# Application of Numerical Simulation Methods in River Ice Jam Water Level Simulation: A Case Study of the Sanhuhekou Bend Section of the Yellow River (Postprint)

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## Abstract

Using the open-source river ice numerical model RIVICE, this study simulates ice jam water levels during the ice breakup period from 2008 to 2010 in the bend section at the Sanhu River mouth of the Yellow River, and conducts sensitivity analysis of model parameters. Flow rate, water level, ice thickness, and other data used in the study were all obtained from hydrological yearbooks. Results demonstrate that the RIVICE model is highly feasible for simulating ice jam water levels during the ice breakup period. Ice jam backwater levels exhibit high sensitivity to upstream boundary flow rates, which underscores the importance of hydraulic engineering regulation. Through numerical modeling of ice jam water levels and evolution prediction, this study provides valuable references for hydraulic engineering regulation and ice flood prevention.

## Full Text

### Numerical Simulation Method for River Ice Jam Water Level: A Case Study of the Sanhuhekou Bend Reach of the Yellow River

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**Abstract**

This study employs the open-source numerical river ice model RIVICE to simulate ice jam water levels during the break-up period in the Sanhuhekou bend reach of the Yellow River, followed by sensitivity analysis of model parameters. Flow discharge, water level, and ice thickness data used in the research were obtained from the Hydrological Yearbook. Results demonstrate that the RIVICE model is highly feasible for simulating ice jam water levels during the breakup period. The backwater level of ice jams shows high sensitivity to upstream boundary discharge, underscoring the importance of hydraulic engineering regulation. This research provides a valuable reference for water conservancy project management and ice flood prevention through numerical simulation and evolution prediction of ice jam water levels.

**Keywords:** Sanhuhekou bend reach of the Yellow River; ice jam water level; RIVICE model

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### 1.3 Ice Jam Calculation Theory and Methods

The RIVICE model, developed by Environment and Climate Change Canada, is an open-source tool that couples one-dimensional hydrodynamic and ice dynamic processes through a bidirectional loose coupling approach. The model solves the Saint-Venant equations using an implicit finite difference scheme while incorporating river ice dynamics. RIVICE can simulate various river ice processes including frazil ice formation, border ice evolution, ice cover formation, ice accretion at the ice cover leading edge, anchor ice, ice transport, ice cover melt and breakup, ice jams, and hanging ice dams. Previous studies have successfully applied this model to ice jam flood forecasting for Canadian rivers such as the Athabasca and Peace Rivers, with results indicating good simulation performance and accurate estimation of backwater profiles during ice jam events. This study utilizes three modules of RIVICE—hydrodynamics, hydraulic roughness, and ice cover forces—to simulate ice jam flood processes at the Sanhuhekou bend of the Yellow River.

**1.3.1 Hydrodynamic Simulation** Although the river channel is covered by ice, the flow is still treated as open channel flow, ignoring ice cover pressure. Similar to conventional hydraulic models, RIVICE employs the Saint-Venant equations to calculate one-dimensional unsteady flow in open channels. Since the channel is generalized as rectangular without lateral inflow, the Saint-Venant equations are simplified as follows:

Continuous equation: $B\frac{\partial}{\partial t} + 2\frac{1}{Ag} =$

Motion equation: $-(1-$

where: $B$ is channel width (m); $x$ is distance (m); $t$ is time (s); $z$ is water level (m); $Q$ is discharge ($m^3/s$); $A$ is flow area ($m^2$); $g$ is gravitational acceleration

(9.8 m/s$^2$); $v$ is flow velocity (m/s); $F$ is Froude number; $K$ is conveyance coefficient; and $A_z$ is the rate of change of flow area with water level. The implicit finite difference scheme is used to solve these equations and obtain flow conditions at each computational cross-section at each time step.

