Deposition and erosion in the fluctuating backwater reach of the Three Gorges Project after upstream reservoir adjustment

Yongjun LU¹, Liqin ZUO², Rongyao JI³, and Huaixiang LIU⁴

Abstract

The construction of hydropower projects, such as Xiluodu and Xiangjiaba Reservoirs, in the upper Yangtze River will lead to variations of the incoming water and sediment conditions and in turn changes in the deposition and erosion processes in the fluctuating backwater reach of the Three Gorges Project (TGP). In this paper, based on the water and sediment characteristics, a 2D mathematical model in the boundary-fitting orthogonal curvilinear coordinate system has been employed to predict the space-time changes of sedimentation in the Chongqing reach, part of the fluctuating backwater reach of TGP, in a period of 100 years with repetition of the 1961–1970 hydrological series with and without the construction of upstream reservoirs. The results show that in the case of natural hydrological series (NHS) without upstream reservoirs, severe deposition occurs in bays with concave bank lines, recirculation flow areas and wide-shallow reaches. In the case with the adjustment of upstream reservoirs, only a little deposition exists in bays with concave bank lines, and the amounts of deposition in the Yangtze River and Jialing River reaches are about 10–20% of those in the case of NHS. Therefore, this is helpful to maintain the effective capacity of the TGP Reservoir and utilize the bank lines of the Chongqing reach.

Key words: Reservoir, Adjustment of water and sediment, Fluctuating backwater reach, Deposition and erosion, Mathematical model, Chongqing reach, Yangtze River, Jialing River

1 Introduction

Sedimentation in a reservoir is of global concern for water management because it gradually reduces the capacity of the reservoir. The overall annual rate of reservoir storage capacity loss due to sedimentation is estimated to be typically 1–2% of the total storage capacity (Yoon, 1992; Yang, 2003). Therefore, research of reservoir sedimentation is necessary for hydraulic structure design and management purposes where different empirical and numerical models are employed to determine the total quantity of deposition, as well as the pattern and distribution of deposits in a reservoir. Empirical models are mainly based on field surveys and observations. Early in 1960, a longitudinal distribution model of reservoir sedimentation was developed according to empirical curves by Borland and Miller. Strand and Pemberton (1982) estimated the siltation ratio from statistics of American reservoirs’ operation in dozens of years. Phatarford et al. (1990) predicted the sedimentation process of the John Martin Reservoir (USA) using a Markov chain model. Jothiprakash and Garg (2009) introduced an Artificial Neural Network method to improve a sedimentation prediction model. Similar empirical models were established by Shen and Julien (1993), Morris and Fan (1998) and others. Likewise, numerical models for predicting reservoir sedimentation were developed based on the flow and sediment transport equations, such as the early models proposed by Chen et al. (1978) and Soares et al. (1982). In recent years, models such as GSTARS 3.0 (Yang and Simoes, 2001) and others (Kantoush et al., 2008;...
Khosronejad, 2009) also use numerical approaches. However, prediction of reservoir sedimentation has never been an easy task due to complex processes involved such as sediment transport, erosion and deposition. Fan (1988) reviewed twelve reservoir sedimentation models and stated that different models may give significantly different results even when using the same set of input data. Therefore, further research on sediment transport modeling is still required.

In China, since rivers have relatively higher sediment concentrations than the world average, reservoir sedimentation has been a serious problem (Long and Chien, 1986; Wang et al., 2008). The Three Gorges Project (TGP), known as the largest hydropower project in the world, was constructed at Yichang, where the Yangtze River’s middle and upper reaches meet (Fig. 1). The reservoir created by TGP is about 660–760 km in length and 1.12 km in width on average, containing 39.3 km³ of water. The fluctuating backwater reach is about 200 km long, from Jiangjin to Jiandao Gorge between the extended backwater ends corresponding to the normal pool level (175 m) and flood control level (145 m) at dam site (Fig. 1). Due to TGP’s different operation schemes the water levels in this reach vary dramatically. The fluvial morphology here tends to be more sophisticated than normal reaches since it is affected by both upstream river flow and downstream reservoir backwater. Dou et al. (1995) and Han et al. (1996) argued that under natural conditions, the riverbed is dominated by deposition during the flood season and by erosion at the end of and after the flood season, so that the erosion and deposition will reach equilibrium within one year’s period. After the impoundment of TGP with the scheme of 175 m, this reach will have severe deposition, so that shoals will be formed at both banks and subsequently most harbors will be abandoned. Especially in the Chongqing reach (Fig. 1), the navigation conditions will be deteriorated, and the prospect of Chongqing Harbor as well as the local flood defense and municipal infrastructure will be threatened.

In recent years, the construction of new large reservoirs in the upper Yangtze River, including Xiluodu, Xiangjiaba, Baihetan and Wudongde (Fig. 1), will lead to a new tendency of sedimentation in the TGP Reservoir. The relevant investigations (Mao, 2005) show that with the effect of reservoirs in the upper reaches, the amount of sediment entering the TGP reservoir has been obviously reduced compared with that of the 1961–1970 hydrological series selected for the preliminary design of TGP. The Xiluodu and Xiangjiaba dams have already cut off the Yangtze River on November 8, 2007 and December 28, 2008,
The total storage capacity of the two reservoirs is over 10 billion m$^3$. After the adjustment of water and sediment by the upstream reservoirs, the deposition and erosion in the fluctuating backwater reach will change correspondingly, and different methods and measures should be used to treat the negative effects. Therefore, it is necessary to carry out studies on the space-time variations of deposition and erosion in this reach under different hydrological conditions. In the present study a 2D mathematical model in the boundary-fitting orthogonal curvilinear coordinate system has been applied to calculate the erosion and deposition in the Chongqing reach after 100 years’ operation of TGP in cases with or without reservoirs in the upstream. The results directly demonstrate the impact of upstream reservoirs on this study reach.

