and the expected thickness and porosity of the ice accumulation, once the ice cover forms, are represented by t_{le} and p_j, respectively. As seen in Fig. 7, the velocity of the ice in the model is determined by the location of the ice front, also known as the leading edge.

The surface ice (solid ice layers and frazil slush) upstream of the leading edge is thought to move at the water's speed ($U_i = U_w$). The under-cover frazil transport layer is supposed to move at the speed of the water ($U_{ui} = U_w$) and the surface ice is considered to be stationary ($U_i = 0$) downstream of the leading edge. As stated by (Shen 2016), estimates for t_{le} depend on the pattern of advancement of the ice cover. In particular, the ice cover advances upstream in juxtaposed mode and the value of t_{le} is set to the thickness of the incoming ice floes (t_{si} + t_{fs}) when Fr is less than the user-specified maximum Froude number for juxtaposition, Fr_jux. In contrast, the ice cover will advance upstream in either mechanical thickening or hydraulic thickening mode when the Froude number is between F_{r_jux} and the maximum Froude number for ice cover advancement, F_{r_max}. The dominating theory is established by looking at which of the two narrow ice jam and equilibrium ice jam theories (Pariset and Hauser 1961)yields the bigger value of t_{le}. Values for μ, a composite jam stress parameter that takes into account the internal friction characteristics and porosity of the ice buildup, and τ_c, the ice cohesion, must be entered into the equilibrium ice jam equation. According to(Shen 2016), the porosity of the ice accumulation is calculated using:

$$P_j = P_c + (1 - P_c)\left(\frac{P_f t_{fs}}{t_{si} + t_{fs}}\right) \tag{22}$$

Where the distance between the ice floes in the freshly produced ice cover is represented by p_c.

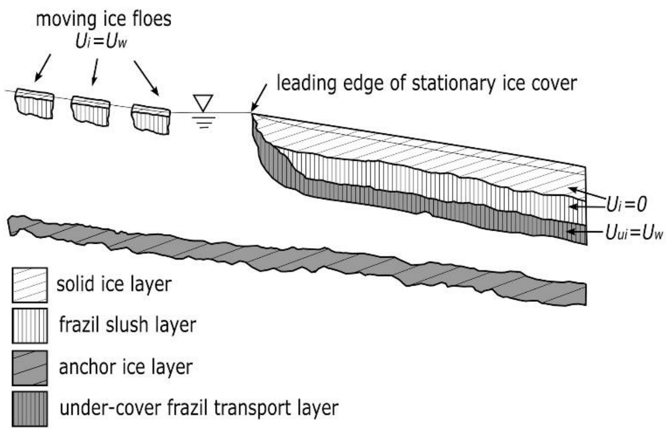


Figure 7.Longitudinal profile definition sketch showing the modelled ice layers(Julia Blackburn 2019)

The surface ice and under-cover transport layers in the model are limited to the channel width in between the border ice. The flow may never develop up to the point where it would in nature to allow the Froude number to drop below F_{r_max} since frazil does not collect below the border ice, and simulated ice cover advance rates may be delayed or stopped in comparison to observed rates.

2.4.7 Under-cover transport of frazil

The definition of frazil transport along the stationary ice cover's underside is:

$$\frac{\partial A_{ui}}{\partial t} + \frac{\partial U_{ui} A_{ui}}{\partial x} = \underbrace{\frac{B_o \eta C_f}{(1 - P_f)}}_{frazil\ rise\ when\ U_i = 0} - \underbrace{B_o C_i \beta_{re} t_{ui}}_{re-entrainment\ of\ under\ cover\ moving\ frazil\ when U_{ui} > U_{i-re} and\ when\ U_{i=0}} - \underbrace{\frac{S_{ui}}{(1 - P_f)}}_{transfer\ to\ frazil\ slush\ layer} \tag{23}$$

where U_{ui} is the layer's velocity and A_{ui} is the cross-sectional area of the under-cover moving frazil layer (A_{ui} = $B_o C_i t_{ui}$). The source phrase is assessed as follows in discrete form:

$$S_{ui} = \frac{Q_{uit} - Q_{uic}}{L} \tag{24}$$

where L is the ice cover length between computational nodes, which the streamwise discretization in the model approximates; Q_{uic} is the ice transport capacity, which is determined by following(Shen, Wang, and Lal 1995): Q_{uit} is the total under-cover ice discharge (A_{ui}Uui$(1 - P_f)$ + $A_w C_f U_w$).

$$Q_{uic} = 5.487 F d_f B_o \sqrt{g d_f \left(\frac{\rho_w - \rho_i}{\rho_w}\right)} (\Theta - \Theta_c)^{1.5}\ where\ \Theta \gg \Theta_c \tag{25}$$

and the dimensionless flow strength, is:

$$\Theta = \frac{\tau_i}{g d_f F^2 (\rho_w - \rho_i)} \tag{26}$$

where F is the frazil particle form factor, d_f is the average diameter of the frazil granules in the under-cover transport layer, and τ_i is the shear tension on the underside of the stationary frazil slush and solid ice layers. Undercover frazil transfer does not occur when Θ is smaller than the critical flow strength, Θc (Q_{uic} = 0).

Chapter 3

Study site and methods

3.1 Study site

The regulated river Orkla flows for approximately 200 km through a typical "V" shaped valley in the upper section and a large and flat valley in the lower half before draining into Orkdalsfjorden. The river is located in mid-Norway (63° 17′ N, 9° 50′ E). This information was provided by Borsányi (2005). The river has an average yearly runoff of 70 m3 /s and a drainage area of 3053 km^2.

In the early 1980s, Orkla was managed with three large reservoirs and five hydroelectric facilities. The river is made up of series of riffles and pools with a wide range of hydraulic characteristics. The modelling effort will focus on an approximately 22 km long section (Fig. 8 B) between the Grana power plant's output and the Svorkmo power plant's intake at Bjørset. The route has a 2.3 m/km average slope. The Grana power station draws its energy from the 139 million cubic meter Grana reservoir. Significant frazil and anchor ice formation at the research site has been documented as a result of the regulation (Stickler and Alfredsen 2009). This river has been the subject of several ice/winter investigations in the past (Bjerke and Kvambekk 1994);(Dahl 1986);(Stickler and Alfredsen 2009; Stickler et al. 2007).

