22nd IAHR International Symposium on Ice
Singapore, August 11 to 15, 2014

A river-ice model for Wanjiazhai reach of the Yellow River

Fan Lin, Mao Zeyu, Bao Jun, Yuan Jing, Ma Zhuang
(Department of Hydraulic Engineering, Tsinghua University, Beijing 10084, China)
l-fan11@mails.tsinghua.edu.cn

A river ice model for the reach of Yellow River from Sanhuhekou to Wanjiazhai is presented. This model mainly consists of three coupled parts. They are hydraulics model, thermal model, and ice model. The model was first validated with the measured data from Toudaoguai Hydrological station upstream of the Wanjiazhai Reservoir, since Toudaoguai is an important control section of the Yellow River for flood control, ice flood control, and water regulation. Using the validated model, the influence of Wanjiazhai Reservoir's operation on the discharge capacity of Toudaoguai Section was investigated. Through the analysis of Wanjiazhai Reservoir in five different flow conditions, the critical water level value of Wanjiazhai Reservoir was proposed. If this critical water level is exceeded, the flow at the Toudaoguai would be affected. The mechanism of this influence was also analyzed.

Key words: Wanjiazhai; Toudaoguai; flow; ice cover; river ice model

Proceedings of the 22nd IAHR International Symposium on Ice

ISBN: 978-981-09-0750-1
doi:10.3850/978-981-09-0750-1_1103

1. Introduction

The 820 km Ning-Meng reach of the northern part of the Yellow River, may produce ice jam flooding and damage to structures. Accurate forecast of the ice conditions of that reach is of great importance to avoid potential disasters. In this paper, a one-dimensional mathematical model for the ice condition of the reach from Wanjiazhai Reservoir to Sanhuhekou, or the San-Wan reach (Figure 1) is presented. Numerical experiments were conducted using the model to analyze the impact of the operation of the reservoir on the ice condition. The main reason of the low flow capacity of the river reach during the freeze-up period was also examined.

2. The study reach

The length of the study reach（San-Wan reach）is 414 km. The observed data from the Toudaoguai Hydrological station is used to examine the calculation results of the model. Toudaoguai cross-section lies at the end of backwater zone of the Wanjiazhai Reservoir. The breakup occurs every year from upstream to downstream in the spring, and the ice run generated by the breakup will flow through Toudaoguai to the downstream. The rise of the water level in the reach from Wanjiazhai Reservoir to Toudaoguai (Tou-Wan reach), which is caused by the backwater of the Wanjiazhai Reservoir, may lead to decrease of ice velocity and the increase of ice concentration. The obstruction of the bridge and the piers may further result in ice jams.

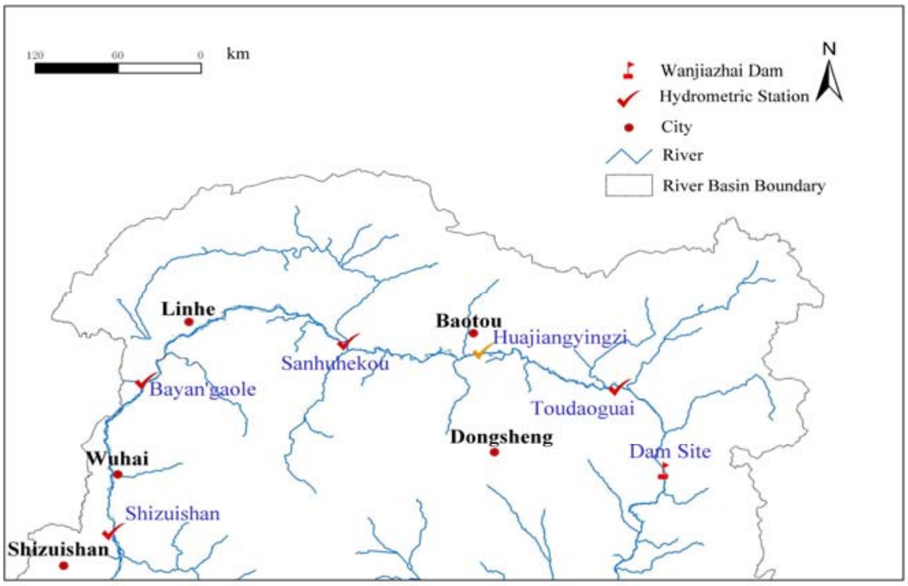


Figure 1. Yellow River from Sanhuhekou to Wanjiazhai

Wanjiazhai Reservoir is mainly built to provide water supply for the Wanjiazhai Water Control Project along with hydroelectric power generation and flood and ice-jam control. Freeze-up in the Tou-Wan reach may cause serious ice jams and resulting in rise of water level in the upper portion of the San-Wan reach. Protecting Wanjiazhai Reservoir from being affected by the ice conditions of the upper reach to assure the normal operation of the reservoir in winters is also essential. Meanwhile, it is of great importance to study and solve the problems of low flow capacity of the Toudaoguai section during the freeze-up period.

