2D Hydraulic modelling of the main urban area of Chongqing, Part 1: model building and calibration

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Abstract. The main urban area of Chongqing reach is located at the fluctuating backwater area of the Three Gorges reservoir. The operation of the reservoir has a significant impact on the erosion and deposition of this reach, not only the total amount and scope, but also the period in one year. In this paper, a two-dimensional hydraulic mathematical model was built in order to simulate the sediment deposition in this reach. The calibration was carried out by using some series of field data to provide the accurate parameters, such as roughness, sediment capacity. And values of roughness, coefficient and index of sediment carrying capacity, saturation coefficient of deposition and erosion are suggested after the calibration.

1. Introduction
The Three Gorges Project (TGP) is a large-scale, multi-objective water conservancy project in the world. It undertakes major tasks such as flood control, power generation, shipping, water supply, water ecological regulation and tourism. On the basis of comprehensive consideration of flood control, comprehensive benefit development, sediment control and project investment, the operation of the TGP is constantly updated. In recent years, the TGP has carried out a middle-small-flood-detention operation in flood season. Since the sediment from the upper Yangtze River is mainly concentrated in the flood season, this operation will accumulates the sediment aggradation in the reservoir. The main urban area of Chongqing reach is located at the fluctuating backwater area of the Three Gorges reservoir, as shown in Figure 1. The operation of the reservoir has a significant impact on the erosion and deposition of this reach, not only the total amount and scope, but also the period in one year. More and more attention has been paid to the erosion and deposition of the Three Gorges Reservoir in the main urban area of Chongqing [1-4]. In this paper, a two-dimensional (2D) hydraulic mathematical model, involved both water and sediment transportation, for the main urban area of Chongqing reach was built. Then the calibration was carried out by using some series of field data to provide the accurate parameters, such as roughness, sediment capacity.

2. Model building
2.1. Study area
The study area, main urban area of Chongqing reach, is located at the end of the backwater of the Three Gorges Reservoir (TGR), with a total length of about 60km. Among them: the main stream section of the Yangtze River is about 40km from Dadukou to Tongluoxia; the Jialing River section is about 20km from the Jingkou to Chaotianmen. Under the influence of geological structure, the river reach in the main urban area of Chongqing reach is in the form of continuous bends, including 6 continuous bends in the main stream of the Yangtze River and 5 in the Jialing River. The curve sections are connected by...
straight transition sections. The proportion of curve sections and straight transition sections is about 1:1, as shown in Figure 1. The width of the river section alternates with that of the narrow section. The width of the open section differs greatly from that of the narrow section. The shoreline is uneven, and there are often stone mouths on the bank. The main stream of the Yangtze River is generally 700-800m wide in flood period, 1300m wide in bifurcated section (Jiulongpo section), and only over 300m wide in the narrowest section (Tongluoxia section. The Jialing River is generally 400-500m wide in flood period, 800m wide in the widest section, and only about 370m wide in the narrowest section.

2.2. Governing equations
The governing equations include the flow and sediment equations. The flow equations include continuous equation and momentum equation can be shown as [5]:

\[
\frac{\partial h}{\partial t} + \frac{1}{C_z C_y} \left( \frac{\partial}{\partial \zeta} \left( C_z u \right) + \frac{\partial}{\partial \eta} \left( C_y v \right) \right) = -g \frac{\partial h}{\partial \zeta} + f v
\]

\[
\frac{\partial v}{\partial t} + \frac{1}{C_z C_y} \left[ \frac{\partial}{\partial \zeta} \left( C_z \frac{\partial v}{\partial \zeta} \right) + \frac{\partial}{\partial \eta} \left( C_y \frac{\partial v}{\partial \eta} \right) + u \frac{\partial C_y}{\partial \zeta} - v \frac{\partial C_z}{\partial \eta} \right] = -g \frac{\partial h}{\partial \eta} - f u
\]

Where \( \zeta \) and \( \eta \) represent two orthogonal curvilinear coordinates in orthogonal curvilinear coordinate system; \( u \) and \( v \) represent velocity along \( \zeta \) and \( \eta \) directions respectively; \( h \) represents water depth; \( H \) represents water level; \( f \) represents Coriolis coefficient; \( C_z \) and \( C_\eta \) represent Lame coefficient in orthogonal curvilinear coordinate system.