3.2 Hydro and climate data

The model's river geometry is derived from cross-sections gathered for flood mapping, as detailed in a flood mapping report by Fjellanger Widerøe Kart (2001), published by the Norwegian Water Resources and Energy Directorate (NVE). To represent the river characteristic further better at sites known for frazil production, additional cross sections were gathered in the steep portions in the downstream portion of the model area. The discharge from the Grana power plant, the lateral inflow in the upstream reach, and the flow from the Brattset hydropower plant make up the discharge at the upstream border. The downstream border has been placed at the water level at the Bjørset intake. Water levels and production data were all acquired from the Orkla hydropower plant. The hydrodynamic model is calibrated using discharge data at Syrstad gauge, which are provided by NVE (Norwegian Water Resources and Energy Directorate). The discharge from the Grana power plant, the lateral inflow in the upstream reach, and the flow from the Brattset hydropower plant make up the discharge at the upstream border. The downstream border has been placed at the water level at the Bjørset intake. Water levels and production data were all acquired from the Orkla hydropower plant. The hydrodynamic model is calibrated using discharge data at Syrstad gauge, which are provided by NVE (Norwegian Water Resources and Energy Directorate). Every input data point is gathered at an hourly time interval. Between Grana and Bjørset, there are a few tributaries that contribute to the lateral flow, totalling 260 km^2. Due to increasing air temperature-induced precipitation as rainfall and snowmelt, the flows are significantly increased during the winter and spring seasons. As a result, the winter flow regime in the river is supported by increased lateral flow as well as increased power output at the Brattset and Grana in the spring and winter. However, because winter flow is so minimal, lateral flow has not been included in the ice simulation. The uncontrolled flow at Brattset has been scaled according to area and a certain runoff ratio from a nearby catchment during the scenario simulations. The model was limited between 10 and 12 m^3 /s because we encountered problems with model stability during the unregulated scenario runs when the flow was lower than around 10 m^3 /s. For most of the winter, the uncontrolled flow is less than 10 m^3/s. As a result, the limitations may cause a freeze-up delay in comparison to the natural state, which must be considered while interpreting the outcome. For the same reason, the lower bound of the upstream water temperature in the unregulated case was set at −0.01 °C. the same reason. Water temperature was measured at Grana outlet, Vella, Hårråøya and Bjørset (see Fig 8 B). Temperature measurements at Grana outlet were used at the upstream boundary, and the remainder of the data was used to calibrate/validate the model. At Vella and Hårråøya, temperature sensors (+/−0.1 °C accuracy and 0.01 °C resolution) was installed to measure water temperature, while temperature data at Grana outlet and Bjørset were available from the hydropower company. Input water temperature for the unregulated scenario was obtained from the Gisnås gauge, located in an unregulated headwater stream. 300 meters downstream from the Grana outflow, at Aunan, a climate station was set up. During both field seasons, hourly data on air temperature, relative humidity, wind speed, wind direction, and short- and long-wave radiation were measured. Furthermore, the power company provided the air temperature at Syrstad throughout the two winters. (Ashton 1986) noted that energy flux from precipitation throughout the winter can be significant.

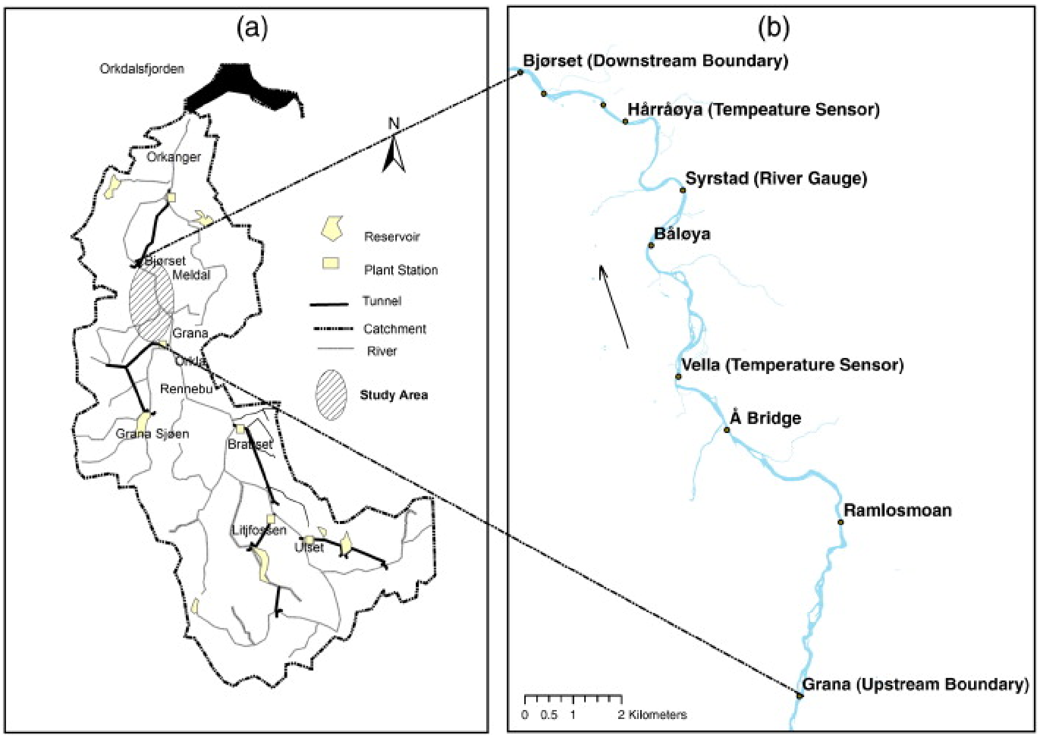


Figure 8.A: Orkla river basin showing the hydropower system, Fig. 8 B: Modeled river reach between Grana outlet and Bjørset intake (Timalsina, Charmasson, and Alfredsen 2013)

3.3 Data from ice monitoring

Data was gathered from field observations to validate the ice simulations. field data was gathered by Netra Timalsina in the winters of 2010 – 2012. To keep an eye on the ice, three distinct techniques were used. 1) Gathering ice data from field campaign observations made from the bankside. 2) Using a small single-engine aircraft, aerial missions were used to analyze the distribution of solid and drifting ice. The study was captured on camera using both handheld video and still cameras. The photos were then geo-referenced, and a GIS was utilized to compare the results with the model data. 3) During the ice season, two Moultrie time-lapse cameras were placed at Bjørset and Hårråøya to capture ice(Netra P. Timalsina a, ∗, and 2013). The amount of drifting ice at Hårråøya was calculated by utilizing a Matlab script to extract picture information and Adobe Photoshop to edit images (Fig. 9). A binary index was used to classify surface ice as present or absent; 1 denotes present ice and 0 denotes missing ice. Visual analysis of each picture was used to extract the extent of the ice cover at Bjørset (Netra P. Timalsina a, *, and 2013).