3. Model Formulation

This model mainly consists of three parts: hydraulics model, thermodynamics model and ice model. The hydraulic model calculates the stage, discharge, velocity, and other relevant hydrodynamic factors of the reach. The thermodynamics model calculates heat exchanges, and water temperature. The ice model calculates the concentration distribution of the frazil, ice transportation, and formation, progression, and thickness of ice cover (Ma, 2012). The model formulation is similar to the RICE model (Lal and Shen 1991), but the hydraulic equations are solved with the MacCormack method (MacCormack 1982).

3.1 Hydraulic model

Profiles of flow through rivers with a floating ice cover can be described by the following one-dimensional equations of gradually varied unsteady flow :

$$\frac{\partial A}{\partial t}+\frac{\partial Q}{\partial x}=0 \qquad \textbf{[1]}$$

$$\frac{\partial Q}{\partial t}+2\frac{Q}{A}\frac{\partial Q}{\partial x}-\frac{Q^2}{A^2}\frac{\partial A}{\partial x}+gA\frac{\partial z}{\partial x}+gn_c^2Q^2\frac{P^{4/3}}{A^{4/3}}=0 \qquad \textbf{[2]}$$

in which, Q = water discharge; A = cross-section area of flow; x = stream wise distance; t = time; g= gravity; $z=z_b+h+t_i$ water lever; z_b = bed elevation; t_i = submerged thickness of the ice cover; h = depth of flow; n_c = composite Manning's coefficient; P = wetted perimeters. An implicit finite-difference MacCormack is used to solve Eqs. 1 and 2 simultaneously. This method has an accuracy of $O(\Delta x^2, \Delta t^2)$. It is a two-step predictor-correct scheme. It uses forward and backward differencing for the predictor and corrector steps alternatively (Ma 2012). The initial flow profile is obtained by a stabilization process, in which the unsteady flow equations for fixed boundary conditions are solved until the flow profile becomes steady. The upstream boundary condition is the water level at Sanhuhekou. The downstream boundary condition is the outflow discharge of the Wanjiazhai Reservoir.

3.2 Water temperature variation

Streamwise variation of depth-averaged water temperature can be described by a one-dimensional advection-diffusion equation in terms of conversation of thermal energy (Lal and Shen, 1991):

$$\frac{\partial \eta}{\partial t}+v\frac{\partial \eta}{\partial x}=B\sum S \qquad \textbf{[3]}$$

in which, B = river width; $\eta=\rho C_P AT$, where C_P = specific heat of water, T = depth-averaged temperature of water, ρ = density of water; $\sum S$ = net rate of heat loss per unit surface area of the river. Equation 3 is solved for T using the same MacCormack method used to solve for Q and A. The initial water temperature along the river reach of interest is taken to be constant. The upstream boundary condition is the temperature variation with time at Sanhuhekou.

3.3 Distribution of surface and frazil ice concentrations

According to the two-layer ice transport theory, the ice discharge in the river is considered to consist of a surface layer and a suspended layer. The equation of mass conservation for surface ice and suspended frazil ice can be written as (Wang, 1999):

$$\frac{\partial C_a}{\partial t}+u\frac{\partial C_a}{\partial x}=-\frac{B}{\rho_i A L_i}\sum S_1+\alpha\left(1-\frac{v_z}{U_i}\right)C_i \qquad \textbf{[4]}$$

$$\frac{\partial C_i}{\partial t}+u\frac{\partial C_i}{\partial x}=-\frac{B}{\rho_i A L_i}\sum S_2-\alpha\left(1-\frac{v_z}{U_i}\right)C_i \qquad \textbf{[5]}$$

in which, C_a = area concentration of surface ice; C_i = average volumetric concentration of suspended frazil ice; ρ_i = density of ice; L_i = latent heat of water fusion; α = an empirical coefficient quantify the rate of supply to surface ice from suspended ice; U_i is the buoyant velocity of ice particles; and v_z is the vertical velocity component due to flow turbulence.