2 Chongqing reach and its water and sediment characteristics

The Chongqing reach is the upstream part of the TGP fluctuating backwater area (Fig. 2). It is about 43.6 km long, with upper boundary at Qiezixi (687.6 km away from Yichang) and lower boundary at Tongluoxia (644 km from Yichang). The channel width is 600–800 m in narrow sections and 1,200–2,000 m in wide sections. There are bare rocks on both banks, forming many stone beams, reefs and protrusions. The bank lines are not smooth. Owing to the alternation of wide and narrow channels, the water depth in narrow sections is much larger than that in wide sections. At the wide sections there are many islands and shoals, with transitional shallow areas at the end of them or in between. The shoals locate in the reaches of Jiulongpo, Tongyuanju, Tongluoxia and Jinsu (Fig. 2). A large tributary, the Jialing River, joins the Yangtze River in this reach, and has great effect on water flows and sediment motion in the confluence reach. Especially when the respective flood periods in the main stream and the Jialing River are not coincident, the interaction of the two rivers results in a decrease in flow velocity and sediment carrying capacity. Thus, a large amount of sediment is deposited and shoals are formed in the Jialing river mouth, which directly affect the navigation in the main stream and tributaries (Wang and Chen, 1993).

A hydrological station is located at Cuntan, downstream of the confluence of the Yangtze River and the Jialing River, characterizing the water and sediment conditions of the Chongqing reach. Based on the data measured at Cuntan and two upstream stations at Zhutuo main stream and Beibei (Jialing River) during 1956–2003 before the impoundment of TGP (Fig. 1), the mean annual runoff at Cuntan station is 343.6 billion m$^3$, with about 80% and 20% from the upstream main stream and the Jialing River, respectively, and with the major portion, about 75%, occurring during the flood season from July to September. The mean annual suspended-load sediment yield is $4.18\times 10^8$ tons, with about 73% and 27% from the upstream main stream and the Jialing River, respectively, and with 78–80% occurring during the flood season. The annual mean flow discharge at Cuntan station is about 11,000 m$^3$/s, with the maximum of over 80,000 m$^3$/s and the minimum of 2,000–3,000 m$^3$/s. The change of water level is large, with the maximum daily change of 6–9 m and the yearly change of 20–30 m. The annual gravel bed-load yield at Cuntan station is 217,000 tons, sandy bed-load yield is 241,000 tons, and their summation is about 0.11% of the suspended-load yield. Generally, the bed materials in narrow and deep reaches are coarser than those in wide and shallow reaches, while the bed materials in main streams are coarser than those on shoals.

The low flow season of the Jialing River is from December to March, and the middle flow and flood seasons are from April to November. The flow discharge is small during the dry season, whereas there are a large number of storms during the flood season. The runoff non-uniformly distributes in a year, with the ratio of high to low flows being about 200–300 times. The change of water level corresponds to the discharge variation, with stable water level during the dry season and sharp rising and falling during the flood season. The mean annual suspended-load yield of the Jialing River is $1.48\times 10^8$ tons, about 1/3 of that at Cuntan station (Wang and Chen, 1993). This ratio is larger, about 41.7%, during the dry season. The median diameter of suspended load at Beibei station is close to that at Cuntan station.

3 Mathematical model

The mathematical model is based on the boundary-fitting coordinate system (Willemse, 1986). Details about the governing equations of the 2D mathematical model for water flows as well as their numerical solutions can be found in Lu and Chen (2002). The governing equations, initial and boundary conditions, and treatments of key problems in the sediment model are presented in the following subsections.
3.1 Governing equations

The sediment moving in the water column is distinguished to bed load and suspended load by using the suspension index \( \omega / ku \) (\( \omega \) = settling velocity; \( k \) = Karman coefficient; \( u_* \) = shear velocity). Particles with \( \omega / ku \geq 5 \) are bed load; otherwise, they are suspended load. The non-uniform suspended load and bed load can be divided into \( n \) and \( M-n \) classes, respectively, according to particle size. Here, \( M \) is the total number of size classes for the entire bed material. Let \( S_L \) stand for the suspended-load concentration of size class \( L \) and \( P_{SL} \) be its fractional representation. Thus, the following relations are obtained:

\[
S_L = P_{SL} S, \quad S = \sum_{L=1}^{M} S_L
\]

For the concentration of size class \( L \) of suspended load, the depth-integrated 2D non-equilibrium transport equation is

\[
\frac{\partial h S_L}{\partial t} + \frac{1}{C_L C_s} \left[ \frac{\partial}{\partial \xi} \left( C_L h u S_L \right) + \frac{\partial}{\partial \eta} \left( C_L h v S_L \right) \right] =
\]

\[
- \frac{1}{C_L C_s} \left[ \frac{\partial}{\partial \xi} \left( \epsilon_L C_s \frac{\partial h S_L}{\partial \xi} \right) + \frac{\partial}{\partial \eta} \left( \epsilon_L C_s \frac{\partial h S_L}{\partial \eta} \right) \right] + \alpha_{SL} \omega_L (S^*_L - S_L)
\]

where \( t \) = time; \( \xi \) and \( \eta \) = axes in the orthogonal coordinate system; \( u \) and \( v \) = depth-averaged velocities in \( \xi \) and \( \eta \) directions; \( h \) = water depth; \( \epsilon_L \) and \( \epsilon_L \) = diffusion coefficients of suspended load; \( \sigma_s \) = Schmidt number, assumed as 1; \( S^*_L \) = suspended-load carrying capacity of size class \( L \); \( \omega_L \) = settling velocity of suspended load; and \( \alpha_{SL} \) = suspended-load recovery coefficient.