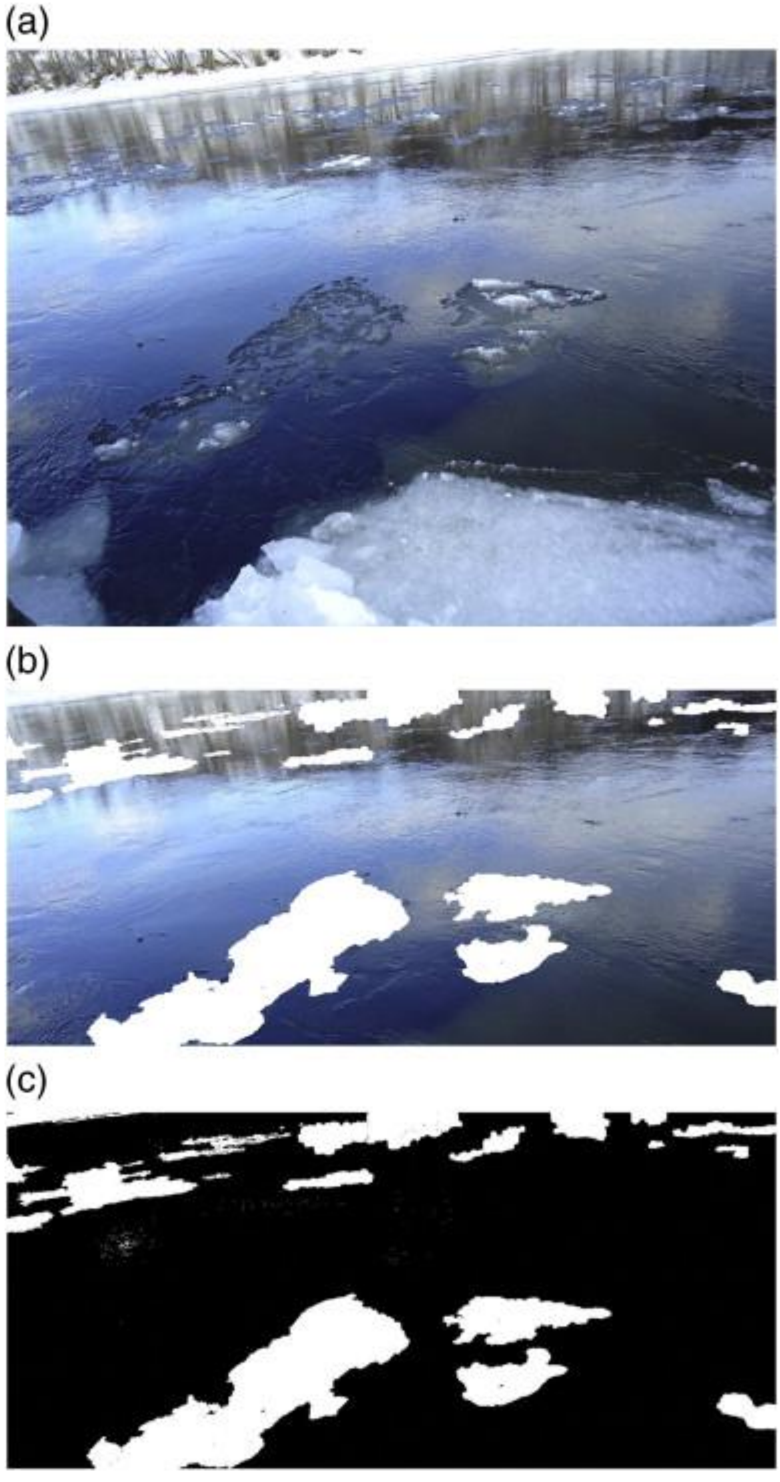


*Figure 9.Steps for processing pictures of drifting ice: (a) Picture from the time lapse camera: (b) after processing in Adobe Photoshop: (c) after processing in MATLAB (Netra P. Timalsina a, *, and 2013)*

Chapter 4

Simulation and Results

4.1 Boundary conditions for River 1D

The climate data and production discharges are shown in Figure 10 for the same year, and this shows a mild winter with several periods with temperature above 0 degrees. The discharge in Controlling the dynamic ice is dependent on the reach's water temperature. The water's temperature is determined by the weather, the power plant's discharge, and the producing water's temperature. The discharge and temperature input data were good, and the missing values were not difficult to fill.

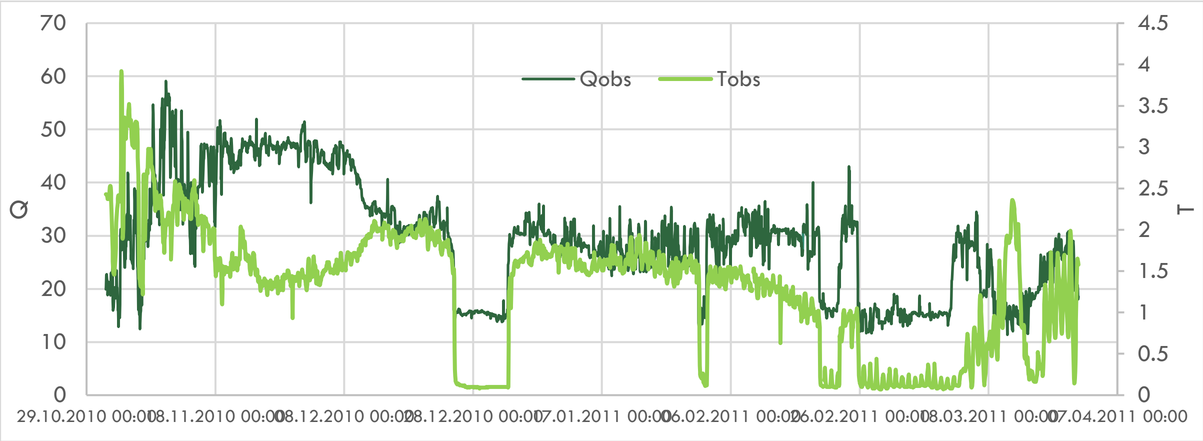


Figure 10.Boundaries conditions for RIVER 1D,) hydrographs at upstream boundaries and water temperature at upstream boundaries.

4.2 Hydrodynamic

With a Nash–Sutcliffe R^2 = 0.78, the hydrodynamic simulation, as illustrated in Fig. 11, exhibits good agreement with discharge as observed at the Syrstad gauge. There were times throughout the winter when ice affected the water levels at the gauge location. These were eliminated from the analysis (Fig. 11, straight lines). Linear interpolation was used to fill in the missing data.

