A ONE-DIMENSIONAL COMPREHENSIVE RIVER ICE MODEL

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ABSTRACT
Since the development of the original RICE model, it has been improved and applied to many rivers. Recently, significant improvements have been made to the CRISSP1D model of the recently developed Comprehensive River Ice Simulation System (CRISSP). In this paper, the improvements made from RICE to CRISSP1D will be presented along with a sample field application.

KEY WORDS: CRISSP1D; Numerical modeling; River Ice; Freeze-up; Break-up.

INTRODUCTION
Since the development of the RICE model (Lal and Shen 1991), it has been applied to many rivers. Many of the concepts and formulations in the model have been adopted by others, e.g. Daly (2002) and Yang et al. (2002). The CRISSP1D model in the recently developed Comprehensive River Ice Simulation System (CRISSP) was developed based on the RICE model and its newer versions (Shen et al. 1991, Lal and Shen 1991, Shen et al. 1995). In this paper the improvements made in CRISSP1D will be discussed and a sample application will be presented.

The improvements made in CRISSP1D include the extension of the hydraulic component to be applicable to river networks with internal hydraulic 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 system. 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 system. 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.
RIVER HYDRAULICS

The CRISSP1D model 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. The Local Partial Inertial (LPI) technique (Fread et al., 1996) is used to enable the model to simulate mixed flow conditions. A stream-tube method (Shen and Ackermann, 1985) 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 and surface ice discharge in branched channels.

THERMAL-ICE TRANSPORT PROCESSES

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. All of these inter-related processes need to be formulated and modeled in a systematic manner. 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:

\[ Q_d' = AUC_v \]  
\[ Q_s' = B_o U_s C_a h_e \]

in which, \( Q_d' \), \( Q_s' \) = volumetric suspended and surface ice discharge rates, respectively; \( A = \) flow cross sectional area; \( B_o = \) open water width; \( C_v = \) cross-section averaged ice concentration in the suspended layer; \( C_a = \) width-averaged area concentration of the surface ice; \( h_e = h_i + h_f (1 - e_f) \) = equivalent thickness of surface ice floes; \( h_i = \) thickness of the solid portion of the surface ice elements; \( h_f = \) thickness of the frazil accumulation on the underside of surface ice elements; \( e_f = \) porosity of the frazil ice portion of surface ice elements; \( U = \) cross-section-averaged flow velocity; and \( U_s = \) cross-section averaged surface ice velocity. In the one-dimensional model, the surface ice velocity is approximated by the cross-section averaged...
flow velocity. The dynamics of the surface ice transport is neglected. Thermal and ice transport processes that govern variations of surface and suspended concentrations, velocity, and thickness of ice in Eqs. 1 and 2 are closely inter-related. Besides the ice production, melting and mass exchanges between the two layers, the rate of change of the suspended ice concentration, $C_v$, is affected by the rate of frazil accretion on the anchor ice. In covered reaches, the surface ice discharge is transported as a cover load on the underside of the cover or frazil jam.

The conservation of thermal energy for the ice-water mixture in the suspended layer can be written as (Shen et al. 1995)

$$\frac{De_T}{Dt} = \frac{1}{A}(\phi_{ss} - \phi_{sk}) + \rho_i L_i E$$

(3)

in which, the material derivative \( \frac{D}{Dt} \) is \( \frac{\partial}{\partial t} + \vec{U} \cdot \nabla \); \( e_T = C_p \rho(1 - C_v)T_w - \rho_i C_i L_i \); \( T_w \) = cross section–averaged water temperature, \( \rho \) and \( \rho_i \) = mass density of water and ice, respectively; \( C_p \) and \( L_i \) = specific heat of water and latent heat of fusion, respectively; \( \phi_{ss} \) = rate of heat gain through top and bottom boundaries; \( \phi_{sk} \) = rate of heat loss through top and bottom boundaries, and \( E \) = net volumetric rate of loss of frazil due to mass exchange with the surface layer and the anchor ice layer.

Frazil and anchor ice growths require the supercooling condition. The supercooling condition can be simulated by including the heat exchange between water and ice in the conservation of thermal energy in water, instead of relying on an empirical method. Using Eq. 3 the following water temperature equation can be obtained:

$$\frac{D(C_p \rho(1 - C_v)T_w)}{Dt} = \frac{1}{A}(\phi_{ss} - \phi_{sk}) + \rho_i L_i \frac{DC_v}{Dt}$$

(4)

Considering that the change in suspended ice concentration can be caused by both thermal growth and mass exchanges with surface ice and anchor ice, i.e.

$$\frac{DC_v}{Dt} = \frac{DC_v^g}{Dt} - E$$

(5)

in which, \( \frac{DC_v^g}{Dt} \) = rate of increase of suspended ice concentration due to thermal growth.

The above formulation for thermal-ice transport processes has been presented by Shen (2000). A Lagrangian parcel method is used to solve the system of thermal-ice equations.

**Border ice simulation**

Based on the simulated flow and thermal conditions, border ice and skim ice 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). Dynamic border ice growth due to hydraulic accumulation is
simulated with the empirical formulation of Michel et al. (1980).

