Flood hazard monitoring and analysis of mountainous riverside country - a case study in Xianfeng, Hubei, China

Zhe Li

1Institute of Spatial Information Technology Application, Changjiang River Scientific Research Institute, Wuhan, Hubei,430010, P. R. China

*Corresponding author’s e-mail:lizhe@mail.crsri.cn

Abstract. Riverside towns are the weakness of flood control and disaster reduction system in China. Flood analysis of riverside towns based on hydraulic model is of great significance to the monitoring and early warning of mountain flood disasters. The paper starts with river system distribution and flood source analysis in case study of Xianfeng County, Hubei Province, China. And a flood calculation program is then proposed. On the basis of TUFLOW software, a one-dimensional hydraulics model is constructed, which is applied to calculate river flood evolution and diffuse embankment process under the designed flood conditions of 0.01, 0.02, 0.05, 0.10 and 0.20 (probability). The comprehensive information of flood range, submerged area and water depth is also retrieved, which is used to calculate flood hazard assessment and mapping. Results reveal that the main parts of Zhongjian River basically meet the flood prevention standard of 0.05 (probability) in Xianfeng County, while the middle-lower section of Taipinggou Valley has lower flood prevention ability. Moreover, this fact proves that the proposed one-dimensional hydraulics flood model is effective.

1. Introduction

Under the combined action of underlying environmental change and global climate change, the frequency of flood disasters in China is gradually increasing, and the impact of disaster losses is expanding. Statistics show that about 50% of China's population and 70% of urban construction are located in flood-threatened areas[1]. Flood disaster has already become a major problem that perplexes the sustainable development of China's economy and society.

The Chinese government attaches great importance to the national flood disaster prevention work. After more than 70 years of hard work, the capital construction of flood prevention projects in major rivers and cities has been completed and played an important role in economic developments. At present, the focus of flood control work is on small and medium rivers and towns along rivers. The Chinese Ministry of Water Resources has set up a major project for mountainous flood disaster prevention and control. Investigation and evaluation of mountainous flood disaster in cities and towns along rivers is an important part of prevention and control of mountainous flood disaster[1-2]. In mountainous riverside countries, it is of great significance for urban flood control and mitigation, population transfer and evacuation, and flood prevention plan compilation to simulate and calculate flood evolution process factors such as flood submerged depth, flood submerged range and flood peak arrival time, and to analyze flood impact combined with GIS, and to indicate the risk degree of flood disaster.

Flood risk analysis has been widely concerned by scholars both at home and abroad, and the combination of model simulation and field verification is the mainstream method at present[3-4].
Aiming at the actual situation of Nanxinwei Flood Control Reserve in Jiangxi Province, Huangping constructed a flood simulation model based on MIKE21 combined with the flood related data in 2010 and 2012, and simulated and analyzed the flood routing process of the flood control area once in 50 years[5]. Shen Shaohong proposed the one-dimensional and two-dimensional coupled hydrodynamic model to evaluate the flood risk of the rivers in Baokang County and the urban areas along the rivers[6]. Wei Kai used the MIKE21 model calibrated by the measured data in 2007 to simulate the time-space change process under a flood diversion condition, which provided technical support for flood control and disaster relief in Mengwa flood storage and detention area. A new flood simulation model was constructed by dynamic coupling of one-dimensional and two-dimensional hydrodynamic models. And the validity of the new model was validated by simulating the breakwater in the flood storage and detention area of Guduiwei Reservoir[8]. In summary, the above studies are mostly the application of new flood calculation methods in some special river sections, while the comprehensive assessment of mountain flood hazards by taking the towns along the river as a whole is still rare, which requires to be deeply explored.

2. Research area
Xianfeng County is located near the valley basin formed by the erosion of mountain rivers. The built area is flat, houses are built mostly along the rivers, the downstream outlet section is narrow, and flash floods caused by sudden rainstorms occur frequently. Local People's Government is in the Gaoleshan Town. It is representative in the analysis of mountain floods in cities and towns along the river.

The main river in Xianfeng County is Zhongjian River. Zhongjianhe River is a tributary of Qingjiang River, which originated from Shiziping in Longjiajie and flowed through Xuan En and then into Qingjiang River. Its watershed area is 238 km², the main stream is 39 km long, and the slope of the river is 6.60‰. Zhongjian River crosses the city from southwest to northeast in Gaoleshan Town. Six tributaries on both sides converge into Zhongjian River. The largest tributary is Taiping Valley. Its watershed is 17.02 km², the length is 3.62 km, and the slope is 3.5‰. Other tributaries are small in scale and have negligible impact on urban areas.

Xianfeng County belongs to the middle subtropical monsoon climate area, located in the vicinity of Zhangjiajie-Wufeng rainstorm area, with abundant rainfall. The average annual rainfall is 1505.1 mm. Rainfall is unevenly distributed in the year. Rainfall from April to October accounts for 83% of the whole year, mostly concentrated in June to August. From 1998 to 2016, Gaoleshan Town of Xianfeng County suffered eight major floods, mainly in 1990, 1991, 1998, 1999, 2000, 2004, 2010 and 2016.