The suspended sediment movement equations is as follows:

\[
\frac{\partial h S_s}{\partial t} + \frac{1}{C_z C_y} \left[ \frac{\partial}{\partial \zeta} \left( C_z h S_s \right) + \frac{\partial}{\partial \eta} \left( C_y h S_s \right) \right] =
\frac{1}{C_z C_y} \left[ \frac{\partial}{\partial \zeta} \left( \frac{C_z}{C_\eta} \frac{\partial h S_s}{\partial \zeta} \right) + \frac{\partial}{\partial \eta} \left( \frac{C_y}{C_\eta} \frac{\partial h S_s}{\partial \eta} \right) \right] + \alpha \omega_s (S_s' - S_s)
\]
Where, \( S_L^* \) is the sediment carrying capacity of group \( L \), \( P_{SL}^* \) means the sediment carrying capacity grading of group \( L \), \( \omega_L \) is the settling speed of group \( L \) sediment, \( K_0 \) is the sediment carrying capacity coefficient, an \( \alpha_L \) is the sediment concentration recovery saturation coefficient of group \( L \) sediment.

The bed load sediment movement equations is as flows:

\[
\frac{\partial S_{bL}^*}{\partial t} + \frac{1}{C_zC_v} \left( \frac{\partial}{\partial \xi} \left( C_z h S_{bL} \right) \right) + \frac{\partial}{\partial \eta} \left( C_v h S_{bL} \right) =
\frac{1}{C_z C_v} \left[ \frac{\partial}{\partial \xi} \left( C_z \frac{\partial S_{bL}}{\partial \xi} \right) + \frac{\partial}{\partial \eta} \left( C_v \frac{\partial S_{bL}}{\partial \eta} \right) \right] + \alpha_{bL} \omega_{bL} (S_{bL} - S_{bL}^*)
\]

Where, \( S_{bL}^* \) is the bed load sediment carrying capacity of group \( L \), \( P_{SL}^* \) means the sediment carrying capacity grading of group \( L \), \( g_{SL}^* \) is the bed load transport rate of single width, \( S_{bL} \) is the bed load sediment concentration of group \( L \) sediment, \( \omega_{bL} \) is the bed load settling speed of group \( L \).

The bed evolution equations is as flows:

\[
\gamma \frac{\partial Z_i}{\partial t} = \alpha_L \omega_L (S_i - S_i^*) + \alpha_{bL} \omega_{bL} (S_{bL} - S_{bL}^*)
\]

Where, \( Z_i \) is the bed evolution depth in \( \Delta t \).

### 2.3. Discrete numerical solution

It can be found that the forms of equation (1) to equation (5) are similar and can be expressed in the following general format:

\[
C_z C_v \frac{\partial \psi}{\partial t} + \frac{\partial}{\partial \xi} \left( C_z \frac{\partial \psi}{\partial \xi} \right) + \frac{\partial}{\partial \eta} \left( C_v \frac{\partial \psi}{\partial \eta} \right) = \frac{\partial}{\partial \xi} \left( C_z \frac{\partial \psi}{\partial \xi} \right) + \frac{\partial}{\partial \eta} \left( C_v \frac{\partial \psi}{\partial \eta} \right) + C
\]