**1.3.2 Hydraulic Roughness** In ice-covered river reaches, flow experiences resistance from both the riverbed and the underside of the ice cover. The conveyance coefficient $K_i$ under ice cover is calculated using a modified Manning' s formula:

$$K_i = \frac{1}{n_c}$$

where $n_c$ is the composite Manning' s roughness coefficient for the bed and ice cover; $R_c$ is the hydraulic radius under the ice cover $[R_c = A/(P_b + P_i)]$; $P_b$ is the wetted perimeter of the channel; and $P_i$ is the wetted perimeter of the ice cover. The composite Manning' s roughness coefficient $n_c$ is calculated using the Sabaneev formula:

$$n_c =$$

The riverbed Manning' s roughness coefficient $n_b$ is calibrated as a parameter using open-water period floods and remains constant during ice jam simulation. For the ice cover Manning' s roughness coefficient $n_i$, the model adopts the Nezhikhovskiy formula, which treats ice cover roughness as a function of ice thickness:

$$n_i =$$

**1.3.3 Ice Cover Thickness** Forces acting on the ice cover include: $F_T$, the thrust force from water flow on the ice cover leading edge; $F_D$, the drag force from water flow under the ice cover; $F_W$, the component of ice cover weight along the slope; $F_F$, friction between the ice cover and river banks; and $F_I$, internal resistance of the ice cover. For this spring break-up period simulation, the cohesion force $F_C$ from ice cover frozen to banks is negligible and therefore ignored.

The thrust force $F_T$ from water flow on the ice cover leading edge is calculated as:

$$F_T =$$

where $d_u$ is water depth upstream of the ice cover leading edge (m); $d_d$ is water depth downstream of the ice cover leading edge (m); $v_d$ is width-averaged velocity under the ice cover leading edge (m/s); $B$ is ice cover width (m); and $\gamma$ is the unit weight of water (9800 N/m$^3$).

The drag force $F_D$ from water flow under the ice cover is:

$$F_D = \gamma d S n_i$$

where $S$ is hydraulic gradient; $d$ is water depth under the ice cover (m); and $A_i$ is the underside area of the ice cover (m$^2$).

The component of ice cover weight along the slope $F_W$ is:

$$F_W = \gamma_i V_o S$$

where $\gamma_i$ is the unit weight of ice (9020 N/m$^3$); and $V_o$ is the volume of ice cover between banks (m$^3$).

The friction force between ice cover and river banks $F_F$ is:

$$F_F =$$

where $f$ is the compressive stress of border ice; $K$ is a coefficient representing the ratio of transverse to longitudinal stress in the ice cover; $\phi$ is the friction angle between ice cover and banks; and $l$ is the distance between cross-sections.

The internal resistance of the ice cover $F_I$ is:

$$F_I =$$

where $e$ is ice cover porosity; and $K$ is a strength coefficient, both calibrated as parameters using ice jam flood data.

If $F_T + F_D + F_W - F_F < F_I$, meaning internal resistance can withstand external forces, incoming ice will accrete at the ice cover leading edge and extend upstream, forming a surface ice jam. If $F_T + F_D + F_W - F_F > F_I$, meaning internal resistance cannot withstand external forces, incoming ice will cause shoving and thickening of the ice cover until internal resistance can balance the external forces, forming an ice dam.

### 1.4 Model Parameters and Sensitivity Analysis

Sensitivity analysis of parameters is crucial for understanding their impact on model results. For this simulation, analyzing the sensitivity of ice jam water level to parameters can reveal the main controlling factors of ice jam flood formation and provide a scientific basis for ice flood prevention. This study employs traditional local sensitivity analysis for parameters and boundary conditions. Based on 2018 data, while keeping other parameters constant, each parameter or boundary condition was increased by 10% to calculate the change in backwater level at the upstream boundary. Parameter sensitivity is expressed by:

$$S_Y = \frac{Y - Y_0}{Y_0} \times 100\%$$

where $Y_0$ is the baseline value of the state variable (water level at the upstream boundary); $Y$ is the modified value; $X$ is the parameter; and $S_Y$ is the sensitivity index of variable $Y$ to parameter $X$.

### 2.1 Open-Water Period Model Calibration

First, to validate the hydrodynamic component of the model and calibrate parameter $n_b$, three flood events were selected for calibration and two for validation. The results show that when $n_b = 0.012$, the simulation performs well. Figure 3 presents the calibration and validation results for five flood events, demonstrating good agreement between simulated and observed water levels. Statistical analysis shows that the deterministic coefficient for water level is 0.95, and for discharge is 0.90. This proves that the RIVICE hydrodynamic component can effectively simulate floods under ice-free conditions, providing a solid foundation for ice jam flood simulation.

### 2.2 Break-Up Period Model Calibration

The processes of ice cover breakup, ice run, ice jamming, and ice jam release during the break-up period involve considerable randomness, posing a significant challenge for simulating the resulting backwater. Since the model cannot precisely capture these complex changes, three ice jam flood events from the 2018 break-up period were selected to validate the feasibility of RIVICE for simulating ice jam backwater levels.