3. Methology
The main river in Xianfeng County is Zhongjian River. Therefore, the source of the flood is the influx of the flood in the main stream of Zhongjian River and the flood in the Taiping Valley, a tributary of Zhongjian River. The incoming water in the local built-up area can be neglected.

3.1. Flood calculation scheme
Considering that the flood prevention standards of the levee in the Gaoleshan Town is 0.05 (probability), the flood calculation scheme is proposed (Table 1). The flood calculation of Zhongjian River is designed to four scales: 0.1(probability, approximately once a 10 years), 0.05(probability, approximately once a 20 years), 0.02(probability, approximately once a 50 years), and 0.01(probability, approximately once a 100years). And the flood calculation of Taiping Valley is designed to five scales: 0.05(probability, approximately once a 20 years),0.1(probability, approximately once a 10 years), 0.05(probability, approximately once a 20 years), 0.02(probability, approximately once a 50 years), and 0.01 (probability, approximately once a 100 years).
Table 1. Flood calculation scheme in Xianfeng County

| Rivers     | $p$  | Flood scale                                                                 |
|------------|------|-----------------------------------------------------------------------------|
| Zhongjian  | 0.01 | Once a 100 years in the Zhongjian River, together with the corresponding flood in the Taiping Valley |
| River      | 0.02 | Once a 50 years in the Zhongjian River, together with the corresponding flood in the Taiping Valley |
|            | 0.05 | Once a 20 years in the Zhongjian River, together with the corresponding flood in the Taiping Valley |
|            | 0.1  | Once a 10 years in the Zhongjian River, together with the corresponding flood in the Taiping Valley |
| Taiping    | 0.01 | Once a 100 years in the Taiping Valley, together with the flood once a 20 years in the Zhongjian River |
| Valley     | 0.05 | Once a 20 years in the Taiping Valley, together with the flood once a 20 years in the Zhongjian River |
|            | 0.1  | Once a 10 years in the Taiping Valley, together with the flood once a 20 years in the Zhongjian River |
|            | 0.2  | Once a 5 years in the Taiping Valley, together with the flood once a 20 years in the Zhongjian River |

3.2. Flood analysis model

The one-dimensional hydraulic method is proposed. According to the topographical, hydrological, and river section observation datasets of Xianfeng County, the flood range, water depth, and submerged area of the Zhongjian River and Taiping Valley is calculated by this one-dimensional model, which is established by Saint-Venant equations on the basis of TUFLOW software.

3.2.1. Calculation range. As shown in Figure 1, the red line represents river system in the calculation range. When calculating the main stream of the Zhongjian River, the upstream starts from the Maliuba and the downstream is at the Yangsiba. Meanwhile, when calculating the Taiping Valley, the upper boundary comes from the Qinglongzui. And the lower boundary is the intersection of Taiping Valley and Zhongjian River. The blue line represents the one-dimensional hydrodynamic model range of the river.

![Figure 1. The rivers (blue line) and flood calculation border (red line) in Xianfeng County](image)

3.2.2. Model principle. The basic equation for solving one-dimensional hydraulic model is the Saint-Venant equations.

\[
\frac{\partial A}{\partial t} + \frac{\partial Q}{\partial x} = q
\]

Momentum equation:

\[
\frac{\partial Q}{\partial t} + \frac{\partial}{\partial x} \left( A \frac{Q^2}{A} \right) + gA \frac{\partial \xi}{\partial x} + g \frac{Q|Q|}{C^2AR} - u \cdot Q = 0
\]
In the above equations, A is cross-section area; Q is cross-section discharge; \( \dot{Q} \) is cross-section flow velocity; x, T are distance coordinates and time coordinates; q is single width discharge of source and sink; \( \alpha \) is momentum correction coefficient; G is gravity acceleration; water; C is Xie Cai coefficient; R is hydraulic radius.

A very stable and accurate second-order Lagrangian scheme is used for one-dimensional numerical solution. The equation can be written as follows:

\[
\frac{\partial (uA)}{\partial x} + B \frac{\partial \zeta}{\partial t} = 0
\]

\[
\frac{\partial u}{\partial t} + u \frac{\partial u}{\partial x} + g \frac{\partial \zeta}{\partial x} + k |u| u = 0
\]

In the above equations, U is the average velocity of cross section, B is the storage width, K is the energy loss coefficient, and the calculation formula is \( k = \frac{g n^2}{R^{5/3}} + \frac{f_1}{2g \Delta x} \) n is the Manning coefficient; \( f_1 \) is the shape energy loss coefficient; and \( \Delta x \) is the grid element in the X direction.

3.2.3. Model boundaries. When calculating the Zhongjian River, the upper boundary conditions is flood process line for each designed frequencies at Maliuba, while encountering the corresponding flood process line of the Taiping Valley. The lower boundary condition is the most downstream section of the river channel. When calculating Taiping Valley, the upper boundary condition is taken from the typical frequency flood process line at Qinglongzui, and the lower boundary is taken from the fixed flood process line(approximately once a 20 years) of the Zhongjian River.