3.4 Ice cover formation

Depending on the hydraulic condition at the leading edge of the ice cover, the ice-cover progression can occur in three different modes: the juxtaposition mode, hydraulic thickening (narrow jam) mode, and mechanical thickening (wide jam) mode (Lal and Shen, 1991). The undercover transport and accumulation is described by the transport capacity theory of Shen and Wang (1995).

3.5 Ice cover thickness

As an accumulation cover progress upstream, it solidifies as porous frazil ice is thermally transformed to monolithic ice and thermally thickens. Thermal thickening is simulated using the following thermal energy equation:

$$\rho_i L_i\frac{dh_i}{dt}=h_{ia}(T_s-T_a)-h_{wi}(T_w-T_m) \qquad \textbf{[6]}$$

in which, h_{ia} = heat transfer coefficient at the air/ice interface; T_s = temperature on the top surface of the ice cover; T_a = air temperature; h_{wi} = heat transfer coefficient at the water/ice interface; T_w = water temperature; T_m = melting temperature, 0℃.

4. Model Schematization

The length of the Tou-Wan reach is 114 km, in which only 48 river sections have been measured. In order to ensure the calculation accuracy, two principles are used as the criterion for setting up the mesh: (1) use the existing measured data fully, put the measured river sections as the nodes in the system; (2) to ensure the convergence of the calculation, the maximum distance between two adjacent nodes is less than 500 m. The cross section geometry of the additional nodes between the measured sections are obtained by interpolation.

The length of the river reach from Sanhuhekou to Toudaoguai is 300 km, in which the reach from Sanhuhekou to Huajiangying is 151 km, with an average river width of 4000 m, and the main channel width of 710 m, the slope is 1.2×10^{-4}. The reach from Huajiangying to Toudaoguai section is of 149 km long, with the average river width of 3000 m, and the main channel width of 600 m, the slope is 1.0×10^{-4}. The bed elevation difference between Sanhuhekou and Huajiangying is therefore derived to be 18.12 m, and the value between Huajiangying and Toudaoguai section is 14.9 m. So the bed elevation difference between Sanhuhekou and Toudaoguai is 33.02 m, with the average slope of 1.1×10^{-4}. The bed roughness of the Tou-Wan reach is calculated by using the measured water surface profile (Figure 2).

