

HEI RIVER FLOOD RISK ANALYSIS BASED ON COUPLING HYDRODYNAMIC SIMULATION OF 1-D AND 2-D SIMULATIONS

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ABSTRACT

To evaluate the flood risk of Black River efficiently and conveniently, the deluge gradual processing in black river gold basin reservoir is established within the one- dimension model and two-dimension model of hydrodynamic coupling. Triangular unstructured grid is adopted to accommodate height and large span, as well as complex underlying surface of Mountain Rivers. Lateral connection, time synchronization and corresponding coupling space node are applied within coupling of one- dimension model and two-dimension model. The numerical simulation of flood in Black river gold basin reservoir which is in different frequencies is in the framework of established coupling model. As a result, the water depth and distribution of flow field in different time are obtained within the calculation areas. Based on the results of coupling simulation, the flood risk map and the analysis of importance of dam break as well as the risk of flood-hit population proceeded. The results coming from the mentioned simulation could provide basis to alarm of Black River flood and evaluation of disaster loss.

Keywords: flood routing, unstructured grids, coupling simulation, risk analysis, lateral connection.

1. INTRODUCTION

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Combining hydrodynamics [1] and numerical simulation [2] is a significant method of studying watercourse flood risk, referring to the calculation and analysis of deluge risk, which is the core and base portion of flood risk graph compilation. As the flood inundates the river way, two dimension is the main path to the research [3-5]. For example, X. M. Yuan [6] established two-dimension hydrodynamic model to simulate the flood inundating the river way and embankment as well as the gradual progress of flood routing in irrigated area. Meanwhile, the meshless methods, such as particle [7] and SPH [8-9], are still in the research process, resulting in the unstructured grid method [10] being chosen as the main path to establish model of two-dimension flood routing. One-dimension hydrodynamic coupling model and two-dimension hydrodynamic coupling model could simulate much faster and calculate more appropriately during the process of flood inrush [11]. Scholars within China and other nations [12-14] coupled one-dimensional saint venant equations and different two-dimensional model separately, even the three-dimensional model to calculate and simulate hydrodynamic force. The core of coupling calculation is about the fluency of mutual calculation based on coupling points from one-dimensional model and two- dimensional model. In order to ensure the calculation fluency, many scholars [15-17] have applied 'conservation of flow quantity',

'overlapping calculation areas', and 'weir flow formula' to couple the connection. Based on the GIS [18-20], combining flood processing model of hydraulics, the flood process within inundated area is simulated, resulting in the important data of inundated areas, water depth and time of process, as well as other significant data in flood risk analysis, comparing with the simulation process of one-dimensional model [21], three one-dimensional model [22], and coupling model [23]. As a result, the analysis model of flood risk is established [24], leading to high convenience and efficiency of analysis process within deluge risk. Besides, reliable data is produced to draw the flood risk map.

Although the flood processing model and the risk analysis research have developed in huge advance, the problems waiting to be studied are as follow:

(a) Homogeneous mesh model could not guarantee the calculation efficiency and model accuracy at the same time, when being applied to Mountain Rivers with complex underlying surface and wide areas.

(b) The core portion refers to the interaction of data, reflected by the calculation of one-dimension and two-dimension model.

According to the problems above, the report referenced the research by other scholars, established one-dimension and two-dimension coupling model, by lateral connection, as well as mesh encryption towards different underlying surfaces, simulated process of flood into reservoir in different frequency, expanding in downstream areas. As a result, the flood risk map was drawn to analyze the importance of dam bursting flood, providing data evidence towards Black River flood alarm and disaster loss evaluation.

2. MATHEMATICAL MODEL

2.1 Principle of One-dimensional Model

One-dimensional calculation model is based on the vertical integration of substance and momentum conservation equations, the application of unsteady flow Saint-Venant equations to simulate the flow of the river or estuary state.

$$\left\{ \begin{array}{l} \frac{\partial A}{\partial t} + \frac{\partial Q}{\partial x} = q \\ \frac{\partial Q}{\partial t} + \frac{\partial \left(\alpha \frac{Q^2}{A} \right)}{\partial x} + gA \frac{\partial h}{\partial x} + \frac{gQ|Q|}{C^2 AR} = 0 \end{array} \right. \quad (1)$$

In the formula: A is the cross section area, m^2 ; t is the time point of the coordinates calculated; Q is overcurrent flows. m^3/s ; x is the space coordinate calculation points; q is lateral inflow of flow, m^3/s ; α is the momentum correction factor; h is the water level, m ; g is the acceleration of gravity, m/s^2 ; C is the Chezy coefficient; R is the hydraulic radius.