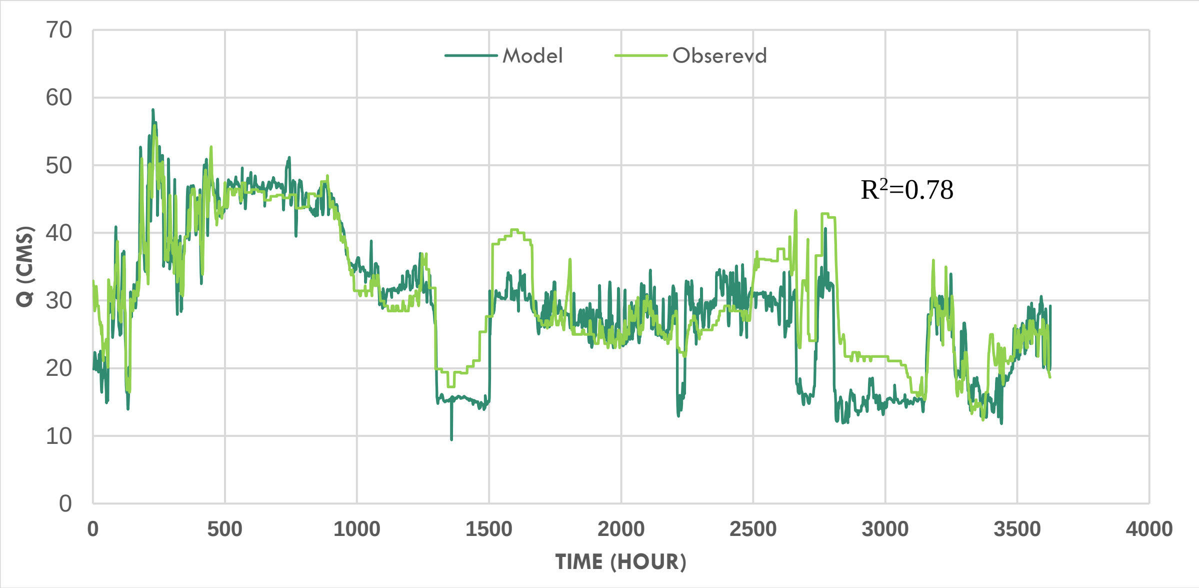
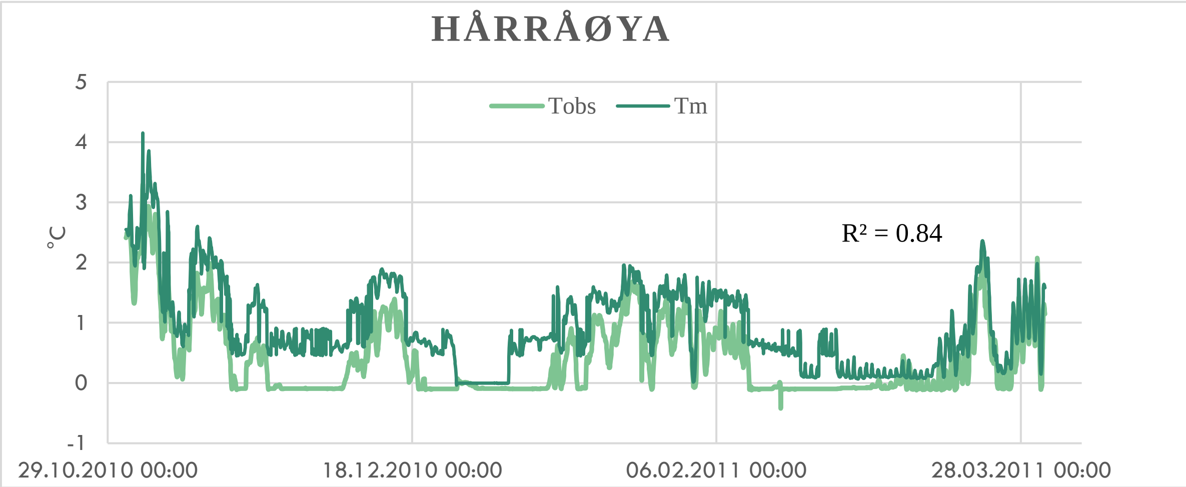


Figure 11.Hydrodynamic simulation at Syrstad gauge.

4.3 water temperature

Controlling the dynamic ice is dependent on the reach's water temperature. The temperature of the water is influenced by the production water's temperature, the power plant's discharge, and the weather. At every location, the simulated water temperature, and the measured water temperature (Fig. 12) agree well, with an R^2 between 0.65 and 0.84. The water temperature in the model is generally over-predicted, especially in the short winter season of 2010–2011, specifically in the third and fourth weeks of February (discrepancy ~1–1.2 °C).



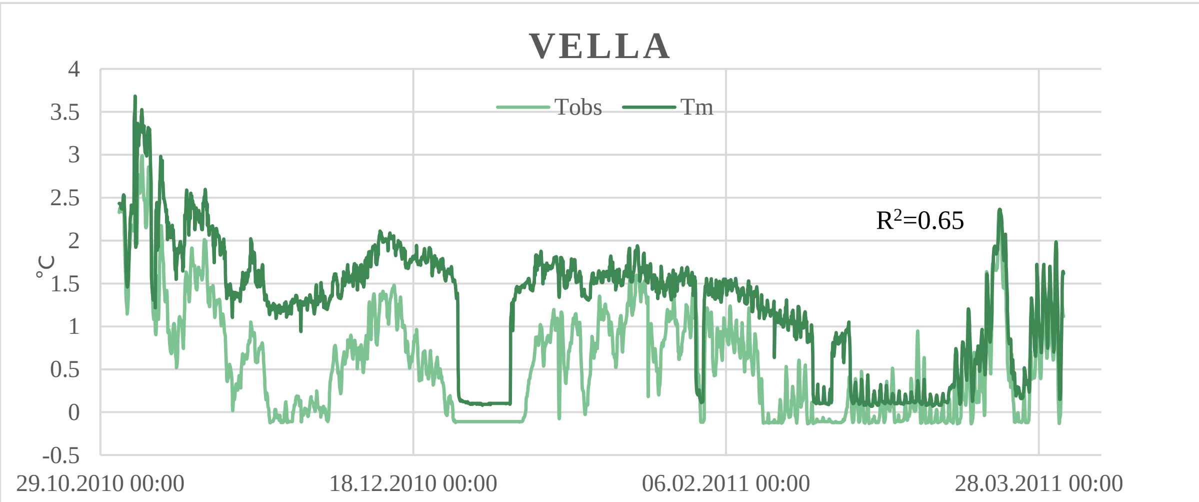


Figure 12.Water temperature simulations for the winter 2010/2011 at Vella, Hårråøya.

Although the simulated water temperature is more than the observed one, the super cooling pattern is largely replicated. We think that we notice an effect of short-wave radiation input in the fluctuations near the conclusion of the period, and the mismatch at the beginning of the series may be due to the start time and initial conditions. The solution to this should be to calculate the location's solar radiation and adjust it for the canyon walls' shading impact. Because there were insufficient hourly data or poor-quality hourly data for a number of the periods, we ran the River1D model with both hourly and daily boundary conditions and climate forcing. In order to get the model to converge with respectable results, a trial-and-error process led to the setting of the model simulation time step at 0.025 hours.

4.4 Ice simulation

In comparison to field observations, we found the model useful to simulate the history of ice production. the model is able to accurately replicate the drifting surface ice.