Equation (1) to equation (5) can be summed up in the form of equation (7). In the numerical calculation, only a general program is needed for equation (7), and all control equations can be solved by this program. Here, \( \Gamma \) is the diffusion coefficient; \( C \) is the source term. The control volume method is used to discretize the control equations [6]. The calculation area is divided into a series of continuous but noncoincident finite volumes - control volumes. Each control volume contains a calculation node, and a group of discrete equations are obtained. The unknown number is the value of the dependent variable \( \psi \) on the grid node. In this paper, the control surface is placed in the middle of the adjacent nodes, and according to the characteristics of the solution of the convection diffusion equation, it is assumed that the physical quantities between nodes change according to the law of power function, which is related to the convection and diffusion intensity. The calculation equation adopts Pantankar pressure correction method (water depth correction) (i.e. SIMPLEC algorithm) principle [7].

### 3. Model Calibration

#### 3.1. Roughness Calibration

The roughness coefficient used in the two-dimensional mathematical model calculation of river channel is actually a comprehensive coefficient, which reflects the influence of many factors such as the flow resistance of river channel, the change of plane shape of river channel, the generalization of river topography, etc., while the measured data of roughness of natural river channel is relatively lacking. Therefore, the roughness in this river reach is inversely calculated according to the measured hydrological data, and the commissioning is carried out in blocks according to the local topography.

#### 3.1.1. Calibration calculation conditions.

The water level stations of Luozhongzi, Egongyan, Xuantanmiao, Cuntan and Tongluoxia are distributed in the main stream of the Yangtze River in the reach, and Qiansimen and Ciqikou are distributed in the Jialing River. In this study, 11 series of filed
data from 2010 to 2011, shown in table 1, were collected to calibrate the roughness in the reach. In this period, the flow range of Cuntan station is 3380 ~ 22400m$^3$/s.

Table 1. Information of the field data.

| No | Date     | Flow range of Cuntan station(m$^3$/s) |
|----|----------|----------------------------------------|
| 1  | 2010-3-30| 3380                                   |
| 2  | 2010-5-17| 8130                                   |
| 3  | 2010-7-31| 22400                                  |
| 4  | 2010-9-30| 13600                                  |
| 5  | 2010-12-6| 4670                                   |
| 6  | 2011-1-13| 4180                                   |
| 7  | 2011-4-17| 4570                                   |
| 8  | 2011-5-23| 7620                                   |
| 9  | 2011-7-28| 14200                                  |
| 10 | 2011-9-24| 12200                                  |
| 11 | 2011-10-13| 10200                                  |

3.1.2. **Results of the roughness calibration.** Table 2 gives a water level error statistics, Figure 2 are the relationship between the roughness and the discharge. It can be seen that the error between the calculated water level value and the measured value is relatively small except for individual measurement times, and the average error of water level of luoneutron, Egongyan, xuantanmiao and Cuntan stations is 0.02m, - 0.05m, 0.01m and 0.03m respectively. According to the results of the roughness determination, there is a certain correlation between the roughness and the discharge in the three reaches of the main stream of the Yangtze River: entrance to Egongyan, Egongyan to Xuantanmiao, and Xuantanmiao to Cuntan. The relationship between the roughness and the discharge of Jialing River is poor, and the fixed roughness of the Ciqikou - Qiansimen is generally between 0.02 and 0.03. The relationship between the roughness and the discharge from Qiansimen to the confluence station is more scattered, and there is no obvious change rule. Considering the close distance between Qiansimen station and confluence, the river bed characteristics are similar to the main stream of the Yangtze River near the confluence. As a result, the correlation between the roughness of the main stream section Xuantanmiao to Cuntan section and the flow is adopted in this section. Based on the calculation results of comprehensive roughness calibration, the average roughness of the calculated river reach is about 0.0283.