Equations using the Abbott-Ionescu six implicit finite difference scheme to solve. The discrete form at each grid point is not to calculate the flow and water levels at the same time, but according to the order of alternate calculation of flow and water level, called Q and H . Abbott-IonescuFormat with a high accuracy, good stability. After discrete linear equations by chasing method.

2.2 Principle of Two-dimensional Model

Due to the horizontal scale is much larger than the vertical scale of flood movement, depth and flow rate of the hydraulic parameters change in the vertical direction is much smaller than the change in the horizontal direction, thus the three-dimensional flow equation can be integrated along the depth, and take an average depth, resulting in a two-dimensional shallow water flow equations of motion.

Flow continuity equation:

$$\frac{\partial Z}{\partial t} + \frac{\partial(hu)}{\partial x} + \frac{\partial(hv)}{\partial y} = 0 \quad (2)$$

Flow equations of motion:

$$\frac{\partial u}{\partial t} + \frac{\partial u^2}{\partial x} + \frac{\partial uv}{\partial y} = fv - g \frac{\partial \eta}{\partial x} - \frac{1}{\rho_0} \frac{\partial p_a}{\partial x} - \frac{1}{\rho_0 h} \left(\frac{\partial s_{xx}}{\partial x} + \frac{\partial s_{xy}}{\partial y} \right) + F_u + u_s S \quad (3)$$

$$\frac{\partial v}{\partial t} + \frac{\partial v^2}{\partial y} + \frac{\partial uv}{\partial x} = -fu - g \frac{\partial \eta}{\partial y} - \frac{1}{\rho_0} \frac{\partial p_a}{\partial y} - \frac{1}{\rho_0 h} \left(\frac{\partial s_{yx}}{\partial x} + \frac{\partial s_{yy}}{\partial y} \right) + F_v + v_s S \quad (4)$$

In the formula: t is the time, s ; x is the transverse spatial coordinate, m ; y coordinates for vertical space, m ; Z is a water level at the x, y, m ; h is the water depth at the x, y, m ; u is the x -direction velocity component, m/s ; v is the y -direction velocity component, m/s ; g is the acceleration of gravity, m/s^2 ; n_z is the Manning coefficient; f_v, f_u is the Coriolis acceleration term; $g \frac{\partial \eta}{\partial x}, g \frac{\partial \eta}{\partial y}$ is the Surface water level acceleration term;

$\frac{1}{\rho_0} \frac{\partial p_a}{\partial x}, \frac{1}{\rho_0} \frac{\partial p_a}{\partial y}$ is the Atmospheric pressure gradient;

$\frac{1}{\rho_0 h} \left(\frac{\partial s_{xx}}{\partial x} + \frac{\partial s_{xy}}{\partial y} \right), \frac{1}{\rho_0 h} \left(\frac{\partial s_{yx}}{\partial x} + \frac{\partial s_{yy}}{\partial y} \right)$ is the Wave radiation stress terms; F_u, F_v is the Horizontal eddy viscosity term; $u_s S, v_s S$ is the source term inflow generated acceleration term.

2.3 The Ways of Coupling Model

It is difficult to simulate the two-dimensional flow of uncertain path by one dimensional model, and needs long time for calculations by two dimensional model, coupled simulation of lateral connections can better take advantage of the one-dimensional model and two-dimensional models, while it can be avoid the presence of the grid resolution and accuracy of a single model problem, and to obtain even better results. Lateral connections coupled model allows two-dimensional grid connection from the side to the one-dimensional part of the river, even the entire river, Figure 1. It can be use formulas to calculate the amount of logistics structures connected by lateral flow, with lateral connections to simulate the movement of water from the river to overflow floodplain is very effective. The key is to ensure that a coupled model, at the connection point of hydraulic elements of the two-dimensional calculation area of equal value.

