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A glance at 25 process-based hydraulic models for river ice

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Many hydraulic models for river ice have been developed over the past several decades (e.g., CRRISP1D/2D, RIVICE, ICEJAM, MIKE-Ice, River1D/2D, JJT, VARY-ICE,...). Their purposes were to improve our understanding of river ice phenomena and better anticipate their timing, extent, and flood risks over the short term (for operational purposes) and the long term (in the context of a changing climate). Twenty-five such models are briefly described in this paper, with information on the processes that are captured by each model, their application (usage), whether or not they are in the public domain, and sources for more information. The processes are divided into various classes: water cooling, frazil ice generation, border ice, anchor ice, ice cover formation, thermal growth and decay, ice cover break-up, ice dynamics for ice jamming/bridging, and water seepage through the keel of the ice jam. Most models are one-dimensional, i.e., they do not account for variations along channel width or depth. Model performance is not discussed – the intent of the article is, instead, to report on the variety of models described in the river ice literature and provide the readership with a summary of what they are.

Keywords: hydraulic model; hanging dam; frazil; flood; ice jam

1. Introduction

River flow is governed by two main forces: gravity and friction (Adams & Pagano, 2016; Armanini, 2018; Radecki-Pawlik et al., 2018). Water flowing down a channel achieves a constant average velocity when the gravitational acceleration is counterbalanced by the shearing action along the wetted perimeter, which is the interface between the water body and the river bed and shorelines. The hydraulic roughness of that interface (soil, sediments, vegetation, ...) is an important parameter in determining discharge and water levels. It is also a major source of uncertainty. For idealistic scenarios, a uniform flow may be assumed, i.e., when the discharge (water volume per unit time), water depth, and the average flow velocity over a given river reach do not vary (e.g., Pagliara and Palermo, 2018). Flow can also be steady if these flow characteristics do not change with time; it is unsteady otherwise. *Hydraulic* modeling is the analytical implementation of mathematical models that describe flow in a river channel and on adjacent floodplains. *Hydrological* modeling, on the other hand, aims at capturing water movement and distribution above and below ground within the watershed, taking into account processes such as precipitation, infiltration, run-off, and evaporation. The output of hydrological models typically feeds into hydraulic models.

Flooding events occur when the natural capacity of a river to convey the water is exceeded, often as a consequence of intense rainfalls. Management of flood control structures (e.g., dikes, levees) can also induce floods either upstream or downstream. Flood analyses, which are done to understand why and how these events happen, factor in information on topography, hydrology, climate, and demography (Adams and Pagano, 2016; Rivera-Trejo et al., 2018). The outcome is used to guide hydrological modeling of run-off coupled with hydraulic modeling of flow behavior. These, in turn, are used to anticipate future events.

Bringing an ice-covered surface into this picture introduces additional considerations. The free surface (the boundary between water and air) in open-water hydraulics is replaced with an ice cover during the winter, which becomes another source of resistance to flow (e.g., Ashton, 1986; Beltaos, 1995; Shen, 2010). The altered flow dynamics result in an increase in the water level (or stage) – the rougher the undersurface (in the case of a broken ice cover), the higher the stage. With time (days to weeks), thermal erosion may contribute to flattening that undersurface, thereby reducing the stage. Furthermore, the intricacies of how an evolving climate is affecting ice dynamics need to be taken into account when anticipating future (long-term) scenarios (e.g., Turcotte et al., 2019; Beltaos, 2021; Burrell et al., 2022).

2. Objective

River ice dynamics is complex – Figure 1 depicts some of the factors involved. This activity takes place at and below the water surface and may vary in time and space. It includes phenomena such as ice formation, transport, accumulation, and deterioration. A considerable amount of research has been dedicated to the hydraulic modeling of these phenomena. Much of it was motivated by a desire to better anticipate and prepare for flooding events caused by ice jams; that work has been the subject of recent reviews (Madaeni et al., 2020; Das and Lindenschmidt, 2021; Rokaya et al., 2022). The objective of this paper is to bring together hydraulic models reported in the scientific and engineering literature. The focus is on process-based models, i.e., based on physics, as opposed to models of an empirical nature, based on statistical or machine learning algorithms. An example of output from such a model is shown in Figure 2, indicating some essential data requirements to be able to anticipate increases in water levels due to the presence of an ice jam.

