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Effects of Three Gorges Dam operation on spatial distribution and evolution of channel thalweg in the Yichang-Chenglingji Reach of the Middle Yangtze River, China

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ABSTRACT

The evolution of the channel thalweg and pool-riffle sequences is a critical feature of morphological adjustments in fluvial systems and might have important effects on aquatic habitat quality, channel stability and navigation. Based on the 220 cross-sectional profiles from 2002 to 2016, residual depths and spatial statistical analyses were used to quantitatively analyse the vertical variations and longitudinal distribution of the pool-riffle sequences and channel thalweg in the Yichang-Chenglingji Reach (YCR) of the Middle Yangtze River, which consists of the Yizhi-Zhijiang, Shashi-Gongan and Shishou-Jianli sub-reaches. The results showed that the dramatic reduction in the sediment loads following the construction of the Three Gorges Dam (TGD) has caused significant adjustments in the size, morphological diversity and spatial distribution of pool-riffle structures in the YCR. The average depth of the pools in the Yizhi-Zhijiang Reach and the Shishou-Jianli Reach overall exhibited a nonlinear growth trend, with the average residual depth increasing by 1.4 m and 1.9 m, respectively. However, the average residual depth in the Shashi-Gongan Reach showed a decreasing trend, with a reduction of approximately 1.2 m. The longitudinal lengths of the riffles in all three reaches contracted to different degrees, and the specific percentage of longitudinal river length occupied by riffles (total riffle length/total sub-reach length) decreased by 8%, 9.6% and 5.9% in the three sub-reaches from upstream to the downstream. In addition, the morphological diversity of the thalweg elevation in the Shashi-Gongan Reach and Shishou-Jianli Reach weakened after the construction of the TGD, while the bed topography in the Yizhi-Zhijiang Reach became more complex and diverse. Moreover, the pool-riffle structures in the YCR were rearranged and distributed regularly following the initiation of the TGD operation, although the variation characteristics of the average pool spacing in the three sub-reaches were quite different. Quantitative relationship between the average residual depth and the previous four-year hydrological condition was proposed for the three sub-reaches based on the Delayed Response Model (DRM) and verified using the measurements from 2013 to 2016.

1. Introduction

The channel thalweg is the curve connecting the deepest points of the river, and it is a typical and essential feature in riverbed topography (Summerfield, 1991). The temporal and spatial variations of the channel thalweg in fluvial systems are influenced by many natural and artificial factors (Madej, 1999; Bartley and Rutherfurd, 2002; Macaire et al., 2010; Li et al., 2017) and have important effects on riverbed stability and navigation conditions. Pool-riffle structures are critical elements of thalweg morphology in alluvial rivers and reflect the spatial distribution characteristics of aquatic habitat (Lisle, 1982; Thompson, 2001, 2012; Cao et al., 2003; Hassan and Woodsmith, 2004; Macvicar and Roy, 2007a,b; Schwartz and Herricks, 2007; Yi et al., 2013), which is of great interest to both ecologists and geomorphologists.

In the study of river geomorphology, pools are generally defined as deep regions with low velocities at low water levels, whereas riffles are defined as regions with high velocities and steep water surface slopes at low water levels; thus, riffles mark the transition zones between successive pools (Thompson, 2001). Several methods have been developed to identify pools and riffles in alluvial rivers, which are mainly divided into two categories. One is on the basis of the flow characteristics (Yang, 1971; Knighton, 1998), and the other is on the basis of the topographic features of the riverbed (Leopold et al., 1964; O'Neill and Abrahams, 1984; Lisle, 1987; Peterson et al. 1992; Carling and Orr, 2000; Yi et al., 2013). For example, O'Neill and Abrahams (1984) proposed a bedform differencing technique to identify pool-riffle

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structures in the channel thalweg. Carling and Orr (2000) suggested a zero-crossing method to distinguish pools and riffles. Since the discrimination of the first category of methods is greatly affected by flow conditions, the second one is generally considered to be more reliable in scientific research (Lisle, 1987; Madej, 1999; Thompson, 2002; Yi et al., 2013). To eliminate the impact of discharge on the discrimination of pool-riffle couplets in different reach-scale bedforms, Lisle (1987) introduced the residual-depth concept of ecology into river geomorphology to analyse variations in bed elevation in the channel thalweg. The residual depth refers to the elevation difference between a pool and the downstream riffle crest, which is equal to the water depth in the channel thalweg when the upstream flow is zero (Lisle, 1987; Madej, 1999). In this case, pools can be classified as the area where the residual depth is greater than zero and the remainder of the riverbed topography can be classified as riffles (where the residual depth is equal to zero). The residual depth represents the production capacity of a river system under extremely low flow conditions (such as the worst water-depth condition for fish spawning) and is thus a critical feature that characterizes the variance in riverbed topography in both geomorphology and ecology. Furthermore, the method of measuring the residual depth is straightforward and unbiased; therefore, this parameter has been widely used in the study of pool-riffle sequences in the channel thalweg (Lisle, 1987, 1995; Richmond and Fausch, 1995; Madej, 1999; Cowie et al., 2015; Hoggard et al., 2017).