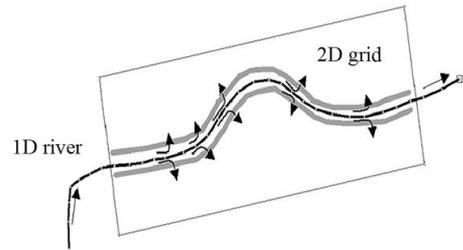


Figure 1. Application of lateral connection

The one-dimensional river and two-dimensional grid connected through the unified connection elevation to achieve overlapping computing unit. Connection elevation of the one-dimensional is determine by river embankment elevation, that using embankment elevation of left and right as the riverbed elevation by coupling connection, the data obtained by interpolation if it has none. Connection elevation of two-dimensional is determined by the terrain that is a two-dimensional grid cell elevation as the riverbed elevation coupling connection. Overlapping unit is setting by the hydraulic calculation nodes lap. One-dimensional computing nodes are calculation points of water level on the right and left bank river bank wire. Two dimensional compute nodes are in the grid cell corresponding to the section endpoint of right and left. Coupling model is calculate for each node

dynamically conduct water, and based on water balance of node, each of the flow has been calculated re-allocated to the two-dimensional and one-dimensional computing grid cell level point, in order to achieve a one-dimensional and two-dimensional coupling calculation. One-dimensional, two-dimensional models are used in a uniform time step, and at each time step, the time will mutual exchange of information, when the water flows from one-dimensional river to two-dimensional grid, physical of computing nodes is solved by one-dimensional model as a two-dimensional model of the boundary conditions. Conversely places in the two-dimensional model of the flow value at the node, as the boundary conditions at the one-dimensional model of the connection. In order to make a stable coupling model calculation, need to ensure that the connection point of hydraulic conditions to maintain homeostasis, which requires a one-dimensional model and two-dimensional model of the initial level and flow conditions, should be the same. The two-dimensional river all the unknown variables end of the first section of the river water level linear expression, then make the flow at the end of the first boundary to boundary water form. It should be noted: coupled model just a platform model by lap one-dimensional and two-dimensional model of interactive computing, the results is still view the display on a one-dimensional river and dimensional flooded area.

3. OPERATING CONDITION

Hei river Jinpen reservoir flood control standard is design flood for 100 years ($P = 1\%$), check flood for 2000 years ($P = 0.05\%$), dam-break flood developed for 10,000 years ($P = 0.01\%$) floods overtopping crashed. The inflow flood hydrograph [25] was drawn in Figure 2. The water storage capacity curve of Hei river Jinpen reservoir was shown in Figure 3. Reservoir regulation prepared for (1)when the reservoir level less than flood control level 591 m, the discharged volume is zero ; (2)when the reservoir water level between flood control level of 591 m to high water level of 594 m , the downstream flow was controlled as the incoming water flow if it is less than the allowed downstream flow of $1800 \text{ m}^3/\text{s}$, otherwise control the discharged volume equal to $1800 \text{ m}^3/\text{s}$; (3) when reservoir water level is greater than the high level of flood control 594 m, the gate fully open. By the flood regulating calculation on three conditions,the 100 years flood and 2000 years flood were released as flood of $P=0.7\%$ and $P=0.3\%$ years flood enter the Hei river caused dike. The 10000 years flood caused dam break when the static water level is equal to 600m at the time $t = 16.4\text{h}$, after spilled into the river as flood of $P < 0.01\%$ (Table 1). Calculated with a gradual sloping bottom without resistance break model, the maximum dam break flow reaches $68266.95 \text{ m}^3/\text{s}$ at the time $t = 17.41\text{h}$, the total dam lasted 3.04h. Accordingly, drawn flow discharged line of the different frequency flood after flood routing process, shown in Figure 4.