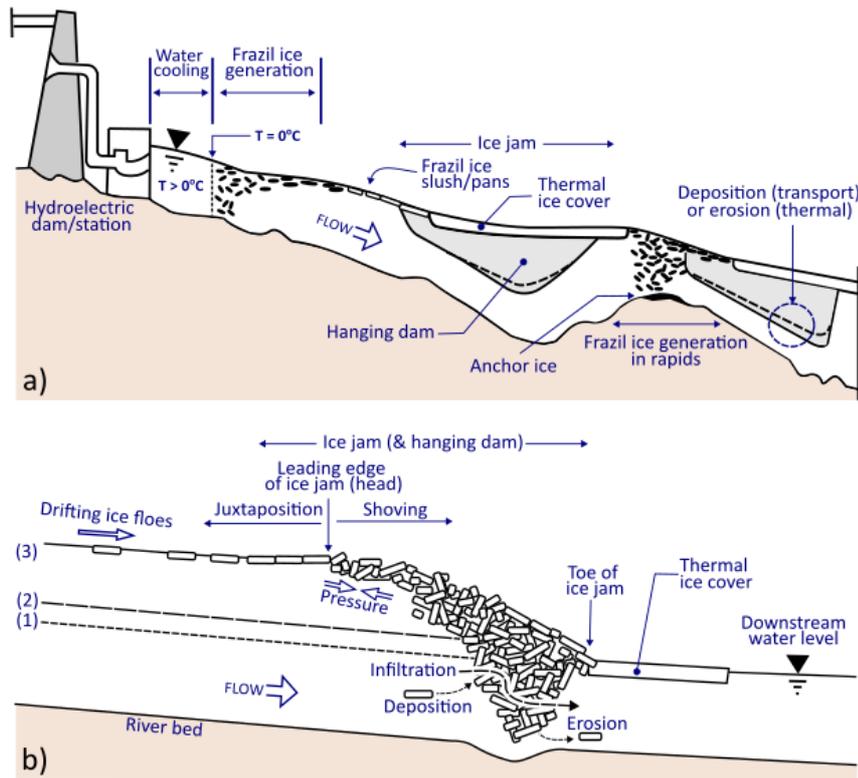


Figure 1. Examples of scenarios and processes that can be simulated by a hydraulic model: a) a reach downstream of a hydroelectric facility where frazil ice is generated – modified after Petryk (1995); b) a generic ice jam involving a broken ice cover, with open water level (1), water level with a uniform ice cover (2) and water level induced by the ice jam (3) – adapted from Rokaya et al. (2022) and references therein. In both illustrations, the vertical scale is exaggerated for illustrative purposes.