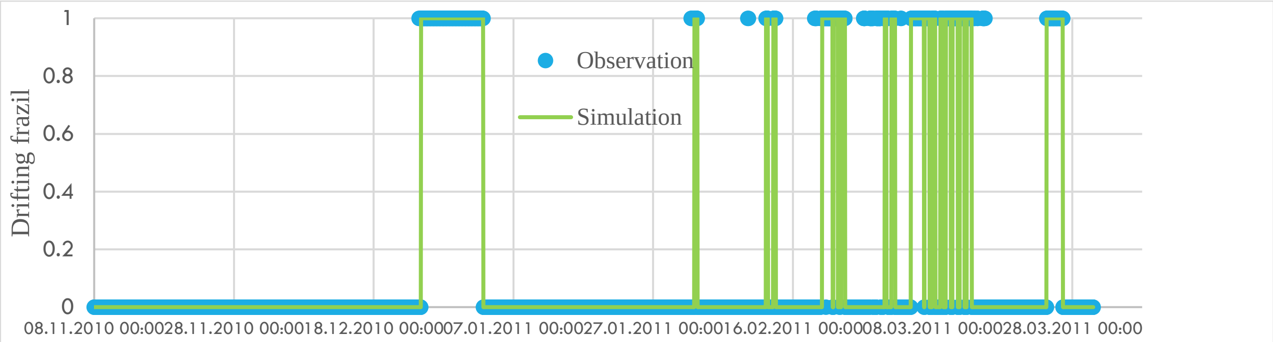


Figure 13. Drifting ice episode winter 2010/2011 at Hårråøya (1 = Drifting frazil ice episode, 0 = No episode)

In the current scenario, major events can happen at any time, while the sporadic events span the entire winter and into early spring. The application of River1D in this instance raises several questions. Insufficient local calibration data exist to confirm the creation of anchor ice and the production and movement of frazil. There is one year's worth of high-quality water temperature data available, however further temperature data might be used to fine-tune the model's temperature component. We haven't calculated the shade at the river valley for sun radiation, but we should consider doing so to see if it enhances the model. The study demonstrates that RIVER 1D is a valuable instrument for researching the ice regime in the River Orkla, provided that it is adjusted and calibrated. The majority of the significant ice evolution mechanisms and ice cover creation along the river can be simulated by the model. The work demonstrates that the model may replicate the observed alterations and offers more insight into the ice regime changes brought about by regulation. The outcomes also highlight the areas in which further investigation is needed to enhance the model's output. Furthermore, the requirement for high-quality data and additional data gathering is crucial, particularly for narrow rivers where remote sensing methods might not be able to give the necessary detail.

Table 1. Adopted values for ice modelling parameters (Julia Blackburn 2019)

Ice modelling parameter	Adopted value	Values in literature
Density of ice, ρ_i (kg/m^3)	917	(Lal and Shen 1991)
Heat transfer coefficient h_{wa} $(W/m2/°C)$	20	19.7 (Lal and Shen 1991) 15(Andrishak and Hicks 2008) 20 (Timalsina, Charmasson, and Alfredsen 2013; Venture 1984)
Frazil seeding concentration, C_{fo}	0.00001	
Typical frazil particle thickness, d_e (m)	0.0003	0.0003(Shen and Wang 1995) 0.00013 (Malenchak 2012)
Typical frazil particle radius, r_o (m)	0.001	0.001(Malenchak 2012; Shen and Wang 1995)
Nusselt number for typical suspended frazil particle, N_f^u	4.0	4.0 (Shen and Wang 1995; Malenchak 2012)
Coefficient of turbulent heat exchange, α_{wi} $(Ws^{0.8}/m^{2.6}/°C)$	1187	1187 (Ashton 1973; Andrishak and Hicks 2008)
Rate of frazil rise, η (m/s)	0.0005	0.001 (Shen and Wang 1995) 0.0001 (Andrishak and Hicks 2008) 0.0004 (Jasek et al. 2015)
rate of surface ice re-entrainment, β_{re} (1/s)	0.00001	0.00001 (Shen and Wang 1995; Malenchak 2012)
Re-entrainment velocity threshold U_{i-re} (m/s)	1.06	
Porosity of frazil slush layer, P_f	0.4	0.5 (Andrishak and Hicks 2008) 0.4 (Lal and Shen 1991)
New frazil pan thickness t_f' (m)	0.2	0.3 (Andrishak and Hicks 2008) 0.2 (Timalsina, Charmasson, and Alfredsen 2013)
solid ice initial thickness t_{si}' (m)	0.001	0.001 (Lal and Shen 1991)
Frazil particle shape factor, F	1.0	1.00 ± 0.03 (Beltaos 2013) 1.0 (Shen and Wang 1995)
Average diameter of frazil granules in cover load $d_f(m)$	0.01	0.01 (Shen and Wang 1995)
Critical flow strength for under-cover frazil transport, Θc	0.041	0.041 (Shen and Wang 1995)

Ice modelling parameter	Adopted value	Values in literature
Porosity of anchor ice, P_a	0.4	0.4 (Malenchak 2012)
Frazil accretion rate, $\gamma(m/s)$	0.00001	0.000001 (Shen and Wang 1995) 0.000005–0.00025 (Malenchak 2012) 0.0001 (Timalsina, Charmasson, and Alfredsen 2013)
Fraction of bed covered by anchor ice, C_{an}	0.25	
Bed material average diameter, d_s (m)	0.05	
Bed material density, ρ_s $(kg/m3)$	2650	2650 (Malenchak 2012)
Border ice equation coefficient, a	14.1	14.1(Michel et al. 1982)
Border ice equation coefficient, b	1.08	1.08 (Michel et al. 1982)
Border ice equation coefficient, d	−0.93	−0.93 (Michel et al. 1982)
Border ice equation coefficient, e	9.75	
Maximum fraction of channel covered by border ice, f_{bmax}	0.7	
Maximum velocity for dynamic border ice growth, $U_{cr}(m/s)$	1.2	1.2 (Michel et al. 1982)
Maximum Froude number for juxtaposition, F_{r-jux}	0.06	0.06 (Lal and Shen 1991)
Maximum Froude number for ice cover progression, F_{r-max}	0.097, 0.15	0.08 to 0.13 (Ashton 1986) 0.09 (Lal and Shen 1991) 0.094 (Venture 1984) 0.08 (Timalsina, Charmasson, and Alfredsen 2013)
Space between ice floes in newly formed cover, P_c	0.4	(Shen 2016)
Composite jam stress parameter, μ	1.28	1.28 (Pariset and Hauser 1961; Pariset, Hausser, and Gagnon 1966)
Ice cohesion, $\tau_c(Pa)$	700	700 (Venture 1984) 980 (Lal and Shen 1991)