Table 1. Condition description

Condition	Inflow flood	Outflow flood	Burst condition
Condition 1	$P=1\%$	$P=0.7\%$	Dike
Condition 2	$P=0.05\%$	$P=0.3\%$	Dike
Condition 3	$P<0.01\%$	$P<0.01\%$	Dike and dam break

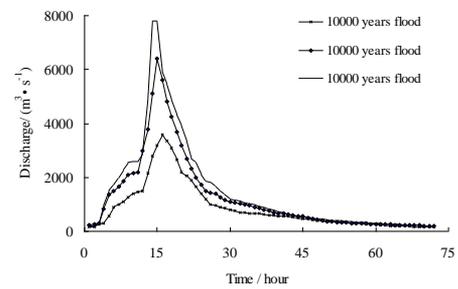


Figure 2. Reservoir inflow hydrograph

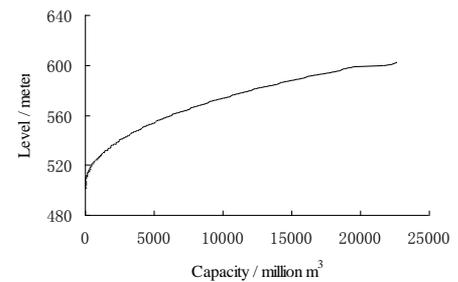


Figure 3. Relationship between water level and storage capacity

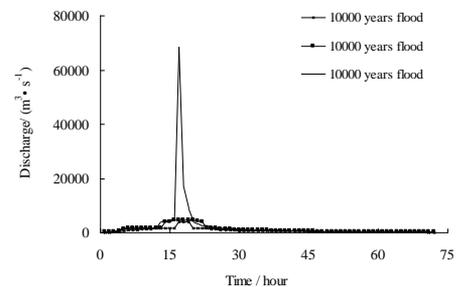


Figure 4. Reservoir outflow hydrograph

4. COUPLED SIMULATION OF FLOOD ROUTING

4.1 One-dimensional Simulation Conditions

The one-dimensional simulation area of Hei river long 30920m. Selecting six sections according to the available information, the selected section were apart from dam sections 2700m, 7300m, 13700m, 19100m, 25000m, 30920m, the position is shown in Figure 5. Using the three flow processes shown in the Figure 4 as inflow boundary conditions of one-dimensional calculation. The flow water relations of section 011 # was set in Hei-Wei sink as a flow condition (Finger 6).

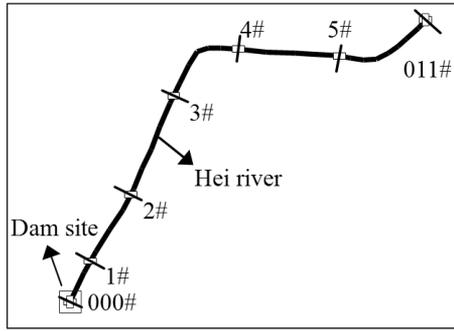


Figure 5. Section location

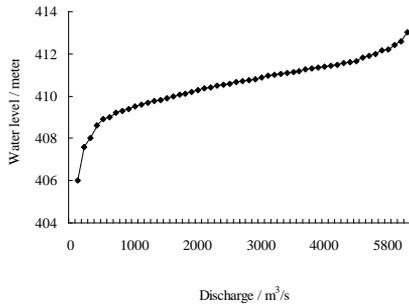


Figure 6. The discharge and water process of the Hei-Wei sink

4.2 The-dimensional Simulation Conditions

Two-dimensional calculation area includes Hei river and part of the Wei river, a total of 1 066 km². The terrain was shown as Figure 7. Unstructured triangular grids of the different sizes were used to generation the mesh of computing area for improving accuracy. Mesh encryption processing at the river and riverbank, by controlling the density of nodes to optimize mutation border. The maximum land and river grid area were not exceeding 0.1 km² and 0.05 km², a total of 19 523 grids and 9974 nodes. Roughness value selecting appropriate or not have a greater impact on the calculation results, but difficult to accurately estimate due to the complexity terrain of Hei river. Roughness is generally in the range of 0.025 to 0.045, with reference to previous literature [25], and ultimately to develop a two-dimensional calculation of selected riverbed roughness value 0.031. Using the three flow processes shown in the Figure 4 as inflow boundary conditions of two-dimensional calculation. Supposing that the flow rate of y direction is zero with open outflow boundary conditions.