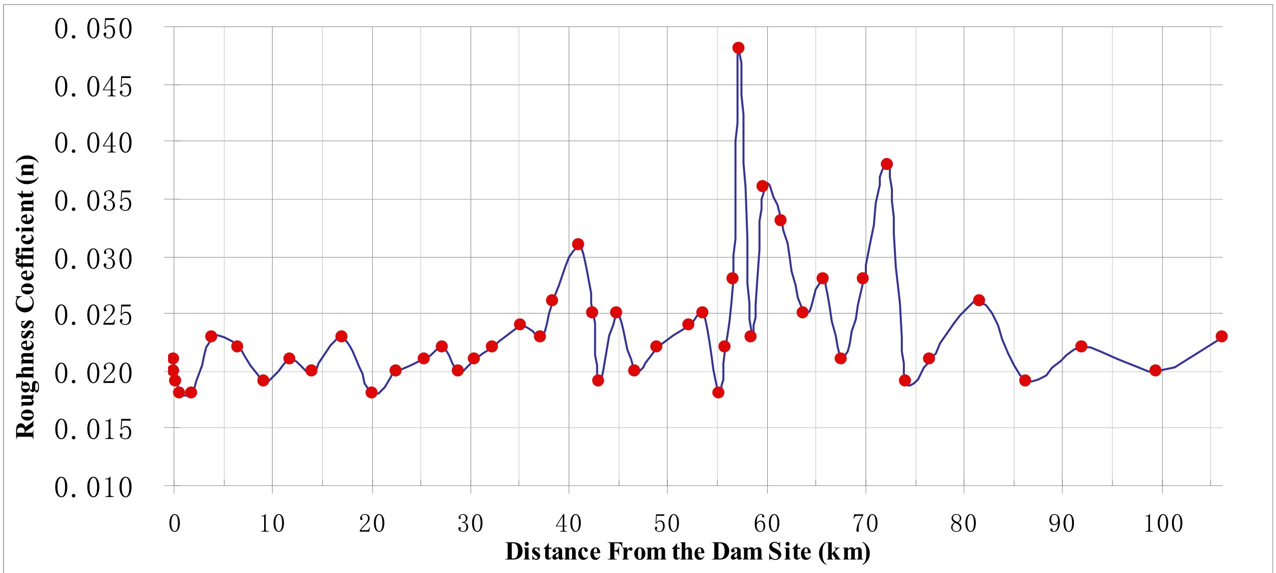


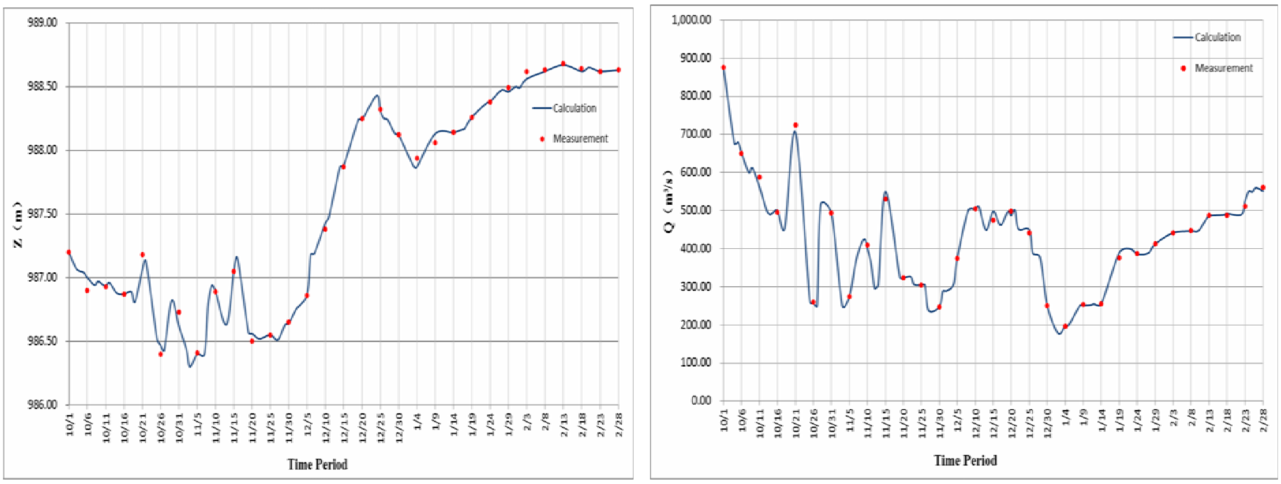
Figure 2. Variation of bed roughness along the river

5. Model Verification

Utilize mathematical model to simulate the freeze-up process in the San-Wan reach, and compare the simulated results with the measurement data, the model parameters are adjusted simultaneously. The length of the reach in this simulation is 414km. The minimum nodal spacing is of 17m, and the maximum space is of 500m long. The duration of the simulation is from November 1st 2009 to February 28th 2010, and the time step is 500s.

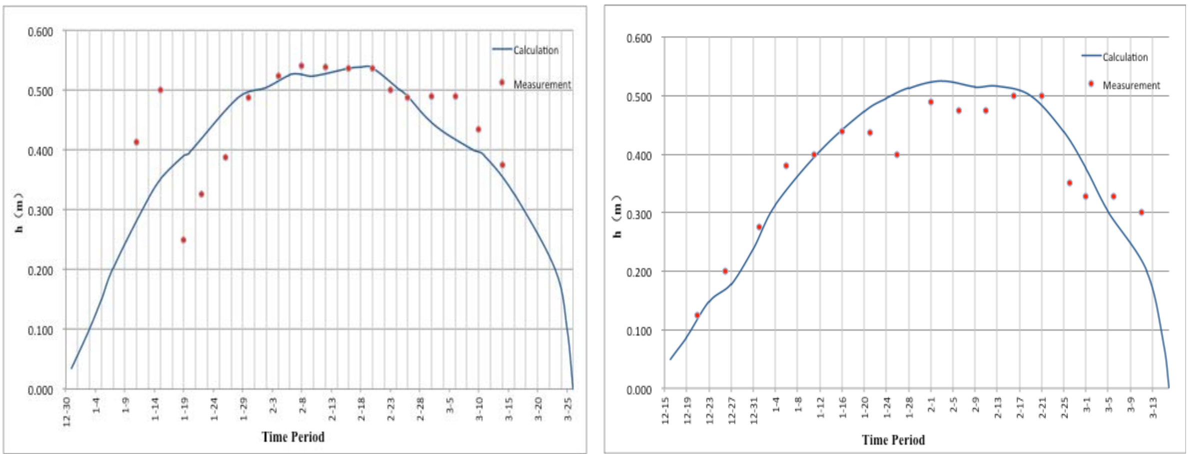
Figure 3(a) shows the comparison of simulation and measurement of water level variation with time at Toudaoguai section. Figure 3(b) demonstrates the comparison of simulation and measurement of flow discharge Q variation with time at Toudaoguai section. It is noted from figure 3 that within the simulation period, the range of water level change is from 986.40m to 988.80m while the range of flow discharge change is from $200m^3/s$ to $900m^3/s$. The range of water level change of Wanjiazhai Reservoir is from 960m to 980m.