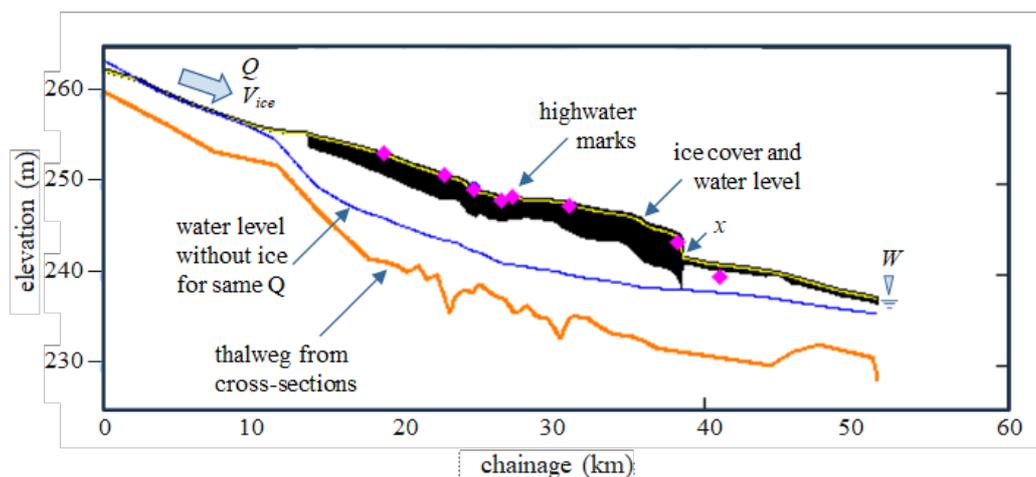


Figure 2. Longitudinal (parallel to water flow) water and ice-cover profiles from RIVICE, a one-dimensional river ice model simulation (adapted from Lindenschmidt, 2023). ‘Thalweg’ is the river bed. Parameters such as flow Q , volume of ice V_{ice} , water level W , ice-jam toe location x , cross-sections and highwater marks are used by the model to anticipate water level rises and, thus, flood risks.

3. Survey methods and limitations

The information provided in this paper was collected through a literature search on Scopus[®], an abstract and citation database, which identified sources on process-based models. This led to additional documents cited in those sources. Information was also collected via communications with authors of the various sources describing the models. The listing in the paper was meant to be as comprehensive as possible but it is not considered all-encompassing. Furthermore, for a detailed description of the models, the reader is encouraged to consult the references provided herein. Finally, information on whether or not a model is still readily available, from where, and in what form (e.g., source code) could generally not be located.

4. Model listing

The models are listed in Table 1. Following is an explanation for table headers, model applications, and processes addressed by each model, whenever information on those aspects was found during our survey. For a historical perspective, the reader is referred to Petryk (1995), who provides a similar model listing, but of those in existence up to the early 1990s.

4.1. Table headers

Model: This is the acronym used to designate the model.

Publicly available: This is when the model can be obtained and used at no cost, i.e., they are not proprietary.

Type: A 1-D model does not account for flow variations with depth or across the channel length. A 2-D model factors in flow variations across channel length.

Steady vs Unsteady: Steady hydraulics is described in the Introduction. Unsteady ice processes are when the model can capture ice cover dynamics (ice cover evolution and drifting ice floes) that vary with time.

Applications: The purpose for which the model is used – these are described further below.

Processes: Those that are included and those that are not. – these are described further below.

Sources: Documents containing more information on the model.

Remarks: Miscellaneous information on the model, including a website in some cases (live as of this writing).

4.2. Applications

Applications in the table are indicated by Roman numerals – the information provided is based on feedback from modelers and from inspecting the sources.

- i. *Water level*: Model used to simulate changes in water level caused by the presence of ice and its dynamics.
- ii. *Ice break-up*: Model used to anticipate when a stable ice cover will break up.
- iii. *Climate impact*: Model used to anticipate the long-term (decades) behavior of a river ice regime at a given location.
- iv. *Ice processes, ice cover/ice jam-related water level, and flood analysis*: Model used to investigate the various processes in the river.
- v. *Active flood forecasting*: Real-time anticipation of flooding events, i.e., via the ongoing monitoring of data and events.

4.3. Ice processes

The ice processes, indicated with Arabic numerals, were divided into several classes corresponding as much as possible to those described in all the sources.

1. *Water cooling*: This is the cooling process of the water column at the beginning of the winter, using energy budget methods.

Table 1: Listing of hydraulic models for river ice, in alphabetical order. See text for explanations on headings, applications, and processes. NI: No information retrieved or available.