The 2D non-equilibrium transport equation of bed load developed by Dou (2001) is

\[
\frac{\partial S_{BL}}{\partial t} + \frac{1}{C_L C_s} \left[ \frac{\partial}{\partial \xi} \left( C_L h u S_{BL} \right) + \frac{\partial}{\partial \eta} \left( C_L h v S_{BL} \right) \right] =
\]

\[
- \frac{1}{C_L C_s} \left[ \frac{\partial}{\partial \xi} \left( \epsilon_L C_s \frac{\partial h S_{BL}}{\partial \xi} \right) + \frac{\partial}{\partial \eta} \left( \epsilon_L C_s \frac{\partial h S_{BL}}{\partial \eta} \right) \right] + \alpha_{BL} \omega_L (S^*_L - S_{BL})
\]
where \( S'_{\text{bt}} \) = bed-load carrying capacity of size class \( L \) in terms of sediment concentration at the full water depth, \( S'_{\text{bt}} = g'_{\text{bt}}/\left( \sqrt{u'' + v''^2} \right) \) with \( g'_{\text{bt}} \) = bed-load carrying capacity in terms of transport rate per unit width; \( S_{\text{bt}} \) is the bed-load concentration defined at the full water depth, \( S_{\text{bt}} = g_{\text{bt}}/\left( \sqrt{u'' + v''^2} \right) \) with \( g_{\text{bt}} \) = bed-load transport rate per unit width; \( \alpha_{\text{bt}} \) = bed-load recovery coefficient; \( \omega_{\text{bt}} \) = settling velocity of bed-load; and \( \sigma_{\text{x}} \) = Schmidt number set as 1.

Extension of the 1D bed material sorting model of Holly and Rahuel (1990) to the 2D case yields the following equation for the bed material gradation in the mixing layer:

\[
\gamma_L \frac{\partial S_L}{\partial t} + \alpha_L \omega_L (S_L - S_L^*) + \alpha_L \omega_L (S_{\text{bt}} - S_{\text{bt}}^*) + \omega_L (S_{\text{bt}} - S_{\text{bt}}^*) = 0
\]

where \( E_L \) = thickness of the mixing layer; \( \gamma_L \) = specific weight of sediment; \( \gamma_s \) = dry specific weight of bed material; \( P_{\text{bt}} \) and \( P_{\text{bt}}^* \) = fractions of size class \( L \) in the subsurface and mixing layers of bed material, respectively; and \( Z_L \) = thickness of erosion or deposition for size class \( L \). The last term on the right-hand side represents the exchange between the subsurface and mixing layers. When the mixing layer digs into the subsurface layer, \( \epsilon_1 = 0 \); otherwise \( \epsilon_1 = 1 \).

The mixing layer thickness \( E_L \) is related to the characteristics of bed material. For beds with gravel and sand mixtures, \( E_L = 1.0-2.0 \text{ m} \) during the initial period of erosion. For a sandy bed, \( E_L \) is equivalent to the height of sand waves, generally about 2.0-3.0 m.

Bed deformation equation is

\[
\gamma_L \frac{\partial Z_L}{\partial t} = \alpha_L \omega_L (S_L - S_L^*) + \alpha_L \omega_L (S_{\text{bt}} - S_{\text{bt}}^*)
\]

and the total thickness of erosion or deposition is

\[
Z = \sum_{l=1}^{1} Z_L.
\]

3.2 Initial and boundary conditions

The initial values of water level, velocity and sediment concentration are given at each node, the time series of flow discharge and sediment concentration are specified at upstream inflow boundaries, and the time series of water level is given at downstream outflow boundaries.

The movable boundary technique is applied to handle changes of the water edges as the water level rises and falls. The grid can be judged whether it is above the water surface or not by comparing the water depth to a threshold value. If it is not dry, roughness takes normal values; otherwise, roughness takes an infinite positive number, e.g., \( 10^3 \) (Lu et al., 2005).

3.3 Treatments of key problems

3.3.1 Effective suspended-load transport capacity

The bed material of the Chongqing reach consists of medium and fine sand with grain size less than 0.5 mm. The majority of suspended load is in the grain size range of 0.025-0.18 mm. Han and He (1990) reported that the carrying capacity for suspended load (\( S'_{\text{st}} \)) of size class \( L \) consists of three parts: (1) medium and fine particles of suspended load, which do not exchange with bed material, i.e., the so-called wash load, \( S'_{\text{st}} \); (2) coarse particles of suspended load that deposit on the bed after exchanging with bed material, and part of the bed material can be lifted up and become suspended load, expressed as \( S'_{\text{st}} \left( \alpha_{\text{st}} \right) \); (3) erodible particles of bed material, which can also be partially lifted up, expressed as \( [1 - \frac{P_{\text{st}} S'_{\text{st}} \left( \alpha_{\text{st}} \right)}{S'_{\text{st}} \left( \alpha_{\text{st}} \right)}] P_{\text{st}} S'_{\text{st}} \left( \alpha_{\text{st}} \right) \). Therefore, the following equation is obtained:
\[ S^*_i = SP_{s1} + SP_{s2} S'(L) \left[ \frac{1 - P' S}{S'(\omega)} \right] P_{ps} S' (\omega) \]  

(5)

where \( P_{s1} = \begin{cases} P_1 / P_1 & (L \leq k) \\ 0 & (L > k) \end{cases} \) ; \( P_{s2} = \begin{cases} 0 & (L > k) \\ P_{s2} / P_1 & (L \leq n) \end{cases} \); \( P_{ps} = \sum_{L=1}^{M} P_{ps} \); \( P_1 = \sum_{L=1}^{n} P_{ps} \); \( k \) indicates the grain size dividing wash load and bed load, \( k \leq n \leq M \);

\[ S'(\omega) = \begin{cases} \sum_{L=1}^{M} P_{s1} S'(L) \end{cases} \] ; \( S'(\omega) = \sum_{L=1}^{M} P_{s2} S' (L) \); \( S'(\omega) = \sum_{L=1}^{M} P_{ps} S'(L) \); and \( S'(L) = K_0 \left( \frac{m(L^2 + v^2)}{h} \right)^m \)

where \( m \) and \( K_0 \) = coefficients for the suspended-load transport capacity. \( m = 0.92 \), as suggested by Han and He (1990). \( K_0 = 0.02-0.03 \), as validated by calculations of sediment deposition and erosion in the upstream reaches of the Yangtze River.

