NUMERICAL MODELING OF ICE REGIME IN RIVERS

E. I. Debolskaya
Water Problems Institute, Russian Academy of Science, Moscow, Russia

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Summary

Numerical river ice models have become valuable tools for investigating many aspects of river ice. The accuracy of a numerical river ice model, as with all numerical models of physical systems, reflects the accuracy of the model input, the empirical coefficients (or parameters), and the model structure. The model input includes the description of the channel geometry, the time-varying boundary conditions that drive the model, and the initial conditions from which the model starts. The model structure is composed of the numerical discretization of the underlying mathematical equations that describe the physical processes, and the mathematical equations themselves.

1. Introduction

Ice is a significant factor influencing peculiarities of planetary biogeochemical cycles and development of certain ecosystems. Formation of ice cover on the surface of rivers, lakes, reservoirs and seas changes habitat of living organisms, as well as living conditions and economical activity of humans. Ice produced an effect on the operation of hydraulic control structures, locks and dams, hydropower plants, and water intakes. Ice cover increases the channel wetted perimeter, reduces the channel hydraulic radius, and typically increases overall effective channel roughness. The increase in river stage can result in flooding, especially during severe ice conditions or in low-lying areas. This situation is particularly critical downstream of hydroelectric power plants because the risk of ice-induced flooding may require to curtail power production and provide more expensive replacement power. Process of freezing of rivers is characterized by a sequence of ice events beginning from appearance of initial ice crystals of surface or underwater origin and finishing with formation of ice cover. Variety of ice events and time and duration of freezing period are determined by a complex of conditions of heat exchange of water with atmosphere and ground as well as by hydraulic and morphological peculiarities of rivers and physical and mechanical properties of ice forming the cover. Ice formation upon surface of water bodies begins when the temperature of the top water layers decreases to freezing-point leading to forming of underwater ice. Heat emission from water surface becomes larger than heat penetration from water mass. Forecasting stages in ice-covered rivers is a complicated problem because complex interacting processes of heat transfer, ice production, ice transport, river flow, and ice cover formation mechanics need to be accounted for. Use of mathematical modeling in study of dynamics of sub-ice fluxes brings forth series of strict requirements to problem definition and ability of legible determining of temporal and spatial scales of processes. These requirements are needed most of all for optimal choice of model dimensionality and applied equations.

2. Ice Jams

Ice jams formed in rivers are a very complicated physical phenomenon. To uncover the formation and development mechanism of ice jams, multi-disciplinary knowledge involving thermodynamics, solid mechanics, hydrology, hydraulics, and river dynamics is needed. Many countries face the problems caused by river ice jams, such as China and Japan in Asia, 82 % of North America, major part of the former Soviet Union, and Norway, Sweden and Finland in North Europe. Due to the presence of ice jams, the effective discharge area of a river decreases. This will cause the increase of upstream water level and may also result in flood and ice damage to land, structures, river transportation and other properties. Meanwhile, ice jams can also cause the interruption of water supply by blocking the intake pipes. Ice jams also scour the bank and bed of a river, which causes the disclosure of buried facilities and damage to ecological environment

Ice jams constitute accumulation of ice material in river-bed that hampers effective cross-section, causing uprising of water level and sometimes leading to significant flooding of surrounding areas. Jams are often forming because of water increase during spring floods. In case of winter warming jams may form during winter as well.

One of main features of jam formation is its multifactor nature, i.e. dependence from a whole set of conditions. Non-simultaneous break of ice along the river length and following difficulties in transport of ice material are main causes of jam formations. Non-simultaneity of breaking is determined by differences in thickness and durability of ice on different river sections. Difficulties in transport of ice material are related to morphometric characteristics of river (changes of longitudinal profile of river bed, river channel narrowing, bends, islands), stopping of moving ice near undisturbed edge of ice cover or near large ice field that corked up the pass.

The necessary condition for ice jam forming on river is a presence of undisturbed ice cover that hinders transport of fragmented ice down the stream. The water velocity during the break must be significant enough (0.6 – 0.8 m/s and more). At this condition hummocking, push-unders, and shearing of ice may occur. Process of jam formation is intensified with presence of any kind of river-bed obstacles: sudden turns, islands, debris cones. Combinations of different kinds of river-bed obstacles like abrupt turn along with narrowing of channel, decrease of slope along with islands and so on are especially favorable for jam forming. At the river reaches where morphometric conditions for ice jamming exist, the jam formation possibility is determined by hydrometeorological conditions of autumn or spring periods. At the same time, it is possible to a certain degree of accuracy to identify the places where ice jams form every year. In spring jams often form in places of sludge ice accumulations during autumn freezing. During winter sludge ice densities, freezes together with ice acquiring greater durability and becomes a nidus of spring ice jams.