The sudden increase in discharge during break-up causes ice cover fracture and mechanical thickening. To better forecast ice jam backwater height under specific ice conditions and discharge rates, the upper boundary condition was set as constant inflow discharge and the lower boundary as constant water level. Since temperature variation was not considered, each simulation lasted 10 days. Three ice jam flood events were used to calibrate and validate the RIVICE model, with simulated water levels under the same discharge during open-water periods used for comparison. Table 1 shows the parameter and boundary values for each simulation.

The simulation included two boundary conditions (upstream discharge $Q$ and downstream water level $W$) and six parameters. The riverbed Manning' s roughness coefficient $n_b$, parameter $n$ for calculating ice cover underside Manning' s roughness, parameter $K$ for calculating ice jam-bank friction, parameter $K$ for calculating ice jam internal resistance, and ice jam porosity $e$ remained constant across simulations. Ice jam leading edge thickness $F_T$, downstream intact ice cover thickness $h$, and ice volume increment $V$ varied annually based on hydrological yearbook data. The simulated reach length was 9.89 km with 20 computational cross-sections, and the ice jam location $x$ was set at the 10th cross-section where the bend constricts.

Figure 4 compares simulated and observed water level hydrographs during the 2018 break-up period with simulated water levels under the same discharge during open-water conditions. Although simulated water level changes are relatively smooth while observed changes are more complex, the trends are consistent. After March 18, when discharge increased sharply to 1800 $m^3/s$, the water level rose dramatically, which the model could not capture well. Statistical analysis shows maximum errors of 0.035 m and 0.182 m, with a deterministic coefficient of 0.85. The results demonstrate that RIVICE can effectively simulate water level rises caused by river ice jams during spring break-up. Compared with open-water simulations, ice jam-affected water levels average 1.4 m higher, highlighting the severity of ice jam floods and the importance of accurate simulation and forecasting.

### 2.3 Sensitivity Analysis Results

Sensitivity analysis results (Figure 5) show that the upstream boundary water level is most sensitive to discharge $Q$, demonstrating the importance of upstream water conservancy project regulation during break-up. Next in sensitivity are parameter $n$ for calculating ice cover Manning' s roughness and downstream boundary water level $W$. Increased discharge not only directly raises water levels but also causes mechanical thickening of accreted ice pans. Increased ice cover roughness enhances flow resistance, and higher downstream water levels raise the base for backwater formation—all critical factors in ice jam flood generation. Increased upstream ice supply creates more severe ice jams and higher upstream water levels.

Parameters for riverbed roughness, ice cover leading edge thickness, and downstream intact ice cover thickness show low or no sensitivity. Due to significant differences in discharge and water level boundary conditions, ice thickness, and upstream ice supply among the three ice jam events based on observed data, parameter and boundary condition sensitivities also show considerable variation. In 2018, the ice jam initiation location moved downstream, causing higher upstream backwater levels, while the opposite occurred in 2019. This fully demonstrates the chaotic and random nature of ice jam events and their resulting flood levels.

## 3 Conclusions

This study applied the open-source river ice model RIVICE to simulate ice jam water levels during spring break-up in the Sanhuhekou bend reach of the Yellow

River. The model was validated using floods from both open-water and break-up periods, and sensitivity of model parameters and boundary conditions was analyzed. The following conclusions are drawn:

1) Under the same discharge, ice jam occurrence causes significantly higher water levels compared to ice-free conditions. The RIVICE model effectively simulates water level increases caused by ice jams by numerically representing ice jamming in river channels, mechanical thickening due to forces, and ice resistance to flow.

2) With known upstream boundary discharge, RIVICE can feasibly simulate ice jam backwater levels in river channels. This can provide scientific basis for regulating upstream water conservancy projects to ensure reasonable discharge without causing severe downstream ice jam floods. In the absence of water conservancy projects or when regulation is impossible, it can provide effective early warning of ice jam flood severity caused by upstream inflow.

3) Ice jam backwater levels are most sensitive to discharge, proving the importance of upstream water conservancy project regulation during break-up. Therefore, the effectiveness of water conservancy project regulation schemes is crucial for ice jam flood prevention and control.

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*Note: Figure translations are in progress. See original paper for figures.*