#	Model	Publicly available	Type	Steady vs unsteady	Applications	Processes included	Source(s)	Remarks
1	CRISSP1D (Comprehensive River Ice Simulation System-1D)	No	1D	Unsteady ice processes / Unsteady hydraulics	i, ii, iii, iv, v	1, 2, 3, 4, 5, 6, 7	Shen (2002; 2005a; 2005b); Chen et al. (2006); Jasek et al. (2011)	Developed for a consortium of North American hydropower companies under the guidance of CEA Technologies Inc. The model is based on RICEN. CRISSP is now publicly available but a license has to be acquired from Manitoba Hydro. The custodian is Milan Bijeljanin (mbijeljanin@hydro.mb.ca).
2	CRISSP2D (Comprehensive River Ice Simulation System-2D)	No	2D	Unsteady ice processes / Unsteady hydraulics	i, ii, iii, iv, v	1, 2, 3, 4, 5, 6, 7, 8, 9	Liu et al. (2006); Malenchak et al. (2011); Lees et al. (2019); Manitoba Hydro (2022a; 2022b)	Developed for a consortium of North American hydropower companies under the guidance of CEA Technologies Inc. See comment above about the availability of CRISSP.
3	Delft3D	Yes	1D	Steady ice processes / Steady hydraulics	iv	8	Oveisy et al. (2015); Mohammadian and Ghobrial (2022)	An ice advection model was developed, coupled with Delft3D, an open-source hydrodynamic and transport model (oss.deltares.nl). The source only deals with ice transport, not ice formation.
4	DEMICE (Discrete Element Method River Ice)	No	2D	Unsteady ice processes / Unsteady hydraulics	i, ii, iv	7, 8	Zhai et al. (2022)	DEMICE has not been available publicly due to a need for further improvement. Drifting ice floes are modeled as discrete elements with coupling between ice motion and flow – it can capture trans-critical flow.
5	DynaRICE	No	2D	Unsteady ice processes / Unsteady hydraulics	iii, iv	5, 7, 8, 9	Shen et al. (2000); Shen et al. (2008); Carr and Tuthill (2012); Kolerski (2018)	Developed by Clarkson University for New York Power Authority and US Army CRREL. It uses the smoothed particle hydrodynamics (SPH) method and simulates transport and jam evolution coupled with flow dynamics and the ice cover is a continuum.
6	HEC-RAS (Hydrologic Engineering Centre - River Analysis System)	Yes	1D	Steady ice Processes / Steady-Unsteady hydraulics	iii, iv	1, 3, 5, 8	Daly et al. (1998); Beltaos and Tang (2013)	A well-known tool used for operational requirements, under any type of hydrological conditions. See also www.hec.usace.army.mil/software/hecras/
7	ICEDYN	No	1D	Unsteady ice processes / Unsteady hydraulics	iii, iv	1, 2, 3, 4, 5, 7, 8	Carson and Groeneveld (1997); Groeneveld et al. (2017); Zare et al. (2019)	Developed by Acres International Limited (now Hatch Ltd.). It is a dynamic version of the 1D steady-state ICESIM model. The model does not directly simulate the degradation of an ice cover in the spring.