Chapter 5

Conclusions and Recommendations

5.1 Conclusions

As river ice is complicated in both space and time, modelling river ice conditions is frequently a difficult task. For the model to be calibrated and validated, a substantial amount of ice observation data is required. River ice processes in small streams are an emerging field of research (Beltaos, 2012). The procedures are especially crucial for making the most use of Norway's water resources because nearly all of the country's rivers are relatively short, narrow, and steep. The fact that many hydropower developments are controlled by ice and that ice formation is influenced by it makes a knowledge of the processes even more necessary. Future alterations in the environment will have an impact on regulated river ice conditions, and also shifts in hydropower operating techniques resulting from variations in future energy demand and input. The importance of river ice models is because of the fact that they are important tools for both engineers and researchers since, they offer a quick and affordable way to investigate how ice affects a river's regime, including its ecology and channel geomorphology, as well as how it affects human infrastructure, including hydropower operations and ice jam flooding. Large amounts of frazil and anchor ice production have an impact on the hydropower output in Orkla. This is because the presence of ice in the river limits the power plant's ability to operate during the winter, and because frazil can clog the trash rack of the Svorkmo power plant's intake (Alfredsen and Bruland 2022). This thesis introduces a new version of River1D, the comprehensive river ice process model developed by the University of Alberta. The capacity to mimic natural channel shape, water supercooling, anchor ice creation and release, border ice formation, under-cover transport of frazil, and ice cover advancement based on leading edge stability requirements has been included to this public-domain model. The first public-domain model with anchor ice evolution and supercooling is called River1D. The Susitna River's data, which included water levels, flows, temperatures, surface ice concentrations, border ice widths, ice cover progression rates, and ice thicknesses, were used in an unprecedentedly thorough calibration and validation of the model. Positive agreements between the observed and simulated data show that the recently improved model can accurately simulate the freeze-up process on this intricate natural river. In comparison to the observed levels, the novel natural channel capabilities allowed for accurate simulation of water levels in both open water and ice-covered scenarios. The fluctuation in the observed border ice widths might be captured by the new border ice component. The border ice model now includes an extra term based on a degree-day approach, giving the user more ways to calibrate the border ice growth and/or a more straightforward model that only needs one parameter calibrated. The simulation of anchor ice—a crucial process on the Susitna River, as data suggest—was made possible by the new supercooling capabilities. Significant frazil slush was found beneath the solid ice cover, confirming the significance of under-cover frazil transfer in the ice regime of the Susitna River and the requirement to incorporate this process in the simulations. It is advised that the River1D ice process model be developed further to enable the simulation of various bridging points and to assess the stability of the produced ice cover. Lastly, in order to assess these model components effectively, comprehensive data on the evolution of anchor ice as well as under-cover transit and accumulation are truly required.

The findings also highlight the processes that require additional investigation in order to enhance the model's output, especially those concerning hydraulic calculations in rivers with substantial anchor ice development and anchor ice formation. Furthermore, the requirement for high-quality data and additional data gathering is crucial, particularly for tiny rivers where remote sensing methods might not be able to give the necessary detail.

5.2 Recommendations for Future Study

According to the results obtained from this research and other important issues, the following recommendations have been made for the future time research studies. Future modifications to hydropower operation tactics and climatic shifts will both affect the ice conditions in regulated rivers. but there are only a few studies exploring the effects of future climate on river ice regime. Therefore, ice problems in the future climate will still be an important issue to be considered. It is advised that the River1D ice process model be developed further to enable the simulation of various bridging points and to assess the stability of the produced ice cover. Finally, to assess these model components effectively, comprehensive data detailing the evolution of anchor ice as well as under-cover transit and accumulation are actually required.

List of symbols

A	Cross sectional area to the water surface
A_{an}	Cross sectional area of anchor ice
A_b	Cross sectional area of border ice

A_{fs}	Cross sectional area of the frazil slush layer
A_i	Cross sectional area of surface ice including border ice and under-cover moving frazil
A_{si}	Cross sectional area of the solid ice layer
A_{ui}	Cross sectional area of under-cover moving frazil layer
A_w	Cross sectional area of water under and through the ice
a	Border ice equation coefficient
B_b	Border ice width from a given bank
B_o	Width of open water between border ice at a cross section
B_{bl}	Width of border ice at the left bank
B_{br}	Width of border ice at the right bank
B_{btotal}	Total width of border ice at a cross section
B_{ws}	Total width of the channel at the water surface for main channel excluding overbank flow
b	Border ice equation coefficient
C_{an}	Fraction of bed covered by anchor ice
C_i	Surface ice concentration
C_f	Volumetric concentration of suspended frazil
C_{fo}	Frazil seeding concentration
C_p	Specific heat of water
D	Mean hydraulic depth of water and ice
D_{wi}	Longitudinal dispersion coefficient for the ice-water mixture
D_w	Mean hydraulic depth of water
D_{wl}	Local water depth at the edge of border ice
D_{si}	Longitudinal dispersion coefficient for the surface ice
d	Border ice equation coefficient

d_e	Typical frazil particle radius
d_f	Average diameter of frazil granules in under-cover transport layer
d_s	Bed material average diameter
e	Border ice equation coefficient
e_{wi}	Thermal energy of the water and the suspended frazil (ice-water mixture)
f_1	Conditional constant in solid ice layer transport equation
F	Frazil particle shape factor
f_r	Froude number
f_{r-jux}	Maximum Froude number for juxtaposition
f_{r-max}	Maximum Froude number for ice cover advancement
g	Gravitational acceleration
H	Water surface elevation above a specified datum
h_{wa}	Heat transfer coefficient between water and air
K_i	Thermal conductivity of ice
L	Length of ice cover between computational nodes
L_i	Latent heat of ice
N_u^f	Nusselt number for typical suspended frazil particle
n_b	Manning's roughness coefficient for the bed
n_c	Composite Manning's roughness coefficient
n_i	Manning's roughness coefficient for the ice
P_b	Bed-affected wetted perimeters of the channel
P_i	Ice-affected wetted perimeters of the channel
P_a	Porosity of anchor ice
P_c	Space between ice floes in newly formed ice cover

P_f	Frazil slush porosity
Q_w	Discharge of water under and through the ice
Q_{uit}	Total under-cover ice discharge
Q_{uic}	Ice transport capacity
r_o	Typical frazil particle radius
S_f	Boundary friction slope
S_{ui}	Source term representing exchange between moving and stationary frazil layers
T	Total width of the channel at the water surface
T_w	Average water temperature in the cross section
t	Time variable
Δt	Simulation time step
t_{an}	Anchor ice thickness
t_b	Border ice thickness
t_{fs}	Frazil slush layer thickness
t'_f	New frazil pan thickness
t_{le}	Thickness of ice at the leading edge
t_{si}	Solid ice layer thickness
t'_{si}	Initial ice thickness of newly formed solid ice between stationary ice pans
t_{ui}	Thickness of under-cover moving frazil layer
U_{cr}	Maximum velocity for dynamic border ice growth
U_i	Ice velocity
U_{i-re}	The ice velocity threshold criteria for re-entrainment
U_{ui}	Velocity of under-cover moving frazil layer
U_w	Average water velocity in the cross section

U_{wl}	Local water velocity at the edge of border ice
X_i	Ice front location
x	Streamwise space variable
α_{wi}	Coefficient of turbulent heat exchange
β	Momentum flux correction coefficient
β_{re}	Rate of surface ice re-entrainment
γ	Frazil accretion rate
ε_{sw}	Ice water mixture longitudinal dispersion paramete
ε_{si}	Surface ice longitudinal dispersion parameter
η	Rate of frazil rise
Θc	Critical flow strength
μ	Composite jam stress parameter
ρ_i	Density of ice
ρ_w	Density of water
ρ_s	Density of bed material
τ_c	Ice cohesion
$\emptyset_{ia}$	Net rate of heat exchange between water and air through the floating ice layer
$\emptyset_{fw}$	Net rate of heat exchange per unit surface area between frazil particles and water
$\emptyset_{wa}$	Net rate of heat exchange between water and air
$\emptyset_{wi}$	Net rate of heat exchange between water and ice
$\emptyset_s$	Net incoming solar radiation

References

1. Alfredsen, Knut, and Oddbjørn Bruland. 2022. 'Hydropower in Cold Regions'.

2. Alfredsen, Knut, and Einar Tesaker. 2002. 'Winter habitat assessment strategies and incorporation of winter habitat in the Norwegian habitat assessment tools', *Hydrological processes*, 16: 927-36.