3.2.4. Model parameter setting
- Roughness coefficients. According to the Chinese manual of hydraulic calculation [12], the roughness coefficient is selected as the follows: the river channel is 0.03~0.035, the water-passing house is 0.15, the village is 0.07, the forest is 0.065, the paddy field is 0.05, and the open space is 0.035.
- Calculation parameters. The full calculation duration of each scheme is 40h, the peak value of the flood peak appears at approximately10-15h, the calculation time step is 5s, and the output time interval is 30m.

3.3. Evaluation of current flood control capability
The evaluation of current flood control capability is based on the maximum submergence range, maximum submerged depth, water level and discharge relationship of each cross-section under each frequency of flood. It determines the typical frequency of flood control objects when they begin to be affected by flood, and analyses the flood risk and current flood control capability of disaster prevention objects such as cities and towns.

According to the Technical Requirements for Analysis and Evaluation of Mountain Flood Disasters compiled by the Chinese Ministry of Water Resources[11], the current flood control capacity is less than 10 years is defined as extremely high-risk area (EHR), the current flood control capacity is between 10 and 20 years is high-risk area (HR), and the current flood control capacity is greater than 20 years is risk area (R).

4. Result and analysis

4.1. Zhongjian River

4.1.1. Submerged area and maximum submerged depth
Taking the once in a 100 year as an example. As shown in Table 2, the main submerged areas of Zhongjian River are concentrated along the Wayaogou-Nanmen Bridge. The total area of the submerged area is about 0.31 km². The average submerged depth is about 2 m. The maximum submerged depth is near Yangsiba, and the water depth is about 6.49 m.
Table 2. Flood Submerged information under different frequency
In Zhongjian River and Taiping Valley

| Flood frequency P(%) | Zhongjian River | Taiping Valley |
|----------------------|-----------------|----------------|
|                      | Submerged area (km²) | Maximum submerged depth (m) | Submerged area (km²) | Maximum submerged depth (m) |
| 0.01                 | 0.31            | 6.49            | 0.11            | 2.57            |
| 0.02                 | 0.25            | 4.25            | 0.09            | 1.89            |
| 0.05                 | 0.19            | 3.79            | 0.07            | 1.07            |
| 0.1                  | 0.14            | 1.24            | 0.05            | 0.84            |
| 0.2                  |                 |                 | 0.04            | 0.49            |

4.1.2. Designed flood process
Taking Xianfeng County Food Bureau Bridge as an example. As shown in Figure 2, the flood peak at each frequency at this section is about 730-732 m, and the flood peak arrival time is about 11-13 hours.

4.2. Taiping Valley

4.2.1. Submerged area and maximum submerged depth
Taking the once in a 100 year as an example. As shown in Table 2, the main submerged areas of Taiping Valley are concentrated along the entrance of Xiejiawan to Zhongjian River confluence. The total area of the submerged area is about 0.11 km². The average submerged depth is about 0.7 m. The maximum submerged depth is near the entrance of Zhongjian River confluence, and the water depth is about 2.57 m.

4.2.2. Designed flood process
Taking Xianfeng Water Conservancy and Fisheries Bureau Bridge as an example. As shown in Figure 3, The flood peak of each frequency at this section is about 731-733 m, and the flood peak arrival time is about 9-13 hours.

4.3. Flood hazard assessment
Based on the calculation results of different flood schemes, the typical flood frequencies of different regions when they are affected by floods are analyzed, and the flood risk and current flood control capacity of different regions are determined, as shown in Figure 4.

As a result of the Zhongjian River levee regulation project, the current flood control capacity of most areas in Xianfeng County is higher than once in 20 years. Only the current flood control capacity of the main stream of Zhongjian River between the county industrial and commercial bureau and the County Grain Bureau is once in 10-20 years. The upstream reaches of Taiping Valley are natural rivers. The disorderly construction on both sides of the middle and lower reaches of the river is very
serious, which leads to insufficient flood-carrying capacity of the river. The current flood-control capacity is less than once in 10 years. It is necessary to carry out river regulation to improve flood-carrying capacity and reduce possible losses caused by floods.

5. Conclusions

Taking cities and towns along rivers in mountainous areas as objects, it is of great significance to construct hydraulic models of rivers and their surrounding areas, to simulate flood submergence process, to calculate flood impact, and to draw the distribution map of flood control capacity, for mountainous flood monitoring and early warning.

According to the river system, meteorological flood, topography and geomorphology of Xianfeng County, a flood analysis scheme is designed. Flood process simulation is carried out based on TUFLOW software. More accurate data of flood submergence depth and area are obtained, and flood risk assessment is carried out with GIS. The results show that the main river sections of the main stream of the Zhongjian River meet the flood control standards of 20 years, and the current flood control capacity of the river section of the Taiping Valley is lower, which are basically consistent with
the Xinanfeng County Flood Control Emergency Plan. Moreover, this fact proves that the proposed one-dimension hydraulics flood model is effective.

The future work is to promote flood hazard map results to urban important units, such as government administration, enterprises, institutions, schools and hospitals, which will extend the availability of the flood simulation results in flood disasters prevention and reliefs.

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