The concentration of suspended load should not be larger than its transport capacity, i.e., \( S_i \leq S^*_i \). When \( S_i > S^*_i \),

\[ S^*_i = P_{ps} S'(\omega) \]  

(6)

3.3.2 Incipient motion and transport rate of non-uniform bed load

For non-uniform bed material, particles with different grain sizes have different degrees of exposure and experience different forces from the flow. Coarse particles on the bed are subject to relatively larger forces, while fine particles are “hidden” under larger particles or in their wake flow areas. A parameter \( \xi \) is applied to take into account the exposure and hiding effects of particles. By using the geometric mean grain size \( D_m \) of bed material as the characteristic size, regression analysis of laboratory data from the literature and field data of the San Luis River yields the following equation for the exposure-hiding coefficient (Lu and Zhang, 1992):

\[ \xi = \begin{cases} \begin{align*} 10^{-0.55 \frac{D_m}{D_o} - 0.204 \frac{D_m}{D_o - 0.112} - 0.095 \frac{D_m}{D_o} - 0.16} & \text{if } D \leq 0.5 D_o \\ \begin{align*} \end{align*} & \text{if } D > 0.5 D_o \end{cases} \]  

(7)

The critical Shields number for the incipient motion of sediment particles with the grain size of \( D_i \) is obtained as

\[ \theta_{cr} = 0.031 \xi_i \]  

(8)

Substituting Eqs. (7) and (8) into Gessler’s (1970) formula for the probability of sediment of size class \( L \) resting on the bed yields

\[ q_i = \frac{1}{\sigma \sqrt{2\pi}} \int_{-\infty}^{0} \exp \left( - \frac{t^2}{2\sigma^2} \right) dt \]  

(9)

where \( q_i \) = probability of size class \( L \) resting on the bed; \( \tau_0 = \gamma R J \), bed shear stress; \( \gamma \) = specific weight; \( R \) = hydraulic radius; \( J \) = energy slope; and \( \sigma \) = standard deviation.

In this study, the following transport formula of non-uniform bed load is applied, which was developed based on the stream power theory (Lu and Zhang, 1991):

\[ g_{st} = K_0 \frac{\gamma \tau_0 u_s P_{s1}}{\gamma - \gamma} \left( 1 - 0.7 \frac{\theta_{cr}}{\theta_i} \right) \]  

(10)

where \( u_s = \sqrt{\tau_0 / \rho} \), shear velocity; \( \rho \) = water density; \( \theta_{cr} \) is calculated by Eq. (8); \( \theta_i = \left[ \gamma (\gamma - \gamma) D_i \right] \); and
A comparison of Eq. (10) with the laboratory data of Samaga et al. (1986) and Gilbert (1987) and the field data of sandy bed load measured at the No. 2 station of Xinchang on the Yangtze River indicates that 90% of the predictions are within the error range of 0.5–2.0 in terms of the ratio of the calculated to the measured values (Lu and Zhang, 1992).

3.3.3 Recovery coefficient $\alpha$

Numerical tests show that the value of $\alpha$ in the non-equilibrium sediment transport equations may not change with grain sizes. Generally, for the situation when all size classes of suspended load exchange with bed material, $\alpha = 0.25$; in the case when the coarse particles of suspended load do not deposit and all the erodible particles of bed material are partially eroded, $\alpha = 1.0$; and for the situation when the coarse particles of suspended load deposit and the medium and fine particles of riverbed material are eroded, $\alpha = 0.5$.

4 Model validation

4.1 Computational domain and orthogonal curvilinear grid

The computational domain includes the reach from Qiezixie (inlet) to Tongluoxia on the Yangtze River and the reach from Jinkou (about 25 km away from the confluence) to the confluence on the Jialing River, as shown in Fig. 2. An orthogonal curvilinear grid system of 407×63 nodes is generated, among which 248×31 nodes are arranged for the mainstream from Qiezixi to the confluence, 248×31 nodes for the Jialing River reach, and 159×63 nodes for the mainstream from the confluence to Tongluoxia. The angles between the $\xi$ and $\eta$ grid lines are 88°–92° except for some grids close to the banks. The grid spacing is 80–120 m in the longitudinal direction and 10–40 m in the lateral direction.

4.2 Validation of flow model

The flow model was validated using the water levels measured in the study reach on March 8, September 22 and November 22, 1986 when the flow discharges at Cuntan station were 3,170, 22,600 and 6,400 m$^3$/s, respectively, and at Beibei station were 447, 1,710 and 716 m$^3$/s, respectively. Differences between the calculated and measured water levels are smaller than 0.1 m, except in a few locations. The flow velocities simulated by the model were also compared with those measured at the hydrological Cross-Section Wen-OIII when the flow discharge of the Jialing River was 716 and 1,710 m$^3$/s and at Cross-Section Cuntan when the flow discharge at Cuntan station was 6,400 and 22,600 m$^3$/s. The simulated velocities are in good agreement with the measured data. The details refer to Lu (2007).

The simulation of flow fields reveals that with increase of flow discharge, beach areas are gradually submerged and recirculation flows are caused by local topography. The interaction between the tributary Jialing River and the mainstream Yangtze River depends on their flow ratio $R$, which is defined as the Jialing River flow $Q_{Jia}$ over the Yangtze River flow $Q_{Cun}$ at Cuntan downstream of the confluence. When $R$ is small, e.g. 0.076 ($Q_{Jia} = 1,710$ m$^3$/s and $Q_{Cun} = 22,600$ m$^3$/s), the Yangtze River flow has significant effect on the Jialing River, resulting in tranquil flow with velocity of only 0.2–0.4 m/s in the mouth of the latter. When $R = 0.45$ ($Q_{Jia} = 4,860$ m$^3$/s and $Q_{Cun} = 11,350$ m$^3$/s), water from the Jialing River directly flows towards the right bank of the Yangtze River and thus forms a large area of recirculation flow at the left bank, which is about 400 m long and 300 m wide, as shown in Fig. 3. When the confluence flow ratio is much larger, e.g. $R = 0.72$ ($Q_{Jia} = 10,500$ m$^3$/s and $Q_{Cun} = 14,500$ m$^3$/s), the flow from the Jialing River has velocities up to 5 m/s, and the recirculation flow area increases to 600 m in length and 400 m in width (Lu, 2007).
4.3 Validation of sediment transport model