Figure 1. Ice jam on the North Dvina River (the photo from personal archive of the author)

Ice jams can be classified by their forming mechanism as “hummocking jams” and “dive-under jams”. The first kind of jams is characterized by strength of ice cover, head part of which is under constant impact of freely floating ice fields and suffers intensive crushing and hummocking. Under pressure of large block of ice lesser blocks are pressed out upon undestroyed solid surface and remain there. Other, much lesser ice blocks crawl atop of them. The process is repeated many times. Hydrodynamic stress caused by flood water is the active factor of destroying ice jam, when during intensive uprise of water level after forming of along-shore cracks ice cover breaks apart into several fields and moving starts in places of stress concentrations.

Second type of jams is typical for areas with increased water velocities and sloping water surface before the jam. Accumulation of ice as a result of diving under is usual mostly for sludge ice jams near the edge of ice cover, tail water of hydroelectric power stations and in cases of increased transport of ice masses coming from upper river sections during ice break.

While in-situ measurement are practically impossible during disastrous events, laboratory modeling in addition to usual troubles for the open streams faces a problem of modeling of crumbling ice cover. Thus forecast methods based on mathematical modeling are primary in case of extreme ecological situations caused by ice effects. It is possible in numerical experiments to calculate large amount of probable variants of future development of situation using different combinations of parameters that lead to jam formation.

3. One-dimensional Modeling

3.1 1-D Models of Ice Regime in Rivers

In the context of hydraulic one-dimensional approximation, a major difference between sub-ice and open fluxes is an additional resistance. Nevertheless, this approximation allows us to forecast dynamics of ice cover (its deformations and possible destructions), since spatial and temporal scales of mechanical changes of ice correspond to changing scales of integral characteristics of the flux. Within the bounds of one-dimensional approximation can be also solved tasks of ice jams origin. In a simplified model (Berdennikov V.P., 1962) for solving the task of floating ice transport without taking wind influence into consideration, river with sludge ice is considered as two-layered flow by analogy with suspension flow with lesser density of top layer comparing to bottom one. As a result, river flow with sludge ice is characterized with certain differences in velocities of top and bottom layers.

In models of distribution of jams for wide rivers (Berdennikov V.P., 1967, Beltaos S., 1983, Kennedy J.F., 1975) stability of ice formations is estimated with methods based on theory of bulk solids. Models represent a system of equations of balance of forces affecting the gathering of ice blocks, hydraulic of sub-ice water flow and ice balance on calculated section.

A one-dimensional mathematical model for river ice processes called RICE (Lal, A.M.W. and Shen, H.T., 1991) is developed for simulating ice processes in rivers. In the river hydraulics component, the flow condition is determined by an implicit finite-difference solution of one-dimensional unsteady flow equations. In the thermal component, distributions of water temperature and ice concentration are determined by a Lagrangian-Eulerian solution scheme for equations of transport of thermal energy and ice. A two-layer formulation is introduced to model the ice transport. In this formulation the total ice discharge is considered to consist of the surface ice discharge and the discharge of suspended ice distributed over the depth of the flow. The effect of surface ice on ice production, as well as the formation of skim ice and border ice, is included. The dynamic formation and stability of the ice cover is formulated according to existing equilibrium ice jam theories with due consideration to the interaction between the ice cover and the flow. The undercover ice accumulation is formulated according to the critical velocity criterion. The growth and decay of the ice cover is simulated using a finite-difference formulation applicable to composite ice covers consisting of snow, ice and frazil layers.

Over 30 years ago, the Corps of Engineers' Hydrologic Engineering Center (HEC) formulated the first version of the program known as HEC-2 for calculating the hydraulics of open-channel flow (U.S. Army 1990). In an effort to model the effect of an ice cover, a utility program called ICETHK (Tuthill, A.M., et al., 1998) was developed at CRREL to be used in conjunction with HEC-2. More recently, the HEC-RAS model (for River Analysis System) was developed by the Hydrologic Engineering Center as a replacement for HEC-2. HEC and CRREL collaborated to include river ice as an integral part of the structure of the new model. As such, HEC-RAS (U.S. Army, 1998) overcomes several limitations that exist in ICETHK, and it applies to a wider variety of river ice situations. ICETHK is a useful engineering tool, since many flood studies and hydraulic design projects require the calculation of ice-affected stages. Before the development of ICETHK, the calculation of ice-affected backwater profiles using HEC-2 was painstaking, requiring many iterations. The model has two strong points. First, ICETHK is used in conjunction with HEC-2, the most commonly used backwater model in the United States, and river geometry data in the HEC-2 format are widely available. Second, ICETHK is designed to help the user understand ice jam processes and is relatively easy to use.

