Catena 172 (2019) 274–284

Contents lists available at ScienceDirect

Catena

journal homepage: www.elsevier.com/locate/catena

Morphodynamic adjustments in the Yichang–Chenglingji Reach of the Middle Yangtze River since the operation of the Three Gorges Project

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ARTICLE INFO

Keywords:
Three Gorges Project
Yichang–Chenglingji Reach
Morphological adjustment
Delayed response
Equilibrium
Channel geometry

ABSTRACT

To investigate the evolution characteristics of the Yichang–Chenglingji Reach (YCR) of the Middle Yangtze River and develop simulation methods, the temporal and spatial morphodynamic adjustments of the YCR were analysed comprehensively on the basis of runoff, sediment load, and cross-sectional profiles data at 220 cross sections from 2002 to 2016. Results showed that significant channel degradation has occurred in the YCR, especially in the low-flow channels, due to a drastic reduction in sediment yield since the operation of the Three Gorges Project (TGP). The variations of upstream flow and sediment regimes would drive equilibrium channels to become increasingly narrow and deep, and the current bankfull width and depth were less than their equilibrium counterparts in the recent period. However, the recent channel evolution was mainly characterized by the prominent channel deepening via a one-way deformation due to the large-scale bank revetments within the YCR, where the reach-scale bankfull depth increased by 1.6 m in the span of 15 years. A semi-empirical method for determining the equilibrium values of channel degradation and aggradation volume at the YCR was proposed on the basis of a comprehensive analysis of the effects of flow, sediment concentration, sediment gradation, and water depth. Moreover, the equilibrium values of the channel width and depth were estimated with the Least Action Principle method. The calculation methods for the equilibrium width, depth, width/depth ratio, and aggradation/degradation volume were combined with the Delayed Response Model (DRM). Then, the methods for calculating the variations in channel geometry and aggradation/degradation volume were derived. Results showed that the proposed methods effectively simulated the channel geometry and cumulative erosion volume in the YCR from 2002 to 2016. In addition, the response of the channel evolution in the YCR was closely related to the previous four-year hydrological conditions, implying that channel evolution may lag behind the variations of flow and sediment discharges.

1. Introduction

The construction of large reservoirs is expected to profoundly change the characteristics of downstream flow and sediment transport, including by decreasing flood frequency and duration, causing seasonal changes of flow, such as increased discharge in dry seasons and drastic reduction of sediment discharge (Makaske et al., 2012; Petts and Gurnell, 2005; Williams and Wolman, 1984). In general, upstream damming can lead to significant erosion downstream (Fang et al., 2012; Han et al., 2011), in which the scouring intensity is much higher than that in natural rivers (Knighton, 1998), along with roughening of the riverbed, increased channel sinuosity, and decreased channel slope and sectional width/depth ratio (Julien, 2002; Lai et al., 2017; Shin and Julien, 2010; Yu et al., 2014). These adjustments usually last for decades (Williams and Wolman, 1984) and place rivers under long-term, strong, and non-equilibrium adjustment processes.

A delayed response is an important characteristic of fluvial systems during non-equilibrium adjustment processes. When upstream and downstream controls such as hydrological conditions and base level change, rivers cannot immediately adjust to a new equilibrium state corresponding to the changed conditions; instead, they require a relaxation time to reach equilibrium gradually by means of scour and silting changes as well as other morphological adjustments (Knighton, 1998; Wu et al., 2012). With ever changing control conditions, external conditions are likely to alter again before the river reaches equilibrium; consequently, fluvial systems continuously develop towards a new equilibrium. Therefore, dynamic adjustments are related to not only the current flow and sediment regimes but also the previous conditions through the channel boundaries (Zheng et al., 2014a, 2017). The methods to describe this delayed response include traditional geometric averaging and moving averaging methods, as well as the recently developed Delayed Response Model (DRM, Wu et al., 2012). In terms of

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https://doi.org/10.1016/j.catena.2018.08.040
Received 9 March 2018; Received in revised form 28 August 2018; Accepted 31 August 2018

geometric averaging and moving averaging, Liang et al. (2005) analysed the relation between channel geometry and previous sectional morphology in the Lower Yellow River and concluded that the fluvial system has a "memory effect." Xia et al. (2014) established an empirical relation between bankfull discharge and the average incoming sediment coefficient (ratio of sediment to flow discharge) during the flood season in the Lower Yellow River by means of moving averaging. Based on the Rate Law, which has been introduced into geomorphology by Graf (1977), Wu et al. (2012) assumed that the adjustment rate of a characteristic channel parameter following disruptions is proportional to the differences between its current and equilibrium values, and then developed the DRM, which is widely used in the Yellow River Basin and some other rivers (Wu et al., 2008; Xia et al., 2014; Zheng et al., 2014a, 2017; Li et al., 2015).

The Three Gorges Project (TGP) is the largest integrated hydro-project in the world. Since its operation in 2003, many scholars have paid close attention to morphological adjustments and the delayed response of channel evolution downstream of the dam. For instance, Xia et al. (2016) found that the channel degradation in the Jingjiang Reach of the Middle Yangtze River is greatly influenced by the previous five-year average fluvial erosion intensity during flood season and then proposed an empirical relation between them. Several mathematical models have been established to analyse the morphodynamic adjustments downstream of the Three Gorges Dam (TGD) and the results demonstrated long-distance and long-term scour would occur in the YCR (Fang et al., 2012; Han et al., 2011). Many scholars have recently attempted to apply the DRM in the Middle Yangtze River, but the results obtained are not satisfactory. For example, Liao et al. (2016) applied the model directly to analyse the variations of the bankfull area in the Jingjiang Reach and arrived at a relatively weak correlation of $R^2 = 0.11$. By introducing the ratio of maximum flow to minimum flow during the year as a parameter of equilibrium bankfull area in the model, the determinant coefficient in the Jianli section was slightly improved ($R^2 = 0.6$).