3. Andrishak, R, and F Hicks. 2008. 'Simulating the effects of climate change on the ice regime of the Peace River', *Canadian Journal of Civil Engineering*, 35: 461-72.

4. Ashton, George D. 1973. "Heat transfer to river ice covers." In *Presented at the East Snow Conference, 30th Annual Meeting, Amherst, Massachusetts, Feb. 8-9, 1973.*

5. Ashton, GHE. 1986. 'River and Lake Ice Engineering Water Resources Publications', *Littleton, CO*.

6. Barnett, Tim P, Jennifer C Adam, and Dennis P Lettenmaier. 2005. 'Potential impacts of a warming climate on water availability in snow-dominated regions', *Nature*, 438: 303-09.

7. Beltaos, Spyros. 2013. *River ice formation* (Committee on river ice processes and the environment, Canadian geophysical …).

8. Billfalk, L. 1992. "Ice effects and control for hydropower production." In *Proceedings of the 11th symposium on ice. IAHR*, 671-82.

9. Bisaillon, Jean-François, and Normand E Bergeron. 2009. 'Modeling anchor ice presence–absence in gravel bed rivers', *Cold Regions Science and Technology*, 55: 195-201.

10. Bjerke, PL, and Aa S Kvambekk. 1994. 'Application of the ice model rice in a rapid river'.

11. Blackburn, Julia L. 2022. 'Numerical Modelling of River Ice in Complex River Systems'.

12. Brooks, Alexander N, and Thomas JR Hughes. 1982. 'Streamline upwind/Petrov-Galerkin formulations for convection dominated flows with particular emphasis on the incompressible Navier-Stokes equations', *Computer methods in applied mechanics and engineering*, 32: 199-259.

13. Clark, S. 2013. 'Border and skim ice', *CGU-HS CRIPE: Edmonton, AB, Canada*: 77-106.

14. Colbeck, Samuel C. 1992. *The Slow Growth of Ice Crystals in Water* (US Army Cold Regions Research and Engineering Laboratory).

15. Dahl, Reidar. 1986. "Ice formation and erosion at river thresholds." In *IAHR Symposium on Ice. IAHR, Iowa City, Iowa*, 485-92.

16. Eliasson, J, and G Orri Gröndal. 2008. 'Development of a river ice jam by a combined heat loss and hydraulic model', *Hydrology and Earth System Sciences*, 12: 1249-56.

17. Gebre, Solomon, Knut Alfredsen, Leif Lia, Morten Stickler, and Einar Tesaker. 2013. 'Review of ice effects on hydropower systems', *Journal of Cold Regions Engineering*, 27: 196-222.

18. Gerard, R., Long, D., Sawatsky, L., and Winhold, T. 1992a. ""Breakup ice regime of Red Deer River at the city of Red Deer"." In *11th IAHR International Ice Symposium*. Banff, Canada.

19. Haresign, M, JS Toews, and S Clark. 2011. "Comparative testing of border ice growth prediction models." In *16th Workshop on River Ice, Winnipeg, MB, Canada*, 18-22.

20. Heggenes, Jan, Knut Alfredsen, Ana Adeva Bustos, Ari Huusko, and Morten Stickler. 2018. 'Be cool: A review of hydro-physical changes and fish responses in winter in hydropower-regulated northern streams', *Environmental Biology of Fishes*, 101: 1-21.

21. Heggenes, Jan, Morten Stickler, Knut Alfredsen, John E Brittain, Ana Adeva-Bustos, and Ari Huusko. 2021. 'Hydropower-driven thermal changes, biological responses and mitigating measures in northern river systems', *River Research and Applications*, 37: 743-65.

22. Hibler III, WD. 1986. 'Ice dynamics.' in, *The geophysics of sea ice* (Springer).

23. Hirayama, Kenichi, K Terada, M Sato, K Hirayama, M Sasamoto, and M Yamazaki. 1997. 'Field measurements of anchor and frazil ice'.

24. Huokuna, M. 1990. "The Finnish River Ice Research Project-the Numerical Model in Use." In *Proceedings, IAHR, International Symposium on Ice, Espoo*, 215-30.

25. Jasek, Martin, Hung Tao Shen, Jiajia Pan, and Kerry Paslawski. 2015. "Anchor ice waves and their impact on winter ice cover stability." In *CGU-HS CRIPE, Proc. 18th Workshop on Hydraulics of Ice Covered Rivers, Quebec*.

26. Julia Blackburn, Yuntong She. 2019. 'A comprehensive public-domain river ice process model and its application to a complex natural river ', *Cold Regions Science and Technology*, 163: 44-58.

27. Kempema, E, R Ettema, and B McGee. 2008. "Insights from anchor ice formation in the Laramie River, Wyoming." In *19th IAHR International Symposium on Ice. IAHR, Vancouver, British Columbia, Canada*, 63-76.

28. Kerr, David J, Hung Tao Shen, and Steven F Daly. 2002. 'Evolution and hydraulic resistance of anchor ice on gravel bed', *Cold Regions Science and Technology*, 35: 101-14.

29. Lal, AM Wasantha, and Hung Tao Shen. 1991. 'Mathematical model for river ice processes', *Journal of Hydraulic Engineering*, 117: 851-67.

30. Lindenschmidt, Karl-Erich, Maurice Sydor, and Richard W Carson. 2012. 'Modelling ice cover formation of a lake–river system with exceptionally high flows (Lake St. Martin and Dauphin River, Manitoba)', *Cold Regions Science and Technology*, 82: 36-48.

31. Malenchak, Jarrod Joseph. 2012. *Numerical modeling of river ice processes on the Lower Nelson River* (University of Manitoba (Canada)).

32. Matousek, V. 1984. "Types of ice run and conditions for their formation." In *Proc. 7th IAHR International Symposium on Ice, Hamburg, Germany*.

33. Michel, B, N Marcotte, F Fonseca, and G Rivard. 1982. "Formation of border ice in the St. Anne River." In *Proceedings of the 2nd Workshop on Hydraulics of Ice Covered Rivers*, 38-61.

34. Morse, Brian, and Faye Hicks. 2005. 'Advances in river ice hydrology 1999–2003', *Hydrological Processes: An International Journal*, 19: 247-63.

35. Netra P. Timalsina a, Julie Charmasson b *, and Knut T. Alfredsen a 2013. 'Simulation of the ice regime in a Norwegian regulated river', *Cold Regions Science and Technology 94 (2013) 61–73*.