The sediment transport model was validated using the measurement data of 1986. The simulation period was from the middle of January to the middle of November, 1986, which was divided to 88 time intervals. The time interval length was 3–4 days on average, with 5–6 days during non-flood season and 1–2 days during flood season. Calculation of suspended-load concentration was conducted for 6 size classes, and the percentage of each grain size at the inflow boundaries on the Yangtze River and Jialing River was given as the annual mean values as shown in Table 1. Calculation of bed-load transport was conducted for 7 size classes ranging 1–200 mm. For the coarse gravels and cobbles with sizes of 10–200 mm, the transport rate at the inlet of the main stream reach was determined using the empirical equation established by the Nanjing Hydraulic Research Institute based on measurement data (Dou et al., 1989):

\[ g_b = 8.0 \times 10^{-12} m Q^{2.60} \]  

(16)

where \( m \) is the efficiency coefficient of instruments and has a value of 11.6. Because there was no measurement data of bed load in the Jialing River, its transport rate was estimated by assuming the sediment and flow have the same ratio between the main stream and the Jialing River. The fine gravel bed load of 1–10 mm was specified as 3\% of the sediment transport rate, and the sandy bed load smaller than 1 mm was taken into account in the calculation of suspended load. The initial gradation of bed material was determined using measurement data, with spatial variation being considered, i.e., coarse bed materials in narrow and deep reaches and fine ones in wide and shallow reaches.

Table 1  Size distribution and settling velocity of suspended load

<table>
<thead>
<tr>
<th>Grain size (mm)</th>
<th>0.005</th>
<th>0.0169</th>
<th>0.0368</th>
<th>0.0736</th>
<th>0.169</th>
<th>0.368</th>
</tr>
</thead>
<tbody>
<tr>
<td>( P_s ) Yangtze River</td>
<td>23.6</td>
<td>20.9</td>
<td>25.9</td>
<td>17.6</td>
<td>8.0</td>
<td>4.0</td>
</tr>
<tr>
<td>( P_s ) Jialing River</td>
<td>17.7</td>
<td>19.9</td>
<td>28.9</td>
<td>24.1</td>
<td>7.0</td>
<td>2.4</td>
</tr>
<tr>
<td>Settling velocity (mm/s)</td>
<td>0.016</td>
<td>0.180</td>
<td>0.855</td>
<td>3.39</td>
<td>16.40</td>
<td>51.10</td>
</tr>
</tbody>
</table>

The calculated sediment concentrations and size distributions at Cross-Section Wen-OIII on the Jialing River and at Cuntan station on the Yangtze River are in good agreement with the ones measured on September 22 and November 22, 1986 (Lu, 2007). Table 2 compares the simulated and measured amounts of sediment deposition and erosion in three selected reaches: Jinshaqi reach and Shimen reach on the Jialing River (0–3 km and 10–12 km upstream of the confluence, respectively) and Jiulongpo reach on the Yangtze River (669–674 km upstream of Yichang) (Fig. 2).

The Jinshaqi reach is located at the Jialing River mouth, so its morphological changes are highly affected by the main stream Yangtze River. During January–June 1986, though there was large inflow...
from April to June, due to large confluence flow ratio $R$ (0.2–0.7), the Yangtze River flow had no effect on the Jialing River and there was little deposition in the Jinshaqi reach. From July to September, i.e., the flood season for the Yangtze River, the confluence flow ratio gradually decreased to about 0.10, the backwater effect from the Yangtze River increased, so that the flow velocity and sediment transport capacity in the Jinshaqi reach decreased; however, the sediment concentration in the Jialing River was high up to 2.6 kg/m$^3$, so that a large amount of sediment (up to 370,000 m$^3$) deposited mainly on the right branch of the Jinshaqi reach. After October, i.e., the low flow season for the Yangtze River, its backwater effect on the Jialing River gradually decreased as the confluence flow ratio increased; because the Jialing River flow is nearly clear water with little sediment concentration of only about 0.01 kg/m$^3$, the sediments deposited in the Jinshaqi reach during the flood season started to be eroded, with about 200,000 m$^3$ washed away till the middle of November. The model reproduced these deposition and erosion processes reasonably well, as shown in Table 2 and Fig. 4.

<table>
<thead>
<tr>
<th>Rivers and reaches</th>
<th>Distance (km)</th>
<th>Amount of deposition from Mar. to Sept. 1986</th>
<th>Amount of erosion from Sept. to Nov. 1986</th>
<th>Scour rate (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yangtze River</td>
<td></td>
<td></td>
<td>Calculated</td>
<td>Measured</td>
</tr>
<tr>
<td>Jiulongpo</td>
<td>669–674</td>
<td>187.4</td>
<td>181.7</td>
<td>-97.0</td>
</tr>
<tr>
<td>Jinshaqi</td>
<td>0–3</td>
<td>37.7</td>
<td>37.8</td>
<td>-20.9</td>
</tr>
<tr>
<td>Jialing River</td>
<td>10–12</td>
<td>20.0</td>
<td>23.1</td>
<td>-11.5</td>
</tr>
</tbody>
</table>

In the Shimen reach on the Jialing River, the widest and shallowest segment is about twice as wide as the upstream narrow and deep segment, so that the flow velocity and sediment transport capacity in the wide segment is fairly smaller than those in the narrow segment. Therefore, during the flood season a large quantity of sediment deposited in the wide segment; during the falling season, the main flow returned to the deep channel and the flow velocity increased, so that the deposited sediment was eroded; the bed topography was basically recovered in the low flow season. In the Jiulongpo reach on the Yangtze River, sediment deposition mainly resulted from rapid increase in channel width and decrease in flow velocity and sediment carrying capacity during the flood season. Table 2 shows that the calculated deposition during March–September 1986 and erosion during September–November for these two reaches are close to the measured data.