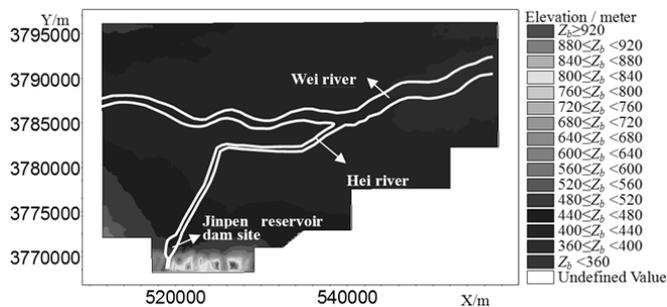


Figure 7. The calculation area topography of Hei river Jinpen reservoir

4.3 Coupling Model Setting

The lateral connection was used for coupled model, one-dimensional calculation section includes the entire Hei river, two-dimensional calculation part was the entire grid area, as shown in Figure 8. Both were overlapped by hydraulic calculation nodes, dam break water flows form one-dimensional river to two-dimensional region by the form of lateral weir.

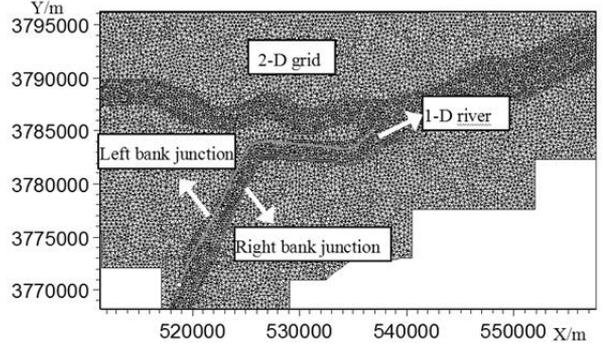
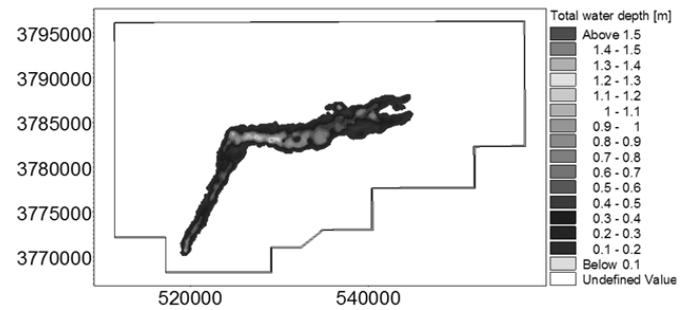


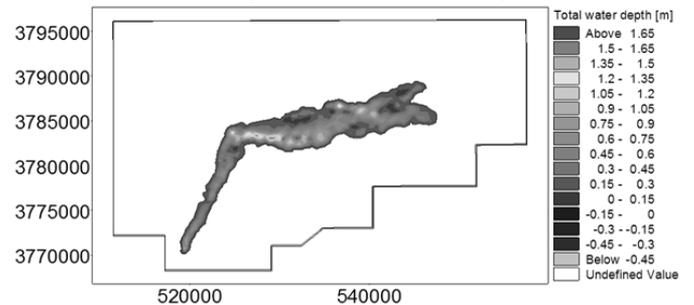
Figure 8. Schematic diagram of one-dimensional and two-dimensional coupling

4.4 The Results of the Coupling Simulation

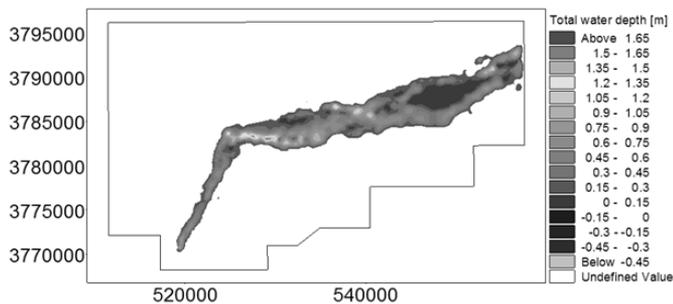
By the coupling simulation can get the instantaneous water depth and flow field distribution of the downstream flood routing, the three frequency flood submerged condition at time $t=12h$ as an example (figure 9). Simulation lasted a total of 72h, the maximum average depth of 100,2000 and 10000 years flood occurred respectively 5.02m, 6.11m and 8.47m, the maximum average velocity were 1.97m/s, 2.14 m/s and 2.31 m/s. Coupled simulation can clear flow movement environment inside channel, and through the connecting point of interactive computing, improve the accuracy of model calculation.