36. Nisters, Carina, and Jörg Schröder. 2021. 'Large Scale Sea Ice Modeling–Problems and Perspectives', *PAMM*, 20: e202000242.

37. Pariset, E, and R Hauser. 1961. 'Formation and evolution of ice covers on rivers'.

38. Pariset, Ernest, René Hausser, and André Gagnon. 1966. 'Formation of ice covers and ice jams in rivers', *Journal of the Hydraulics Division*, 92: 1-24.

39. Prowse, Terry, Knut Alfredsen, Spyros Beltaos, Barrie R Bonsal, William B Bowden, Claude R Duguay, Atte Korhola, Jim McNamara, Warwick F Vincent, and Valery Vuglinsky. 2011. 'Effects of changes in arctic lake and river ice', *Ambio*, 40: 63-74.

40. Schaefer, Vincent J. 1950. 'The formation of frazil and anchor ice in cold water', *Eos, Transactions American Geophysical Union*, 31: 885-93.

41. Secil Uzuner, Mehmet. 1975. 'The composite roughness of ice covered streams', *Journal of Hydraulic Research*, 13: 79-102.

42. She, Yuntong, Faye Hicks, Peter Steffler, and Dan Healy. 2009. 'Constitutive model for internal resistance of moving ice accumulations and Eulerian implementation for river ice jam formation', *Cold Regions Science and Technology*, 55: 286-94.

43. Shen, Hung Tao. 2010. 'Mathematical modeling of river ice processes', *Cold Regions Science and Technology*, 62: 3-13.

44. Shen HT. 'River ice processes', *Advances in Water Resources Management. 2016*: 483-530.

45. Shen, Hung Tao, Lianwu Liu, and Yi-Chin Chen. 2001. "River ice dynamics and ice jam modeling." In *IUTAM Symposium on Scaling Laws in Ice Mechanics and Ice Dynamics: Proceedings of the IUTAM Symposium held in Fairbanks, Alaska, USA, 13–16 June 2000*, 349-62. Springer.

46. Shen, Hung Tao, and De Sheng Wang. 1995. 'Under cover transport and accumulation of frazil granules', *Journal of Hydraulic Engineering*, 121: 184-95.

47. Shen, Hung Tao, De Sheng Wang, and AM Wasantha Lal. 1995. 'Numerical simulation of river ice processes', *Journal of Cold Regions Engineering*, 9: 107-18.

48. Stensland, Stian, Anders Dugstad, and Ståle Navrud. 2021. 'The Recreational value of Atlantic salmon angling under different fishing regulations', *Fisheries Management and Ecology*, 28: 362-72.

49. Stickler, Morten, and Knut Alfredsen. 2005. "Factors controlling anchor ice formation in two Norwegian rivers." In *Proceedings of the 13th workshop on the hydraulics of ice covered rivers. CGU HS Committee on River Ice Processes and the Environment, Hanover, New Hampshire*.

50. Stickler, Morten, Knut Alfredsen, David A Scruton, Curtis Pennell, Atle Harby, and Finn Økland. 2007. "Mid-winter activity and movement of Atlantic salmon parr during ice formation events in a Norwegian regulated river." In *Developments in Fish Telemetry: Proceedings of the Sixth Conference on Fish Telemetry held in Europe*, 81-89. Springer.

51. Stickler, Morten, and Knut T Alfredsen. 2009. 'Anchor ice formation in streams: a field study', *Hydrological Processes: An International Journal*, 23: 2307-15.

52. Thériault, Isabelle, Jean-Philippe Saucet, and Wael Taha. 2010. "Validation of the Mike-Ice model simulating river flows in presence of ice and forecast of changes to the ice regime of the Romaine river due to hydroelectric project." In *Proceedings of the 20th IAHR international symposium on ice, Lahti, Finland*, 14-17.

53. Timalsina, Netra P, Julie Charmasson, and Knut T Alfredsen. 2013. 'Simulation of the ice regime in a Norwegian regulated river', *Cold Regions Science and Technology*, 94: 61-73.

54. Tsang, G. 1982. 'Frazil ice and anchor ice: A monograph', *National Research Council of Canada, Subcommittee on Hydraulics of Ice-Covered Rivers, Ottawa*.

55. Uzuner, Mehmet S, and John F Kennedy. 1976. 'Theoretical model of river ice jams', *Journal of the Hydraulics Division*, 102: 1365-83.

56. Venture, Harza-Ebasco Susitna Joint. 1984. *Instream ice calibration of computer model* (Alaska Power Authority).

57. Wigle, T, P Doyle, F Fonseca, H Mark, L Parmley, R Raban, and S Robert. 1990. 'Optimum Operation of Hydroelectric plants during the ice regime of rivers-A Canadian experience', *Prepared by a Task Force of the Subcommittee on Hydraulics of Ice-Covered Rivers, National Research Council of Canada, NRCC*, 31107.

58. Wigle, TE. 1970. 'Investigations into frazil, bottom ice and surface ice formation in the Niagara River'.

IAHR AIRH
Hosted by
Spain Water
and IWHR, China

27th IAHR International Symposium on Ice

Gdańsk, Poland, 9 – 13 June 2024

Modelling ice using *University of Alberta's* River 1D Ice Model

Delaram kazemian[1] and Knut Aldredsen[2]

[1]Department of civil and environmental engineering Norwegian University of Science and Technology 7491 Trondheim, Norway

Delaram.kazemian@.ntnu.no

[2] Department of civil and environmental engineering Norwegian University of Science and Technology 7491 Trondheim, Norway

knut.alfredsen@ntnu.no

Abstract

The Orkla River, located in Norway, is a prominent waterway known for its diverse hydrological characteristics and significant ecological value. Situated in the central part of the country, the Orkla River flows through the counties of Trøndelag and Innlandet. It spans approximately 179 kilometres, originating from the high mountain areas around Orkelsjøen and flows into the Trondheimsfjord. The river was regulated for hydropower in the 1980s and hydropower operation has changed the seasonality of flow and water temperature. With the current regulation, we have several hydropower outlets and a river intake on the main river in the Orkla valley. River ice dynamics play a crucial role in the hydrological and ecological processes of cold regions, impacting water flow, flood risk, and habitat availability. Regulation for hydropower is known to influence river ice and this is also the case in Orkla, having effects both on the physical conditions in the river and on the operation of the hydropower plant. This paper presents a study on modelling ice in the Orkla River using the University of Albertas River 1D ice model. This paper describes the setup of the model and how it is adapted to the winter conditions in river Orkla on the reach between the outlet of the Grana power plant and the intake to Svorkmo power plant. The model is calibrated and validated using observed data, including observed drifting ice, ice cover observations on the intake pond to the Svorkmo power plant and temperature and discharge measurements to ensure its accuracy in simulating the ice dynamics specific to the Orkla River.

The outcomes of this research can support decision-making processes related to ice management, flood forecasting, and environmental planning in cold regions.

Keywords: River ice; River 1D ice model; Ice formation; Ice cover; Hydropower

NTNU

Norwegian University of
Science and Technology