Most previous research into channel thalweg evolution has focused on lateral migration (Xu, 1997; Jin et al., 2000; Li et al., 2017); however, fewer studies have investigated the vertical variation and longitudinal distribution of pool-riffle sequences in channel thalwegs. Rayburg and Neave (2008) proposed and tested 12 three-dimensional asymmetry indices to evaluate the morphological diversity and complexity of pool-riffle structures in alluvial rivers and determined their most effective combination. Although the location of individual pools and riffles is random in a river system, the pool-riffle sequences usually present a stable statistical characteristic in space (Leopold et al., 1964; Graf, 1979; Myers and Swanson, 1997; Thompson, 2012). Harvey (1975) found that pool–riffle spacing is correlated with a five-year recurrence-interval flow and the mean annual floods. Thompson (2001) proposed a minimum length assumption that will create a minimum pool spacing. In addition, a large number of studies have suggested that the average pool spacing is between five and seven times the bankfull width in alluvial rivers with a stable distribution of pool-riffle structures (Leopold et al., 1964; Keller and Melhorn, 1978; Lofthouse and Robert, 2008). Madej (1999) selected residual depth as a tool to analyse the distribution of the channel thalweg in Redwood Creek in the northern Coast Ranges of California and found that the pool-riffle sequences had a spatial autocorrelation feature. Furthermore, self-formed pool-riffle sequences tend to exhibit a certain regularity or self-similarity; however, this spatial self-similarity between forced pool-riffle sequences is usually poor, which means that a random distribution pattern of pools and riffles likely occurs in forced channels.

Human activities (including upstream damming and bank revetments) can profoundly modify downstream riverbed topography and thus influence the size and frequency of pool-riffle structures (Williams and Wolman, 1984; Yuan et al., 2012; Dai and Liu, 2013; Lai et al., 2017; Zhou et al., 2017; Lv et al., 2018). The Yangtze River, the third longest river in the world, was remarkably affected by the Three Gorges Dam (TGD). Since the TGD operation in 2003, considerable hydromorphological adjustments have occurred in the Yichang-Chenglingji Reach (YCR) of the Middle Yangtze River (Dai and Liu, 2013; Tang et al., 2014; Mei et al., 2015, 2018; Yuan et al., 2016; Xia et al., 2017; Wang et al., 2018; Yu et al., 2018). With substantial suspended sediment being trapped in the TGD (Mei et al., 2015, 2018), the downstream sub-saturated flow triggered severe channel degradation (CWRC, 2016; Xia et al., 2017), and the thalweg elevation presented an obvious down-cutting trend (Dai and Liu, 2013; Wang et al., 2018; Yu et al., 2018). Wang et al. (2018) found that the total area of sandbars in the YCR, which were mainly formed by riffle accumulations and floodplain avulsions, decreased from 149 km^2 to 120 km^2, based on remote sensing images from 2002 to 2016. Yuan et al. (2016) performed an analysis of bed topography and found that riffles in the Yichang-Hankou Reach contracted to different degrees following the operation of the TGD, which was consistent with the findings reported by Tang et al. (2014). However, most previous studies have been mainly based on qualitative descriptions, and little attention has been paid to the transformation of pool-riffle structures; thus, quantitative investigations into the evolution of pool-riffle sequences in the channel thalweg downstream of the dam under strong scouring conditions are required.

In this study, the YCR was selected as the study area, and residual depths and spatial statistical analyses were performed to comprehensively analyse variations in the channel thalweg and the distribution of the pool-riffle sequences in the YCR caused by the TGD operation, based on 220 profiles that were repeatedly surveyed from 2002 to 2016. The main objectives of the current study are to (i) calculate the residual depths of the channel thalweg in the YCR from 2002 to 2016 and analyse the variation characteristics of bed topography; (ii) quantitatively analyse the spatial distribution of the pool-riffle sequences in the YCR following the TGD operation; (iii) develop quantitative relationships between the average residual depths and the previous hydrological conditions based on the Delayed Response Model (DRM, Wu et al., 2012); and (iv) identify the possible influencing factors on the evolution of the pool-riffle sequences in the channel thalweg and discuss the impacts of previous hydrological conditions on variations in the average residual depth based on the DRM.

2. Study area

The Yangtze River is the largest river in China and has a total length of 6300 km. This river is usually classified into upper, middle, and lower reaches according to different geographical environments and hydrological characteristics (Cao and Wang, 2015). The 408-km-long study reach, i.e., the YCR, is located between Yichang and Chenglingji in the Middle Yangtze River, and it is composed of the Yizhi, Zhijiang, Shashi, Gongan, Shishou, and Jianli sub-reaches (CWRC, 2016). The YCR is located immediately upstream of the Middle Yangtze River and approximately 44 km downstream of the TGD, as shown in Fig. 1. Three diversion branches can be identified in the right bank of the YCR, and they link the Middle Yangtze River to Dongting Lake (Xia et al., 2017; Yu et al., 2018).

As shown in Fig. 1 and Table 1, the YCR covers 220 specified cross sections surveyed by the Changjiang Water Resources Commission (CWRC), with an average spacing between two successive sections of approximately 2 km. In this study, the YCR is classified into three sub-reaches according to different hydrological conditions, river patterns, and local geology. Sub-reach I is a slightly curved or relatively straight channel, and the surface layer of the riverbed in this sub-reach is mainly composed of gravel, pebbles, and sand. This sub-reach is mainly restricted by stable riverbanks and hills; thus, the channel geomorphological configuration remains stable, with sandbars widely distributed along this sub-reach. Sub-reach II, which is located on an alluvial plain, is a typical multi-branched channel with frequent migrations of mainstream flow, and the riverbed consists mainly of moderately fine and fine sand. The riverbanks in this sub-reach consist mainly of a clay upper layer and a thin sand lower layer (Xia et al., 2017; Wang et al., 2018). Sub-reach III is a predominately meandering channel with complex pool-riffle structures, and most riverbanks in this sub-reach consist of loose sediments that are often stratified. The riverbed consists mainly of fine sand, with a median diameter of 0.16 mm (Cao and Wang, 2015; CWRC, 2016; Wang et al., 2018). The three hydrometric stations Zhicheng, Shashi, and Jianli are located approximately 105, 198, and 347 km downstream of the TGD, respectively (Fig. 1), and these hydrometric stations are representative of the hydrological