5 Hydrological series and boundary conditions

5.1 Hydrological series
With the construction of reservoirs and the improvement of vegetation cover in the upstream river system and basin, the amount of sediment entering the TGP Reservoir has an obvious decrease trend.
compared with that based on the 1961–1970 hydrological series, which was selected at the preliminary design stage of TGP. The mean annual sediment yield at Zhutuo station (Yangtze River) during 1992–2003 is 88.3% of the annual average of 1961–1970. The ratio is 73.2% at Cuntan station (Yangtze River) and only 29.2% at Beibei station (Jialing River). After the construction of Xiangjiaba and Xiluodu Reservoirs, the incoming sediment of TGP will further greatly decrease. The construction of Xiangjiaba Reservoir will reduce the total incoming suspended load by about 5 billion tons at Zhutuo station in 10–70 years, and the construction of Xiluodu Reservoir will reduce the total incoming suspended load by about 11.5 billion tons at Zhutuo station in 10–100 years of service of TGP (Mao, 2005).

In order to quantify the space-time changes of sediment deposition and erosion at the Chongqing reach in the TGP backwater water area after the construction of upstream reservoirs, two hydrological series are selected here: the 1961–1970 series used at the preliminary design stage of TGP (called herein the natural hydrological series or NHS) and the assumed series after the completion of key reservoirs in the upper reaches (called the post-reservoir hydrological series or PHS). The key reservoirs include the Xiangjiaba and Xiluodu reservoirs on the upper Yangtze River and the Tingzikou Reservoir (more than 300km upstream of Chongqing) on the Jialing River.

Table 3 gives the mean values of flow discharge, sediment concentration and median diameter at Zhutuo station on the Yangtze River and Beibei station on the Jialing River under the two selected hydrological series. The mean flow discharges at Zhutuo station for NHS and PHS are close in the range of 8,459–8,609 m³/s, while the mean flow discharges at Beibei station for NHS and PHS are the same at 2,386 m³/s. At Zhutuo station, the mean sediment concentration is 1.22 and 0.48 kg/m³ for NHS and PHS, respectively, with a decrease of 60.7%, while \( D_{50} \) is 0.040 and 0.018 mm for NHS and PHS, respectively. At Beibei station, the sediment concentration is 2.30 and 0.55 kg/m³ for NHS and PHS, respectively, while the grain size for PHS (0.034 mm) is close to that for NHS (0.033 mm).

### Table 3: Mean flow discharge, sediment concentration and \( D_{50} \) with different hydrological conditions

<table>
<thead>
<tr>
<th>Hydrological series</th>
<th>( Q ) (m³/s)</th>
<th>( S ) (kg/m³)</th>
<th>( D_{50} ) (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Zhutuo</td>
<td>Beibei</td>
<td>Cuntan</td>
</tr>
<tr>
<td>NHS</td>
<td>8609</td>
<td>2386</td>
<td>10994</td>
</tr>
<tr>
<td>PHS</td>
<td>8459</td>
<td>2386</td>
<td>10844</td>
</tr>
</tbody>
</table>

5.2 Boundary conditions

Boundary conditions required in the present 2D model for the sedimentation processes in the Chongqing reach in cases of NHS and PHS are determined using the 1D model results for the entire TGP Reservoir in the period of 2003–2102 (Mao, 2005). The inlet conditions include the flow discharges, sediment concentrations and gradations at both Qiezixi (Yangtze River) and Jingkou (Jialing River) cross-sections, and the outlet conditions are the water level time series at Tongtianba cross-section (Fig. 2). The 2003 river bathymetry is chosen as the initiation in the calculation.

Figure 5 shows the changes of suspended load (Qiezixi) entering the Three Gorges Reservoir after the construction of Xiluodu and Xiangjiaba Hydropower Projects. The accumulated amount of suspended load at Qizixi is 15.07 billion tons after the operation of both reservoirs for 100 years, indicating a reduction of 18.23 billion tons (54.7%) compared with that of 33.30 billion tons without the adjustment by the two reservoirs. After the operation of 60 years, the sediment deposition in the two reservoirs reaches equilibrium, and the sediment amount from them gradually increases. The incoming suspended load at Qiezixi is 1.46 billion tons during the 61st–70th years of operation of the two reservoirs and 2.31 billion tons during the 71st – 90th years, showing a decrease of 30.6% compared with those in the case of NHS. However, the incoming water at Qiezixi has little change, with a decrease of only 1.7%.

The incoming sediment at Jingkou on the Jialing River for NHS is 1.78 billion tons, and the incoming sediment after the channelization of the Jialing River is only 0.41 billion tons, with a decrease of 77.7%. The Three Gorges Reservoir was operated in the schemes with dry-season impoundment water levels of 135–139 m at dam site during June 2003–September 2006. The impoundment water level in dry season was raised to 156 m during October 2006–September 2007, to 172 m during October 2007–September 2012, and will be at 175 m after October 2012. The Chongqing reach was basically in a natural state during 2003–September 2006, but has been in the fluctuating backwater area since October 2006. Due to
the backwater effect, the water level increases, the flow velocity and sediment transport capacity decrease, so that sediment deposition occurs there.

![Fig. 5 Changes of incoming suspended load of Three Gorges Reservoir for every 10 years](image1)

Figure 6 shows the water levels at the model outlet Tongtianba in the 11th year of operation of Three Gorges Reservoir. The water level under PHS is obviously lower than that under NHS, which is closely related to the reservoir sedimentation.