The variation of the thickness of ice cover with time at Toudaoguai is presented in Figure 4 (a). The measured data indicates that the beginning date of freeze-up at Toudaoguai section is December 31st 2009, while the calculated results implies that it is in the night of December 30th 2009, so the calculated results agree well with the measured data. In addition, the measured data shows that the average maximum thickness of the ice cover is 0.540m, which occurs in February 6th, while the calculated results show that the maximum value is also 0.540m, occurring in February 18th. The calculated thickness in February 6th is 0.526m, which is close to the measured data. The calculated results also imply that the maximum thickness of ice cover does not emerge in the end of the freeze-up period or the beginning of breakup period. The reason is that the border ice develops in the upper reach, 67 km away from the dam. As the border ice extends to the middle of the river, grows thicker, the surface ice in upper reach is finally blocked by the border ice. So the thickness of the initial ice cover in this reach is larger than the floating ice. It is quite different from the situation in which the incoming surface ice from upper reach is blocked by artificial obstacles downstream, resulting in ice accumulates and extending the ice cover upstream.



（a） Water level (b) Flow discharge

Figure 3. (a) The water level variation with time at Toudaoguai section and (b) the variation of flow discharge with time at Toudaoguai section (From Oct 1- Feb 28)



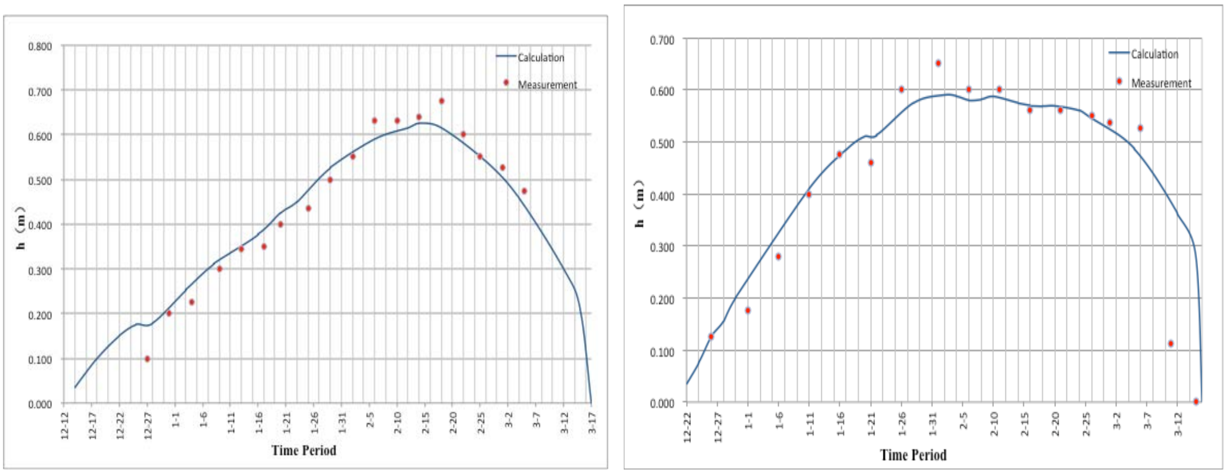
(a) 2009 -2010 **(b) 2006-2007**

Figure 4. The variation of the thickness of ice cover with time at Toudaoguai section

To examine the accuracy of the model, the measured data of ice cover thickness for three winters, i.e. 2006-2007, 2007-2008 and 2008-2009, are compared with the calculated data, as shown in Figures 4 (b), 5 (a), 5 (b). The calculated results are in good agreement with the measured data. The measured data-points distributed evenly on both sides of calculated curves with very closeness. A few measured data points deviating from the calculated data, due to the measurement errors.

