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Morphological responses in a meandering and island-braided reach of the Middle Yangtze River to the Three Gorges Reservoir impoundment

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ABSTRACT

Lateral migration is an important form of morphological changes on the Middle Yangtze River (MYR), particularly for the lower Jingjiang reach. The Three Gorges Reservoir (TGR) has substantially reduced sediment supply to the downstream river channels since its impoundment in June 2003. The scientific understanding of how decrease of sediment influences the processes of bank erosion and channel adjustments is complex and limited. In the present paper, the morphological responses in a typical meandering and island-braided river segment of the MYR to the filling of the TGR were investigated by a 3-D morphodynamic model. The potential of the 3-D model has been demonstrated by the observed data. The morphological evolutions in the Shishou bend during the first 12 years of the TGR impoundment were predicted. The effects of the TGR operation on the planform evolutions in the study reach were analyzed based on the simulated results. Sediment load is decreased by 75% due to the early filling of the TGR. The magnitude of bed degradation with less sediment load due to the TGR operation is increased compared with the pre-dam situation. Qualitatively, the overall planform evolution trends in the Shishou bend after the TGR operation are similar to that without the TGR operation. The magnitude of lateral migration has been increased in some part of the channel bend, where the morphological response of the TGR operation exhibits more lateral migration rather than vertical degradation. Scouring at the bank toe enhances bank failure. Decrease of sediment load and weak bank anti-scour ability as well as the significant helical flow can be responsible for intensified bank erosion in the channel bend.
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1. Introduction

The Three Gorges Reservoir (TGR) has substantially reduced sediment supply to the downstream river channels since its impoundment in June 2003. Among the many physical processes triggered by the filling of the TGR, the degradation of river channel downstream of the project will develop very quickly in the next few decades. Bank erosion frequently occurs on the lower Jingjiang reach of the Middle Yangtze River (MYR), which exhibits a typical meandering channel pattern. The rate of bank retreat in this section reached a maximum of 88.4 m/year after several meander cutoffs in the 1960s and 1970s before the bankline was stabilized (Chien et al., 1987), and increased again following the reduction of sediment supply during the last decade due to sediment trapping by tributary reservoirs, even before the impoundment of the TGR in 2003 (Jia et al., 2010). Therefore, the characteristics of lateral migration due to bank erosion in this reach should be considered when predicting the morphological changes after the filling of the TGR. Nevertheless, the processes of bank erosion were not taken into consideration when modeling the fluvial processes in the MYR after the filling of the TGR in the past researches (e.g., Lu et al., 2005; Zhou et al., 2009). Interaction between bank collapse and riverbed evolution is quite complex because of numerous affecting factors (Yu et al., 2015). Scientific understanding of how decrease of sediment influences bank erosion and it's interaction with bed deformation is limited. Recently, numerical simulation of lateral migration and bank erosion processes

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in alluvial channels has attracted the increasing concerns of hydraulic engineers and morphologists. In order to predict long-term migration behaviors of meandering rivers, the analytical models were developed and used (e.g., Ikeda et al., 1981; Lancaster & Bras, 2002; Abad & Garcia, 2004; Huang et al., 2014), which usually assumed that the rate of bank erosion was proportional to the near bank velocity. Several 2-D numerical models have been developed to simulate the channel evolution considering geotechnical failures of riverbanks (e.g., Darby et al., 2002; Zhong & Zhang, 2004; Chen & Duan, 2008; Wang et al., 2008; Wang et al., 2010; Motta et al., 2012; Sun et al., 2015). However, the highly complex 3-D flow in channel bends may undermine the reliability of a depth-averaged 2-D model. More reliable results could be obtained if a 3-D model was applied (Mosselman, 1998). The advantage of 3-D approaches is that many processes in complex river geometries are modeled directly instead of using simplifications (e.g., Lin & Falconer, 1996; Fang & Wang, 2000; Wu et al., 2000; Ruther & Olsen, 2007; Hu et al., 2013). Especially in meandering channels, the secondary flow plays an important role in the bed deformation process (Bai & Wang, 2014).

The objective of this paper is to evaluate the impacts of the TGR operation on the planform evolutions in a meandering and island-braided river segment of the MYR. To achieve this purpose, a 3-D morphodynamic model, in which a physical-based approach for simulation of bank erosion was integrated into a 3-D flow and non-uniform sediment transport model, was applied. The observed data of fluvial processes during the period from 2002 to 2004 in the Shishou bend of the MYR, which is about 270 km downstream from the Three Gorges Dam, were used to validate the model. The morphological changes in the Shishou bend after the first 12 years of the TGR filling were estimated. The effects of the TGR operation on channel adjustments (including lateral migration and vertical degradation) in the channel bend were analyzed based on the simulated results.