Most previous research on river evolution focused on the channel geometry of alluvial rivers under equilibrium or quasi-equilibrium conditions (He and Wilkerson, 2011; Huang et al., 2014; Knighton, 1998; Lai et al., 2017; Lee and Julien, 2006; Leopold and Maddock, 1953; Liu et al., 2016; Park, 1977). For instance, empirical relationships between equilibrium bankfull geometry and three independent hydraulic elements, namely, discharge, median bed particle diameter, and channel slope, were developed by Lee and Julien (2006), which were tested by 1485 measurements through nonlinear regression analysis. Hadadin (2017) established hydraulic geometry relations (including bankfull discharge, width, depth, sectional area, longitudinal slope, unit stream power and mean velocity) as a function of drainage area in the Yazoo River basin. Franzoia and Nones (2017) developed the 0-D model based on simplified hydro-morphological equations to simulate morphological adjustments of fluvial systems. By introducing the width/depth ratio as an independent variable, the equilibrium channel width and depth were derived by Huang et al. (2014) based on a sound theory of basic flow relationships. However, these equilibrium conditions of hydrodynamic geometry may be not applicable to rivers experiencing remarkably complicated riverbed deformation under the serious influence of human activities, especially the YCR in the immediate downstream of the TGD. Furthermore, little attention is being directed towards the intrinsic mechanism of the self-adjusting process of reach-scale geometry and the development trend of channel equilibrium in the YCR. Hence, combining existing equilibrium theories to accurately describe non-equilibrium morphodynamic adjustments and the delayed response phenomenon of the YCR is a meaningful and important task.

The main objectives of the current study are to: (i) calculate the reach-scale current values and equilibrium values of channel geometry in 2002–2016; (ii) calculate the cumulative erosion volume in the YCR and propose a method to estimate the equilibrium values of channel degradation and aggradation on the basis of a comprehensive analysis of the effects of multiple driving factors; and (iii) analyse the variations of bankfull channel geometry and cumulative erosion volume since the TGP operation, while establishing quantitative relations between current values and equilibrium values through the DRM for both bankfull channel geometry and cumulative erosion volume of the YCR.

2. Study area

The Yangtze River is the largest river in China with a total length of

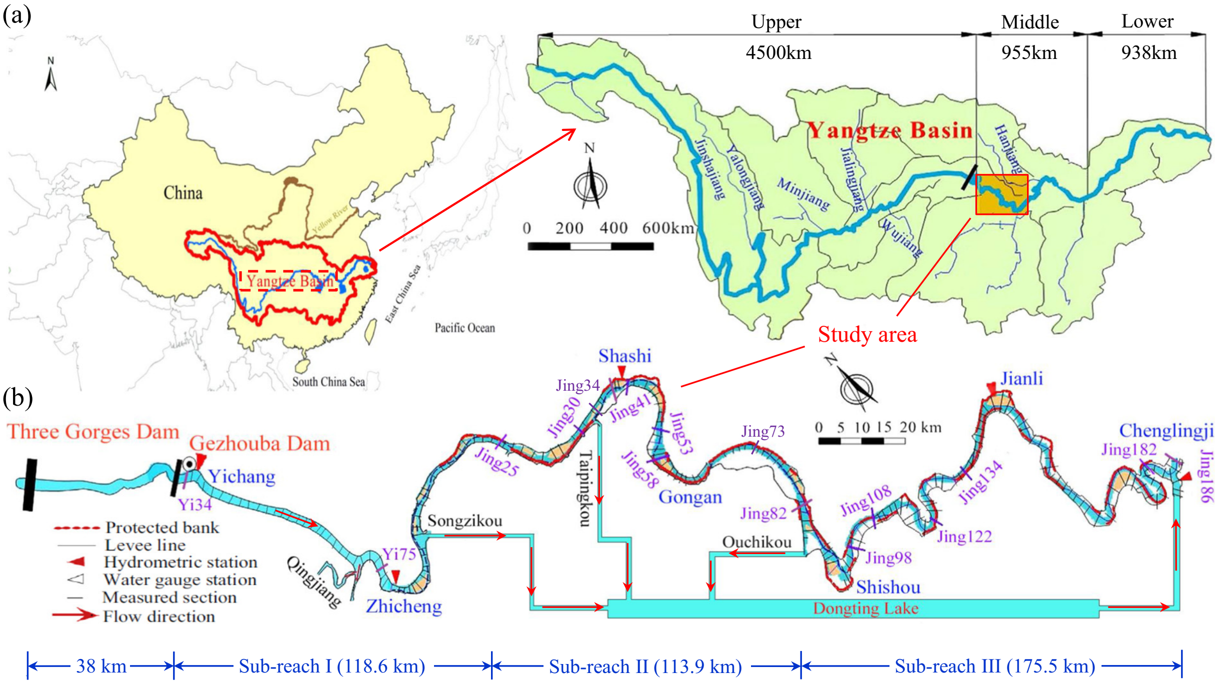

Fig. 1. Sketch map of study area: (a) Yangtze River Basin and (b) the Yichang–Chenglingji Reach with the locations of the 220 cross sections and hydrometric stations.