![Fig. 6 Changes of water level at the model outlet](image2)

6 Changes of deposition and erosion at chongqing reach

6.1 Amount of sediment deposition

Table 4 and Fig. 7 show the amounts of sediment deposition in the main stream and tributary of the Chongqing reach in 100 years of service of Three Gorges Reservoir in cases of NHS and PHS, and Fig. 8 shows the percentage of sediment deposition under PHS to that under NHS. After 20 years of service of TGP, the amount of sediment deposition in the Qiezixi–Tongtianba reach of the Yangtze River is 63,073,000 and 16,951,000 m³ in cases of NHS and PHS, and the sediment deposition in the Jingkou–Chaotianmen (confluence) reach of the Jialing River is 68,942,000 and 9,324,000 m³ in cases of NHS and PHS, respectively. After 100 years, the sediment deposition is 229,241,000 and 39,843,000 m³ in the Qiezixi–Tongtianba reach for NHS and PHS, and 170,870,000 and 17,665,000 m³ in the Jingkou–Chaotianmen reach for NHS and PHS, respectively. The sediment deposition after the adjustment of water and sediment by upstream reservoirs is obviously smaller than that for NHS, only 15.0–27.3% and 10.3–13.5% of the latter in the Qiezixi–Tongtianba and Jingkou–Chaotianmen reaches, respectively. The main reason is that though the mean annual incoming runoffs have little change, but the mean incoming sediment concentrations at both Zhutuo and Beibei stations for PHS reduce to only 39.3%
and 23.9% of those for NHS. The suspended-load $D_{50}$ at Zhutuo station decreases from 0.040 mm for NHS to 0.018 mm for PHS, which also results in increase of sediment transport capacity and decrease of sediment deposition probability.

### Table 4  Amount of sediment deposition in the Chongqin reach for different years of service of Three Gorges Reservoir ($10^6$ m$^3$)

<table>
<thead>
<tr>
<th>Reaches</th>
<th>Service of Three Gorges Reservoir (year)</th>
<th>NHS</th>
<th>PHS</th>
<th>(2)/(1)</th>
<th>NHS</th>
<th>PHS</th>
<th>(4)/(3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Qiezixi–Tongtianba on Yangtze River</td>
<td>20</td>
<td>6307.3</td>
<td>1695.1</td>
<td>26.9</td>
<td>6894.2</td>
<td>932.4</td>
<td>13.5</td>
</tr>
<tr>
<td></td>
<td>40</td>
<td>11239.7</td>
<td>2331.1</td>
<td>20.7</td>
<td>10958.1</td>
<td>1308.0</td>
<td>11.9</td>
</tr>
<tr>
<td></td>
<td>60</td>
<td>15541.8</td>
<td>2652.9</td>
<td>17.1</td>
<td>13630.7</td>
<td>1508.8</td>
<td>11.1</td>
</tr>
<tr>
<td></td>
<td>80</td>
<td>19228.6</td>
<td>2915.4</td>
<td>15.2</td>
<td>15574.3</td>
<td>1640.7</td>
<td>10.5</td>
</tr>
<tr>
<td></td>
<td>100</td>
<td>22924.1</td>
<td>3984.3</td>
<td>17.4</td>
<td>17087.0</td>
<td>1766.5</td>
<td>10.3</td>
</tr>
<tr>
<td>Jingkou–Chaotianmen on Jialing River</td>
<td>20</td>
<td>6307.3</td>
<td>1695.1</td>
<td>26.9</td>
<td>6894.2</td>
<td>932.4</td>
<td>13.5</td>
</tr>
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<td></td>
<td>40</td>
<td>11239.7</td>
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<td></td>
<td>60</td>
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<td>17.1</td>
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<td></td>
<td>80</td>
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<td>15574.3</td>
<td>1640.7</td>
<td>10.5</td>
</tr>
<tr>
<td></td>
<td>100</td>
<td>22924.1</td>
<td>3984.3</td>
<td>17.4</td>
<td>17087.0</td>
<td>1766.5</td>
<td>10.3</td>
</tr>
</tbody>
</table>

**Fig. 7** Temporal variation of sediment deposition and erosion at the Chongqing reach

**Fig. 8** Percentage of sediment deposition at the Qiezixi–Tongtianba reach and Jingkou-Chaotianmen reach under PHS to that under NHS

The model results illustrate that the seasonal morphological changes in the Chongqing reach is highly affected by the upstream inflow and downstream TGP operation. In October–November after the flood season, the TGP begins to impound. When the water level at dam site gradually rises to 175 m, the water level in the Chongqing reach increases and the flow velocity and sediment transport capacity decrease,
resulting in sediment deposition. In the flood season of each year, the water level at dam site decreases to 145 m, the water level of the Chongqing reach experiences little backwater effect from the TGP, so that its main channel bed is slightly eroded. Therefore, the Chongqing reach has an alternative deposition and erosion within a year, with a net deposition tendency in general. Sediment deposition mainly occurs during the period from October to May of the next year, and erosion occurs during June–September. This demonstrates that the Three Gorges Reservoir’s operation guidance “storing clear water and releasing turbid water” works very well to preserve the effective capacity of the reservoir.

6.2 Location of sediment deposition

Figure 9 shows the distribution of sediment deposition along the Chongqing reach after 100 years of TGP service. In the case of NHS, the Chongqing reach has severe deposition, and the channel width for the contour of 175 m after deposition is about 60–70% of that before the TGP construction. In other words, the width of sediment deposition is about 30–40% of the original channel width. Sediment deposition mainly occurs in bays with concave bank lines, recirculation flow areas and wide-shallow reaches, and the bank lines after deposition tends to be smoother. In the case of PHS, there is a little sediment deposition only in bays with concave bank lines, and almost no sediment deposition in other reaches. It has advantages of maintaining the effective capacity of the Three Gorges Reservoir and utilizing the existing bank lines of the Chongqing reach. Note that only the adjustment of water and sediment by the Xiluodu and Xiangjiaba Hydropower Projects is considered in the simulation. If the Baihetan and Wudongde Hydropower Projects in the upstream are constructed, the incoming water and sediment will be further adjusted. In addition, soil and water conservation is to be improved in the upper Yangtze River basin. Therefore, the sediment problem in the Chongqing reach would be much slighter than that estimated in the preliminary design stage of TGP (Dou et al., 1989).