The HEC-RAS model of river hydraulics contains code that enables the user to model ice-covered channels at two levels. The first level applies to an ice cover with known geometry. In this case, the user specifies the ice cover thickness and roughness at each cross section. Different ice cover thickness and roughness values can be specified for the main channel and for each overbank, and both the thickness and roughness can vary along the channel. The second level addresses a wide-river ice jam. In this case, the ice thickness is determined by an ice jam force balance. The ice jam can be confined to the main channel or can include both the main channel and the overbanks. The material properties of the wide-river jam can be selected by the user and can vary from cross section to cross section. The user can specify the hydraulic rough-ness of the ice jam, or HEC-RAS will estimate the hydraulic roughness on the basis of empirical data.

RICEN (Shen et al. 1995) - this is an updated version of the one-dimensional river-ice simulation model RICE. The model consists of two major parts: (1) an unsteady flow model for a channel network with ice; (2) a thermal and ice condition simulation model.

The model simulates the water-temperature variation along the river, including supercooling; frazil-ice concentration; anchor ice growth, decay, and release; surface ice transport; ice-cover progression; undercover ice transport, deposition, and erosion; thermal growth and decay of ice covers; and ice-cover stability.

Since the development of the RICE model it has been applied to many rivers. The CRISSP1D model in the developed Comprehensive River Ice Simulation System (CRISSP) was developed based on the RICE model and its newer versions (Lal and Shen 1991, Shen et al. 1995). The improvements made in CRISSP1D include the extension of the hydraulic component to be applicable to river networks with internal structures and mixed flow conditions, improved formulations on freeze-up ice discharges, undercover transport, cover stability/secondary consolidation, and breakup. Other modifications were made to make the model more robust and capable of simulating more complicated river systems. The updated model allows the user to have multiple weather stations for a given river systems. The weather data used in the ice simulation for a given reach is estimated based on the distance of that reach to the nearest weather stations. The boundary condition subroutine has been modified to allow different types of hydraulic boundary conditions and multiple upstream/downstream boundaries. Multiple ice boundary conditions are also allowed in the model. For example, it may have two upstream boundaries both with ice floes coming into the river systems. The water temperatures and ice concentrations for each of those boundaries may be different. At channel junctions, the ice discharge is distributed based on the flow distribution.

The CRISSP1D model (Chen F., 2006) can simulate unsteady flows in single channel rivers or complex networks of interconnected channels, coupled with in-channel hydraulic controls (such as a gate, weir, bridge or a combination of these structures). A four-point implicit finite difference method is used for the unsteady flow simulation. A stream-tube method is used to calculate the transverse flow distribution in the channel. This flow distribution can be used in various parts of the ice simulations, such as in border ice formation, and frazil ice discharge in branched channels.

Variations of water temperature, frazil generation, and the formation of surface ice runs during freeze-up are closely related phenomena. Frazil ice production over the depth of the flow occurs when the water temperature is supercooled. In open water reaches, frazil ice particles in the suspension will grow both in size and number due to the continuous surface heat loss. Under the influence of the buoyant velocity, some of the frazil particles may move up against the turbulent mixing to the water surface to form surface ice runs. Turbulent mixing can also carry frazil particles to the channel bottom contributing to anchor ice growth. In the meantime, the latent heat released due to frazil production tends to raise the water temperature to 0°C. This recovery of water temperature is enhanced by the insulation effect of the surface ice pieces and the latent heat released due to the thermal growth of anchor ice. Shen et al. (1995) formulated these processes along with a two-layer ice transport model for surface and suspended ice runs. In the two-layer formulation, the ice discharge in the river is considered to consist of surface ice and suspended ice discharges. The dynamics of the surface ice transport is neglected. Based on the simulated flow and thermal conditions, border ice and skim uce runs during freeze up are simulated. The skim ice run and the static border ice development are simulated based on the formulation of Matousek (1984).

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Biographical Sketch

Elena I. Debolskaya is a Doctor of Science (Engineering), Senior Research Scientist, Institute of Water Problems of Russian Academy of Sciences. He is author about 90 publications. His field of scientific interests is mainly Hydrology, Marine Physics, Hydrodynamics, Turbulence, Ice-covered Flow Dynamics, Mathematical Modeling