Table 2. Statistics of the water level error in calibration calculation.

| Date     | Luozhongzi | Egongyan  | Xuantanmiao | Cuntan | Qiansimen | Ciqikou |
|----------|------------|-----------|-------------|--------|-----------|---------|
| 2010-3-30| -0.22      | -0.19     | +0.01       | +0.03  | +0.01     | +0.14   |
| 2010-5-17| +0.05      | -0.09     | +0.01       | +0.04  | +0.02     | +0.01   |
| 2010-7-31| +0.11      | +0.00     | +0.01       | +0.04  | +0.17     | +0.01   |
| 2010-9-30| +0.08      | +0.03     | +0.03       | +0.04  | +0.02     | +0.01   |
| 2010-12-6| +0.01      | +0.03     | +0.00       | +0.05  | -0.07     | -0.03   |
| 2011-1-13| +0.01      | -0.01     | +0.00       | +0.04  | -0.02     | -0.01   |
| 2011-4-17| +0.00      | -0.23     | +0.00       | +0.01  | +0.04     | +0.04   |
| 2011-5-23| +0.03      | -0.17     | +0.00       | +0.02  | +0.02     | +0.00   |
| 2011-7-28| +0.07      | +0.03     | +0.04       | +0.05  | +0.03     | -0.01   |
| 2011-9-24| +0.05      | +0.01     | +0.01       | +0.02  | +0.02     | -0.01   |
| 2011-10-13| +0.03     | +0.01     | +0.00       | +0.04  | -0.02     | +0.06   |
3.2. River bed evolution calibration

In the study of the unbalanced transport of suspended load, the value of the coefficient of sediment recovery and saturation is very important. It reflects the recovery speed of the sediment concentration close to the sediment carrying capacity. It is a very complex parameter, which is related to both the incoming water and sediment conditions and the riverbed boundary conditions. In addition, the coefficient and index of sediment carrying capacity also play an important role in riverbed erosion and deposition.

In order to analyze the influence of parameters on the calculation of scour and deposition, 8 conditions are considered to carry out the river bed evolution Calibration. The calculation period is from June 2009 to December 2012, and the initial terrain is measured in 2009. The values of each parameter are shown in table 3, and the corresponding calculation results are shown in Figure 3.

Table 3. Case of the calculation of river bed evolution.

| Case No | Coefficient of sediment carrying capacity | Index of sediment carrying capacity | Coefficient of sediment recovery and saturation |
|---------|------------------------------------------|-----------------------------------|-----------------------------------------------|
|         |                                          |                                   | Deposition | Erosion |
| 1       |                                          |                                   | 0.25       | 0.10    |
| 2       | 0.24                                     | 0.98                              | 0.05       | 0.05    |
| 3       | 0.24                                     | 0.98                              | 0.10       | 0.05    |
| 4       | 0.12                                     | 0.98                              | 0.05       | 0.50    |
| 5       | 0.36                                     | 0.80                              | 0.05       | 0.05    |
| 6       | 0.24                                     | 1.20                              | 0.25       | 0.10    |

According to the calculation results, the analysis shows that the changes of saturation coefficient of erosion recovery has little effect on the cumulative erosion and deposition, but that of the deposition has great effect. At the same time, the value of sediment carrying capacity coefficient and index has relatively little effect on the calculation results. Since the reach is within the range of the variable backwater area of the Three Gorges Reservoir, sediment deposition is mainly phenomenon is this area, the calculated scour and siltation amplitude is closely related to the saturation of deposition. Considering that there is no great difference in riverbed topography and sediment movement in the calculation river section, it is suggested that the parameters of case 3 should be taken as sediment calculation parameters.
4. Conclusion
A two-dimensional hydraulic mathematical model, involved both water and sediment transportation, for the main urban area of Chongqing reach was built in this paper. And then the calibration was carried out by using some series of field data to provide the accurate parameters, such as roughness, sediment capacity and saturation coefficient. The results shows that the average roughness of the calculated river reach is about 0.0283. And the changes of saturation coefficient of deposition has great effect on the erosion and deposition. The values of coefficient and index of sediment carrying capacity, saturation coefficient of deposition and erosion is suggested taken as 0.24, 0.98, 0.1 and 0.05, respectively.

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