6.3 Effects of sediment deposition on harbor and navigation channels

6.3.1 Chaotianmen harbor area

The Chaotianmen reach is located 660.0 km upstream of Yichang, including both the main stream Yangtze River and the tributary Jialing River. The Chongqing Harbor, the largest harbor in the southwest regions of China, is located in this reach (Fig. 9). Under natural conditions, sediment deposition and erosion processes in this reach are affected by the interactions of the two rivers, as described in Sections 4.2 and 4.3. The Jinshaqi reach on the Jialing River is about 800 m wide, whereas it connects to a narrow upstream reach of 400 m in width. During the flood period, the main flow tends to be straight along the
side of Jinshaqi, and sediment deposition occurs in the slack flow area along the right main channel. After October, the water level falls, the main flow returns to the right channel and the velocity can rise to as high as 5 m/s, which may erode the sediment deposited in the flood season and sometimes result in sand barriers. This lasts for 1–3 days and causes difficulty for vessels to navigate.

After the Three Gorges Reservoir is operated in the 175 m impoundment scheme, the water depths of the Chaotianmen reach are 15–18 m and 3–6 m during dry and flood periods, respectively. Before the TGP water level is risen to 175 m, the main locations of sediment deposition in this reach include the main channel of the Jialing River, the mouth, Yueliangqi and Zhuerqi, due to interactions of the two rivers. During the reservoir impoundment period (dam-site water level at 175 m), the sediment deposition almost has no effect on the water depth in the harbor area of this reach; however, during the reservoir drawdown period, the confluence reach becomes shallow and torrent, the flow velocity reaches up to over 3 m/s, and the navigation of vessels is affected.

Figure 10 shows changes in bed elevation at a typical cross section (location is shown in Fig. 9) of Linjiangmen Port after different years of TGP service under NHS and PHS. Table 5 gives the displacement distances of 175 m contour towards the main river channel after sediment deposition in the harbor area. It is seen that as for the port front, the displacement of 175 m contour towards the main channel after sediment deposition under PHS is only 19.2%–24.0% of that under NHS.

6.3.2 Jiulongpo harbor area

The Jiulongpo reach is located 671.0 km upstream of Yichang, in the middle of the fluctuating backwater area. It is a wide, curved and bifurcated channel (Fig. 9). It has one of the major harbors connecting land and water transportation in the southwest regions of China. During the dry season after the TGP impoundment the raising of water level is about 7–9 m, and about 3–5 m during the flood season. Like in the Jinshaqi reach described in Subsection 6.3.1, due to the shifting of the main flow during dry and flood seasons, there are recirculation and slow flows and in turn sediment deposition in the Jiulongpo Harbor area. During the low-flow reservoir-drawdown period, there would be strong flows with velocity of over 2.5 m/s, which may have certain effect on navigation of vessels.

Figure 11 shows changes in bed elevation at a typical cross section (location is shown in Fig. 9) of Jiulongpo harbor after different years of TGP service under both NHS and PHS. Table 5 gives the displacement of 175 m contour towards the main channel after deposition in the harbor area. The displacement under PHS is only 5.6%–25.5% of that under NHS.

7 Conclusions and suggestions

In this paper, a 2D flow and sediment transport model in the boundary-fitting orthogonal curvilinear coordinate system developed by the authors was applied to simulate the deposition and erosion processes in the Chongqing reach, part of the fluctuating backwater area of the Three Gorges Project. The model was first validated using the field measurement data in the study reach, showing it reproduced well the amounts and locations of deposition and erosion. Then, the model was applied to predict the space-time changes of the sediment deposition and erosion in the Chongqing reach in cases of the selected NHS
(natural hydrological series) and PHS (post-reservoir hydrological series, including Xiluodu and Xiangjiaba Reservoirs on the upper Yangtze River and Tingzikou Reservoir on the Jialing River).

<table>
<thead>
<tr>
<th>Reaches</th>
<th>Front of Jiulongpo Port on the Yangtze River</th>
<th>Front of Linjiangmen Port on the Jialing River</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reservoir service (year)</td>
<td>NHS (1)</td>
<td>PHS (2)</td>
</tr>
<tr>
<td>20</td>
<td>248</td>
<td>14</td>
</tr>
<tr>
<td>40</td>
<td>330</td>
<td>59</td>
</tr>
<tr>
<td>60</td>
<td>367</td>
<td>86</td>
</tr>
<tr>
<td>80</td>
<td>469</td>
<td>92</td>
</tr>
<tr>
<td>100</td>
<td>534</td>
<td>136</td>
</tr>
</tbody>
</table>

The calculated results show that for the NHS, there are 229 million m$^3$ of sediment deposition in the 38.6 km long Qiezixi-Tongtianba reach of the Yangtze River after 100 years of TGP service, whereas due to the adjustment of water and sediment by the reservoirs constructed in the upstream, the sediment deposition reduces to 39 million m$^3$, only 17.4% of that for NHS. The sediment deposition in the 25.0 km long Jingkou-Chaotianmen reach of the Jialing River is 170 million m$^3$ in the case of NHS, but after the construction of reservoirs in the upstream, it reduces to 17 million m$^3$, only 10.3% of that for NHS. In the case of NHS, the Chongqing reach has severe deposition, which covers about 30–40% of the original river width and mainly occurs in bays with concave bank lines, recirculation flow areas and wide-shallow reaches. In the case of PHS there is a little sediment deposition only in bays with concave bank lines. It is in favor of maintaining the effective capacity of the Three Gorges Reservoir and utilizing the bank lines of the Chongqing reach.

The displacement of 175 m contour adjacent to the Jiulongpo port’s frontline under PHS is only 5.6–25.5% of that under NHS. As for the Chaotianmen (Linjianmen) port, this ratio is only 19.2–24.0%. Therefore, after the adjustment of water and sediment in the upstream, the effect of sediment deposition on harbors and navigation channels in the TGP fluctuating backwater reach is much sligher than that in the case of NHS estimated at the preliminary planning and design stage of TGP.

Owing to the complexity of turbulent flows and sediment transport, further studies on the relevant problems discussed in the paper are needed. With the soil and water conservation and the hydropower development in the upper basin of the Yangtze River, the amount of incoming sediment from the upstream still changes. Thus, it is recommended that further investigations should be carried out on the effects of sediment deposition and erosion in the fluctuating backwater reach on the water level, harbors and navigation channels near Chongqing City under new water and sediment conditions.

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