6. Effect of Wanjiazhai Water Level on the River Discharge

The backwater effect caused by the rising water level near the reservoir would propagate to the upper reach, causing changes of water level and discharge at the Toudaoguai section. In this paper, the influence of different water levels of the reservoir on the flow process of Toudaoguai section is investigated to find out the water-level threshold value in the Wanjiazhai Reservoir, which if being reached, the flowing pattern and flow discharge capacity of Toudaoguai section would start to be affected. Based upon the analysis of field data, the flow condition at the Sanhuhekou section upstream, which is 400km away from the reservoir is most likely free from the influence of reservoir operation, so it is reasonable to set Sanhuhekou as the upstream boundary for the numerical simulation. Furthermore, since the range of the flow discharge of Toudaoguai section during the freeze-up period is between 200m^3/s and 900m^3/s based on the analysis of field observation data (October 2009 to October 2010), the range of flow discharge between 200m^3/s and 1000m^3/s is used in the numerical experiment, and the range of water level in front of the dam is from 960m to 980m. The calculation conditions are shown in Table 1 below. The calculate results are shown in Table 2.



(a) 2007 -2008 **(b) 2008-2009**

Figure 5. The variation of the thickness of ice cover with time at Toudaoguai

Table 1. The boundary condition of numerical experiment

Calculation conditions	Upstream flow discharge (m³/s)	The water level of Wanjiazhai reservoir (m)
Condition 1	200	960 965 970 971 972 973 974 974.77 975 980
Condition 2	300	960 965 970 971 972 973 973.72 974 975 980
Condition 3	500	960 965 970 971 972 972.80 973 974 975 980
Condition 4	800	960 965 966 967 968 969 970 970.63 971 975 980
Condition 5	1000	960 965 966 967 968 969 969.53 970 975 980

Table 2. The water-level threshold values at Toudaoguai section for different upstream flow discharge

Flow discharge (m^3/s)	200	300	500	800	1000
Water level (m)	987.74	988.36	989.41	991.05	992.42
Water depth (m)	2.813	3.429	4.479	6.12	7.493
The initially influencing water level value z_o(m)	974.77	973.72	972.8	970.63	969.53

Based on the results listed in the 4th line in Table 2, the relationship between the initially influencing water level of Wanjiazhai Reservoir and discharge of Toudaoguai is

$$z_o = -0.00065 \cdot Q_u + 975.92 \quad \textbf{[7]}$$

in which, z_o =water level of Wanjiazhai reservoir; Q_u=upstream incoming flow discharge. The correlation coefficient R = 0.996.

7. Conclusions

A river ice model for the reach of the Yellow River from Sanhuhekou to Wanjiazhai Reservoir was developed. Irrespective of the change of upstream flow discharge and river boundary condition, when the water level of Wanjiazhai reservoir exceeds a critical value, the flow at Toudaoguai will be affected, resulting in higher water level and milder water surface gradient in the upper reaches. The flow discharge decreases and river channel storage increases. In addition, the backwater effect would also slow down the upstream flow velocity, to cause sediment deposition and induce the formation of ice jams. The water level at Toudaoguai increases with the water level in Wanjiazhai Reservoir, resulting in the decreasing of water surface gradient in the upper reaches, which would lead to the reduction of the flow capacity of the reach.

References

Department of hydraulic engineering, Tsinghua University, 2011. The study on the river-ice mathematical model for the reach of Wanjiazhai reservoir. Beijing. (in Chinese)

Lal, A. W., and Shen, H. T., 1991. Mathematical model for river ice processes. Journal of hydraulic Engineering, 117(7), 851-867.

Ma, Z., 2012. The study on the one-dimensional river-ice mathematical model for the reach in Wanjiazhai reservoir. Master Thesis. Tsinghua University, Beijing, China. (in Chinese)

MacCormack, R. W., 1982. A numerical method for solving the equations of compressible viscous flow, AIAA journal, 20(9), 1275-1281.

Shen, H. T., Wang, D. S., and Lal, A. W., 1995. Numerical simulation of river ice processes. Journal of Cold Regions Engineering, 9(3), 107-118.

Wang, Y. T. 1999. Numerical simulation of river ice and analysis of ice characteristics during Water-transfer in winter. Ph. D. Dissertation. Beijing: Tsinghua University. (in Chinese)