2. 3-D morphodynamic model

The 3-D morphodynamic model for flow and sediment transport as well as bank erosion simulation used in the present study was developed by Jia et al. (2010). The 3-D model is based on a collocated grid system in curvilinear coordinates to better fit the irregular boundaries of natural channels. The governing equations for water flow including the continuity and momentum equations (Jia et al., 2010). The transport of non-uniform suspended sediment is governed by the following convection-diffusion equation (Jia et al., 2013):

$$\frac{\partial s_n}{\partial t}+\frac{\partial\left[\left(u_j-\omega_{sn}\delta_{j3}\right)s_n\right]}{\partial x_j}=\frac{\partial}{\partial x_j}\left(\frac{\nu_t}{\sigma_c}\frac{\partial s_n}{\partial x_j}\right) \tag{1}$$

where s_n is the sediment concentration of the nth size fraction (kg/m^3); δ_{j3} is the Kronecker delta; ν_t is the eddy viscosity; σ_c is the Schmidt number relating turbulence diffusivity of sediment to the eddy viscosity, set as 1.0 in this study; and ω_{sn} is the settling velocity of the nth size fraction.

The non-equilibrium bed-load transport equation for non-uniform sediment reads (Wu et al., 2000):

$$\frac{1}{L_s}(q_{bn}-q_{bn*})+D_b-E_b+\frac{\partial(\alpha_{bx}q_{bn})}{\partial x}+\frac{\partial(\alpha_{by}q_{bn})}{\partial y}=0 \tag{2}$$

where L_s is the non-equilibrium adaptation length for bed-load transport; q_{bn} is the bed-load transport rate of the nth fraction; q_{bn*} is the bed-load transport rate of the nth fraction under equilibrium conditions;. D_b and E_b are the downward and upward sediment fluxes at the top of bed-load layer, respectively; α_{bx} and α_{by} are the direction cosines.

The bed deformation is calculated by the sediment mass conservation equation (Jia et al., 2010):

$$\rho_s'\frac{\partial Z_b}{\partial t}+\frac{\partial q_{Tx}}{\partial x}+\frac{\partial q_{Ty}}{\partial y}=0 \tag{3}$$

where Z_b is the local bed level; ρ_s' is the dry bulk density of bed material; q_{Tx} and q_{Ty} are the components of total-load sediment transport (including both suspended load and bed-load) in the x and y directions, respectively.

In order to simulate morphological changes due to bank failure, the bank erosion model considering composite structure presented by Jia et al. (2010) was used in this study. Most of riverbanks on the MYR are stratified with a cohesive upper layer and a non-cohesive lower layer of sand. The present analysis of bank failure is limited to cantilever stability, which is most widely observed on the MYR. Erosion of the bank toe by water flow leads to collapse of the upper riverbank. Stability of the cohesive upper layer of the riverbank depends on the actual width of the cantilever, ΔW, and the critical width of the cantilever, ΔW_c. The critical width of the upper cohesive layer ΔW_c can be expressed as (Jia et al., 2010):

$$\Delta W_c=\sqrt{\frac{T_bH_u}{3\{\gamma_b-c[p(i-1)+p(i+1)]/B\}}} \tag{4}$$

in which ΔW_c is the critical width of the cantilever upper cohesive layer; T_b and c are the tensile strength and cohesion of the cohesive material, respectively; γ_b is the specific weight of the bank material; B and H_u are the longitudinal length and height of the upper cohesive layer, respectively; $p(i-1)$ and $p(i+1)$ are the coefficients.

This 3-D numerical simulation was based on the finite volume method using a non-orthogonal grid system. The pressure–velocity coupling was achieved by applying the SIMPLEC pressure correction algorithm and the momentum interpolation procedure of Rhie and Chow (1983). Based on calculated results of flow velocity and shear stresses, the amount of bed load sediment transport can be evaluated, in addition to suspended load calculations by solving the convection-diffusion equation for suspended sediment transport. Bed bathymetry is updated each time step after sediment transport calculation is completed. The width of bank retreat is evaluated by the bank erosion module based on the calculated amount of bed scour at bank toe (Jia et al., 2010). At certain locations where erosion control revetment or emerging bedrocks are present, neither bed erosion nor bank erosion will be predicted.

3. Calibration of the 3-D model

3.1. Description of the study area and simulation setup

In order to evaluate the potential of the 3-D model for simulation of complex morphological changes in a natural channel bend, the observed data of fluvial processes in the Shishou bend during the period from 2002 to 2004 were used. The Shishou bend is a typical meandering and island-braided river segment on the MYR. Total length of the bend is about 16 km, as shown in Fig. 1. The simulation starts with the 2002 survey data as the initial channel topography (Fig. 1). The horizontal mesh in the computational domain is a non-orthogonal structured mesh with 171×80 grid points, as shown in Fig. 2, which has 171 cross-sections in the streamwise direction, and each cross-section is divided into 80 lateral grid steps. The vertical mesh will be re-generated each time after the water level is changed, and the number of nodes in the vertical direction is 12.

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