Ice jamming/bridging
Since ice dynamics are not considered in the surface ice transport simulations, ice jamming/bridging cannot be simulated analytically in CRISSP1D. However, the user may specify the time and location of bridging or let the model determine when and where a jam/bridge will form based on pre-defined jamming conditions. The user has two options: 1) User may define a maximum ice discharge for each downstream cross-section of a reach. If the simulated ice discharge is greater than the user defined maximum ice discharge capacity at that location, jamming will occur; 2) If the thickness of the surface ice element is greater than a certain fraction of the river depth, and the rate of increase of the thickness of the surface ice is greater than a specified value, jamming will occur.

Undercover transport and frazil jam simulation
Ice discharge from an open water reach upstream of an ice cover could transport and accumulate on the underside of the cover in the form of a frazil jam or hanging dam. This phenomenon is simulated based on the ice transport capacity theory (Shen and Wang 1995).

ICE COVER BREAKUP
The breakup of a river ice cover can generally be classified as a thermal breakup or a mechanical breakup. In a thermal breakup the ice cover melts in place with no significant movement. Mechanical breakup of a river ice cover is due to the fragmentation of a floating cover by hydraulic and mechanical forces associated with rapid changes in river discharge and water level. Thermal melt out is included in the simulation of the thermal growth and decay of the ice cover. However, an analytical formulation of the mechanical breakup mechanisms is not available for long-term prediction of breakup ice runs. In this model, the strength dominant breakup of an ice cover is modeled by comparing the compressive stress and strength of the cover to determine the cover stability, as did in the RICE model (Lal and Shen 1991). Additional empirical methods are included in CRISSP1D to simulate the occurrence of breakup. In CRISSP1D the following options are available to simulate mechanical breakups, which will result in breakup ice runs. The user may also specify the stranding loss of the ice run resulting from cover breakups.

Option 1: User may artificially set up breakup times and locations.
Option 2: Breakup is initiated for a specified stage
In this category, user has 3 choices: 2a, 2b and 2c.

\[ H' - H_{ref} > \Delta H_{cr} \]  \hspace{1cm} (6)

where \( H' \) = the water level at breakup time. \( H_{ref} \) = a user specified freeze-up stage, above which the ice breakup may occur. \( \Delta H_{cr} \) = a user specified water depth above the freeze-up level.

When stage increases, options 2a and 2b can be used.
2a. \( \Delta H_{cr} = 0 \), user only specifies \( H_{ref} \).
2b. $\Delta H_{cr} > 0$, user gives both $H_{ref}$ and $\Delta H_{cr}$.

2c. Sometimes breakup occurs when water level decreases from $H_{ref}$. The user may want to use the following criteria.

$$|H' - H_{ref}| > \Delta H_{cr}$$  \hspace{1cm} (7)

Option 3: Breakup is initiated when a specified discharge is reached.

3a. Use the following criteria when discharge increases.

$$Q' - Q_{ref} > 0$$ \hspace{1cm} (8)

where $Q'$ = the discharge at breakup time. $Q_{ref}$ = a user specified reference discharge, above which the ice breakup may occur.

3b. Sometimes breakup occurs when discharge decreases from $Q_{ref}$. The user may want to use the following criteria.

$$|Q' - Q_{ref}| > \Delta Q_{cr}$$ \hspace{1cm} (9)

where $\Delta Q_{cr}$ = a user specified change of discharge during.

Option 4: The model determines when and where the ice cover breaks based on the maximum freeze-up level.

$$\frac{\Delta H}{t_{ice}} = \frac{H' - H_{peak}}{t_{ice}} > C_{bk}$$ \hspace{1cm} (10)

where $t_{ice}$ = ice cover thickness at time $t$; $H'$ = water level at breakup time $t$; $\Delta H$ = accumulated water level increase from $H_{peak}$ at time $t$; $C_{bk}$ = a parameter determined by the user as input data. This criteria is illustrated in Fig.1.

4a. In addition to Eq. (10), the model determines when and where the ice cover breaks based on the rate of change of stage.

$$\frac{dH}{dt} > R_{hk} \text{ for a given time period}$$ \hspace{1cm} (11)

where $\frac{dH}{dt}$ = rate of change of stage.

4b. Model determines when and where ice cover breaks based on the rate of change of discharge.

$$\frac{dQ}{dt} > R_{gk} \text{ for a given time period}$$ \hspace{1cm} (12)

where $\frac{dQ}{dt}$ = the rate of change of discharge.
Jasek et al. (2005) used the model to examine the storage release due to cover breakup using the above criteria.

![Figure 1 - Ice cover breakup criteria.](image)

**SAMPLE APPLICATION**

An example of a field application, a 813 km reach of the Peace River, from Peace Canyon to Fort Vermillion, in northern British Columbia and Alberta (Figure 2), is presented here to demonstrate the applicability of the CRISSP1D model. Fig 3 shows the comparisons of the model results with the field observations of surface ice floe concentration (Andres 1995). Table 1 shows the comparisons of the model results with the observed ice floe thicknesses. Figures 4 and 5 compare the model results for ice front and water levels with field data. More detailed simulation conditions are given in Chen et al. (2005), and are not presented here due to page limitations.
Table 1 - Ice Floe Thickness ($a V_b = 2 \times 10^{-4}$ m/s, $\beta = 0.0$ 1/s).

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Figure 3 – Surface Ice Concentration Ca

Figure 4 – a) Comparison of ice front locations; b) Water levels at Town of Peace River.

ACKNOWLEDGEMENTS

The study was supported by CEATI Project 0401. The writers would like to thank the CRISSP Technical Committee for valuable discussions. Thanks are also due to Dave Andres and Martin
Jasek for field data and discussions on Peace River simulations.

REFERENCES