8	ICEJAM	Yes	1D	Steady ice processes / Steady hydraulics	iv	8	Flato and Gerard (1986); Healy et al. (1997); Carson et al. (2003)	Developed as a research tool at the University of Alberta, Canada. It calculates the thickness and water surface profiles for a cohesionless, wide channel ice jam with a floating toe.
9	ICEPRO	No	1D	Steady ice processes / Steady hydraulics	ii, iv	2, 3, 5	Carson et al. (2003); Carson et al. (2011)	Owned by KGS. Improved version of ICESIM to include shoving mechanisms. “[T]he model has been used frequently to simulate the evolution of breakup ice jams and their potential effects on water levels.” (R. Carson, written comm. 2023)
10	ICEROUTE	No	1D	Steady ice processes / Unsteady hydraulics	i, iv	1, 2, 3, 8	Petryk (1995)	Developed by Crippen Acres Engrg for Manitoba Hydro, for simulating the formation of hanging dams in Burntwood River. ‘Routing’ refers to the sub-division into ‘ice reservoir’ and ‘ice generating’ segments. Ice accumulation is either through juxtaposition at the surface or below-ice deposition.
11	ICESIM	No	1D	Steady ice processes / Steady hydraulics	iii, iv	1, 2, 3, 4, 5, 7	Petryk (1995); Carson and Groeneveld (1997); Carson et al. (2011); Groeneveld et al. (2017)	Steady-state version of ICEDYN, its sister model. Initially developed by R. Carson in Fortran with Acres International Ltd. for a power generating station on the Nelson River (Alberta, Canada).
12	ICETHK	Yes	1D	Steady ice processes / Steady hydraulics	iv	5, 8	Tuthill et al. (1998)	Developed by Cold Regions Research and Engineering Laboratory (CRREL) to simulate equilibrium ice jam profiles in studies that required the calculation of ice jam affected by stage. Bottom roughness is considered.
13	JJT	No	1D	Unsteady ice processes / Unsteady hydraulics	i, iv	1, 2, 3, 5, 6, 8	Huokuna (1990); Huokuna et al. (2021)	Originally developed in Finland during the River Ice Research project 1985-89 by Consulting Engineers Reiter Ltd., it is a combination of 1D flow dynamics with ice formation and dynamics.
14	KHIONE	Yes	2D	NI	NI	1, 2, 3, 8	Bourban et al. (2018)	KHIONE is a module for TELEMAC, an open-source hydraulics modeling platform. It was based on CRISSP2D. Solar radiations, static vs dynamic border ice formation, frazil clogging of trash racks.
15	MIKE-Ice	No	1D	Unsteady ice processes / Unsteady hydraulics	iii, iv	1, 2, 3, 4, 5, 6, 8, 9	Carson et al. (2007); Thériault et al. (2010); Carson et al. (2011)	MIKE-Ice is a module that plugs in DHI’s (Danish Hydraulic Institute) MIKE-11 software. It was developed in a collaboration between Hydro-Québec, DHI, and LaSalle Consulting (now Lasalle NHC).
16	RHIVER	No	1D	NI	iv	1, 2, 3, 4, 5, 6	Marcotte and Duong (1973); Marcotte (1981; 1984); Petryk (1995)	Developed by Hydro-Québec, this model focuses on thermal exchange and the formation of an ice cover but does not address break-up. Also spelled ‘RIVHER’ in the 1984 source.
17	RICE1D	No	1D	Unsteady ice processes / Unsteady hydraulics	ii	1, 2, 3, 4, 5, 6, 7, 9	Huang et al. (2021)	RICE1D is derived from RICEN and CRISSP1D to enable the simulation of trans-critical flows with rapids and overflow to floodplains.