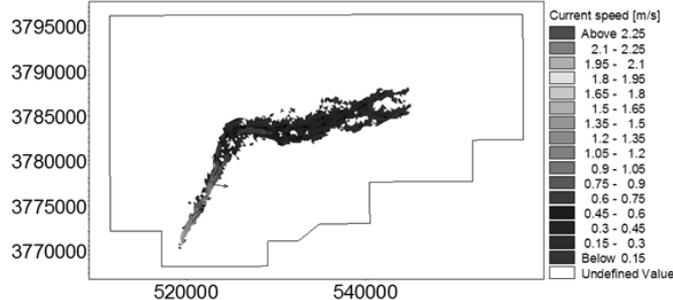
(a) The water depth distribution of 100 years flood



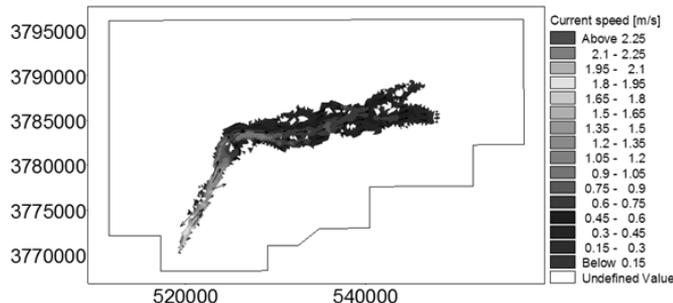
(b) The water depth distribution of 2000 years flood



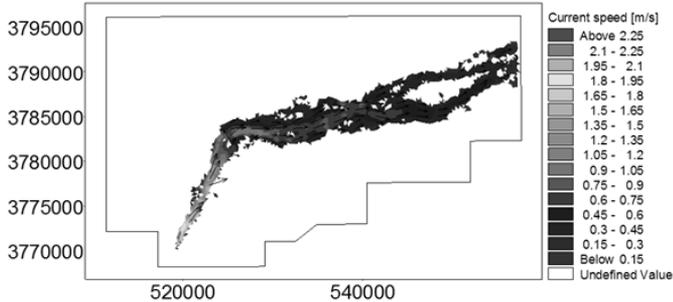
(c) The water depth distribution of 10000years flood



(d) The water velocity distribution of 100 years flood



(e) The water velocity distribution of 2000 years flood



(f) The water velocity distribution of 10000years flood

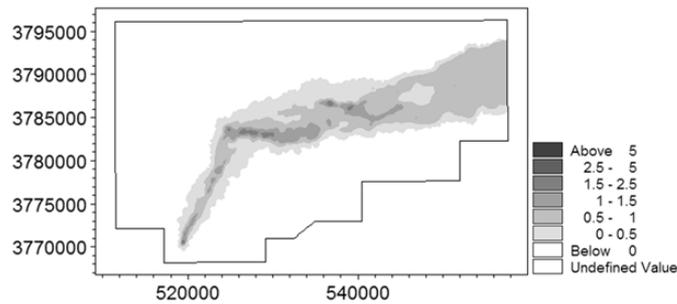
Figure 9. Instantaneous water depth and velocity distribution (t=12h)

5. FLOOD RISK ANALYSIS

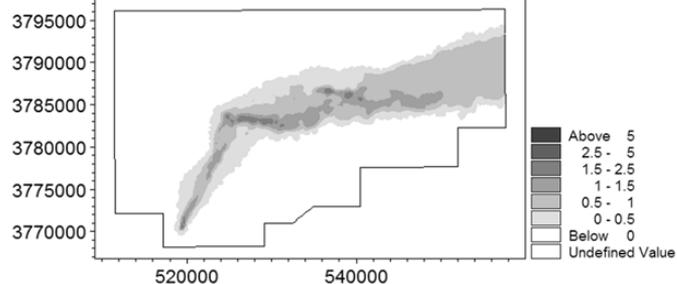
According to the simulation results, the submergence risk map and flood velocity risk map at different frequencies and dam break flood arrival time risk map were preparation, and dam-break flood severity and risk population for analysis.