18	RICE	No	1D	Steady ice processes / Unsteady hydraulics	iv	1, 2, 3, 4, 5, 6, 7	Lal and Shen (1991); Petryk (1995)	RICE was developed to be a more comprehensive river ice model than those available in 1991.
19	RICEN	No	1D	Unsteady ice processes / Unsteady hydraulics	iv	1, 2, 3, 4, 5, 6, 7	Shen et al. (1995); Wang et al. (1995)	RICEN was an improved version of RICE (e.g., supercooling, ice transport, anchor ice, flow resistance due to drifting ice).
20	River1D	Yes	1D	Unsteady ice processes / Unsteady hydraulics	ii, iii, iv	1, 2, 3, 4, 5, 6, 7, 8	Andrishak and Hicks (2008); She et al. (2009); Blackburn and She (2019); Blackburn and She (2023)	Developed by the University of Alberta, used to assess various breakup criteria. It can simulate thermal break-up, also for dynamic break-up, but these functionalities are not included in the released version. It has not been used in any water level management studies but it can simulate water levels under open water and ice cover conditions.
21	River2D	Yes	2D	Unsteady ice processes / Unsteady hydraulics	NI	8	Steffler and Blackburn (2002); Brayall and Hicks (2009); Brayall and Hicks (2012); Lotsari et al. (2019)	Developed by the University of Alberta. It addresses specific ice cover conditions (static ice) for studying fish habitat. It has not been used in any water level management studies but it can simulate water levels under open water and ice cover conditions. More information on www.river2d.ca
22	RIVICE	Yes	2D	Unsteady ice processes / Unsteady hydraulics	i, iii, iv, v	1, 2, 3, 4, 5, 6 (decay), 8	Lindenschmidt (2017); Das et al. (2023); Lindenschmidt (2023)	No capability for the thermal thickening of an ice cover. The user manual states: “The program is oriented mostly towards the formation stage of ice covers and ice jams. The technology in predicting the break-up and movement of previously established ice covers is poor.”
23	RIVJAM	Yes	1D	Steady ice processes / Steady hydraulics	NI	9	Beltaos (1993); Petryk (1995); Healy et al. (1997)	Developed at the National Water Research Institute in Burlington, Canada, RIVJAM models the longitudinal configuration of ‘wide’-type, cohesionless jams of known thickness and water level, and accounting for water seepage at the toe section, including when it is grounded.
24	SIMGLACE	No	1D	Steady ice processes / Unsteady hydraulics	i, iv	1, 2, 3, 5, 6, 8	Petryk et al. (1981); Petryk (1995)	Developed in support of the hydroelectric sector in the 1970s. The thickness of the ice cover is a function of frontal progression, shoving, border ice growth, and erosion under the ice jam.
25	VARY-ICE	No	1D	Steady ice processes / Unsteady hydraulics	ii, iv	2, 3,5	Curi et al. (2011); Curi et al. (2019); Wazney and Carson (2023)	Owned by KGS. Evolution of ICEPRO that “include[s] new logic based on the St. Venant equations and simulation of varying flow conditions.” Although it does not account for break up directly “the model has been used frequently to simulate the evolution of breakup ice jams and their potential effects on water levels.”

2. *Frazil ice generation*: These are crystals that form in a turbulent, supercooled water column (high currents in shallower reaches) below an open water surface, typically during cold nights. That ice is known to block water intakes that are critical to shoreline facilities such as potable water plants and hydroelectric dams. Massive amounts of frazil ice can also obstruct entire river channels.
3. *Border ice*: Ice that develops from the shoreline where current speed is low, and grows laterally toward the center of the river, as a continuous sheet or through the incorporation of drifting ice.
4. *Anchor ice*: This is ice that either grows from or becomes attached to, the river bed – this occurs in a water column that is supercooled.
5. *Ice cover formation*: The establishment of a stable ice cover.
6. *Thermal growth and decay*: Vertical growth (ice cover thickening) at low air temperatures. Decay occurs under high air temperatures, which occurs in the spring and during mid-winter warm spells.
7. *Ice cover break-up*: This is when an ice cover breaks up into pieces in the spring and during mid-winter warm spells.
8. *Ice dynamics for ice jamming/bridging*: This is a general category encompassing any process involved when ice in its various forms gets juxtaposed at the surface (and accumulates below it) as it becomes or has become stationary.
9. *Seepage through the ice mass*: Some models account for the portion of the river flow that percolates through the keel of an ice jam.

5. Conclusion

The ice engineering literature of the past few decades has a considerable number of hydraulic models that simulate river ice dynamics. The motivation behind this paper was a desire to succinctly bring them together in one document. The purpose is to inform researchers who may not be aware of these resources, past and present, as well as to guide decisions of researchers who contemplate venturing into river ice modeling. The paper does not address model capabilities/performance and comparison thereof. For those aspects, the reader is referred to other sources (Healy, 1997; Carson et al., 2003; Carson et al., 2007; Shen, 2010; Carson et al., 2011). For a discussion on model ability to assess climate change's impact on river hydraulics, the reader is referred to Das and Lindenschmidt (2021).

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