5.1 Flood Risk Map

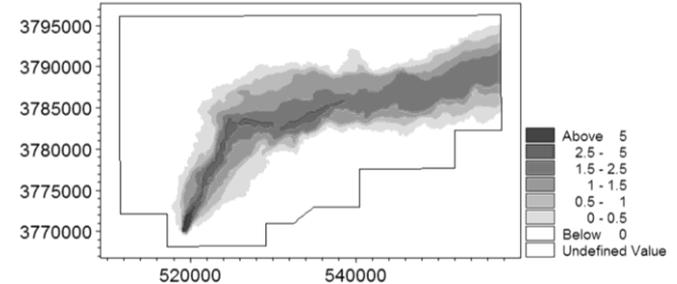
The submergence risk map and flood velocity risk map at different frequencies were shown as the figure 10. Among them, the submerged depth grading is 0~0.5 m, 0.5~1.0 m, 1.0~1.5 m, 1.5~2.5 m, 2.5~5.0 m, >5.0 m, and flood flow rate classification standard for 0~0.5 m/s, 0.5~1.0 m/s, 1.0~1.5 m/s, 1.5~2.0 m/s > 2.0 m/s.



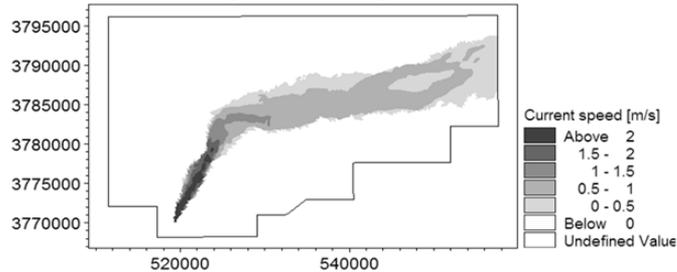
(a) The submergence risk map of 100 years flood



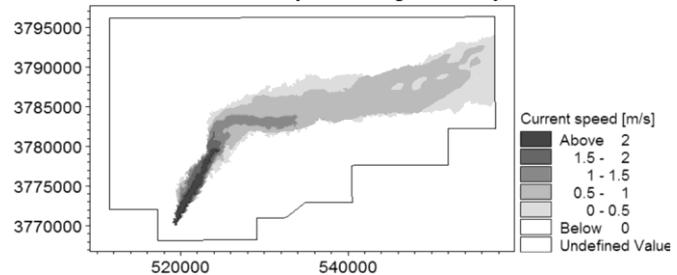
(b) The submergence risk map of 2000 years flood



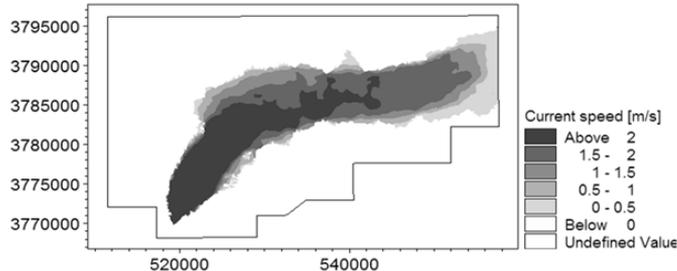
(c) The submergence risk map of 10000 years flood



(d) The flood velocity risk map of 100 years flood



(e) The flood velocity risk map of 2000 years flood



(f) The flood velocity risk map of 10000 years flood

Figure 10. Flood risk map of different frequency floods

5.2 Dam Break Flood Risk Analysis

Large dam break flood water, strong currents, formed the people downstream a serious threat to the safety of life and property, seize the arrival time of the dam break flood to risk warning and evacuation of great significance. Dam break flood arrival time risk map of the 10000 years flood condition was shown as the figure 11, time grading standards for 0-1h, 1-2h, 2-3h and 3h above after dam break. Obviously, Hei river and Wei river region near have been affected in 1hour in. The affected area focused almost drowned in 3 hours. Recommend evacuation before the dam break occurred.

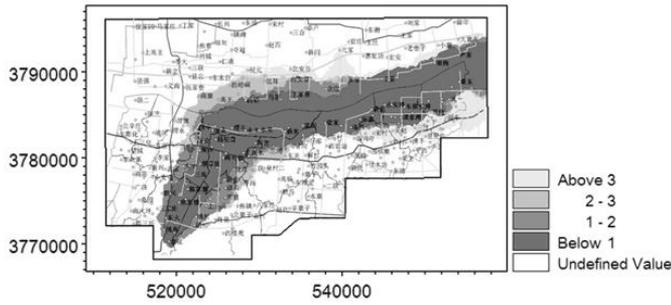


Figure 11. Dam break flood arrival time risk map

S_D is a dam-break flood severity index, indicating the extent of the flood damage to the residents, etc., can be expressed as

$$S_D = D \cdot V \quad (5)$$

Where, D is the water depth, m; V is velocity, m / s.

For a grid in the i -th computing step, there is

$$S_D = D_{\max} \cdot V_{\max} \geq \max(D_i \cdot V_i) (i = 1, 2, \dots, n) \quad (6)$$

Where, D_{\max} for a maximum depth of the grid in the i -th step, m; V_{\max} is the maximum velocity of a grid in the i -th step, m/s. The safety factor of the S_D value for evaluating the severity of the dam break flood is higher.

Graham method [26] divided dam break flood severity of S_D types: 1) low risk, there is no flood washed away the building foundation, $DV \leq 4.6 \text{ m}^2/\text{s}$; 2) medium risk, flood destroyed houses generally, but the trees or destroyed houses can still provide shelter for people, $4.6 \text{ m}^2/\text{s} < DV \leq 12 \text{ m}^2/\text{s}$; 3) high risk, flood washed away everything in the area, $DV > 12 \text{ m}^2/\text{s}$. Based on the above classification criteria, combined with the simulation results of the statistical coupling analysis, dam break flood severity distribution was shown in Figure 12. Total area affected 378.39 km^2 , 112 villages and 257, 317 people affected, in Table 2.

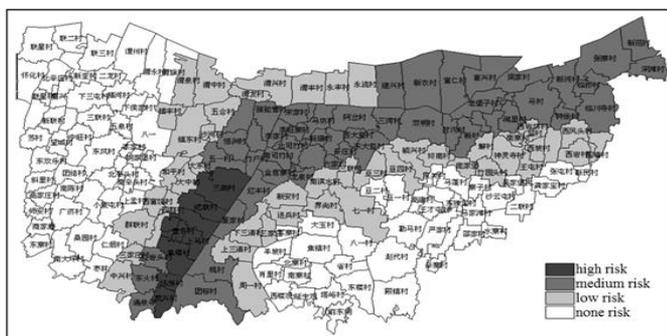


Figure 12. Dam break flood severity distribution

Table 2. Dam break flood severity analysis

S_D value (m ² /s)	severity	Affected village	Affected area (km ²)	Affected population(people)
$SD \leq 4.6$	low risk	47	169.34	130164
$4.6 < SD \leq 12$	medium risk	54	175.85	109726
$SD > 12$	high risk	11	33.2	17427

6. CONCLUSIONS

In this paper, the unstructured grids of non-uniform density have been used to solving model adaptive problems of complex underlying surface of mountain rivers. One-dimensional and two-dimensional hydrodynamic models have been coupled to balance calculation accuracy and efficiency by the lateral connection. The downstream flooding evolutions of different frequencies have been simulated after diking even dam breaking. The instantaneous distribution of water depth and flow field under different conditions can be shown. The maximum average depth of 100, 2000 and 10000 years flood occurred respectively 5.02m, 6.11m and 8.47m, the maximum average velocity were 1.97m/s, 2.14 m/s and 2.31 m/s. Based on the statistical analysis of the simulation results, the submergence risk map and the flood velocity risk map at different frequencies and the dam break flood arrival time risk map have been prepared and the dam-break flood severity and risk population have been analyzed. Total areas of 378.39 km^2 , 112 villages and 257, 317 people have been affected.

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