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RESEARCH ARTICLE

Channel evolution under changing hydrological regimes in anabranching reaches downstream of the Three Gorges Dam

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Abstract Elucidating the influence of dams on fluvial processes can benefit river protection and basin management. Based on hydrological and topographical data, we analyzed channel evolution in anabranching reaches under changing hydrological regimes influenced by the Three Gorges Dam. The main conclusions are as follows: 1) the channels of specific anabranching reaches were defined as flood trend channels or low-flow trend channels according to the distribution of their flow characteristics. The anabranching reaches were classified as T1 or T2. The former is characterized by the correspondence between the flood trend and branch channels, and the latter is characterized by the correspondence between the flood trend and main channels; 2) on the basis of the new classification, the discrepant patterns of channel evolution seen in anabranching reaches were unified into a pattern that showed flood trend channels shrinking and low-flow trend channels expanding; 3) flood abatement and the increased duration of moderate flow discharges are the main factors that affect channel adjustments in anabranching reaches after dam construction; and 4) in the next few decades, the pattern of channel evolution will remain the same as that of the Three Gorges Dam operation. That is, the morphology will fully adapt to a flow with a low coefficient of variation. Our results are of interest in the management of the Yangtze River and other rivers influenced by dams.

Keywords anabranching river, channel evolution, Three Gorges Dam, Yangtze River

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1 Introduction

The anabranching river pattern, which is one of the most common river patterns, describes rivers with multiple channels separated by alluvial islands (Huang and Nanson, 2007; Eaton et al., 2010; Mendoza et al., 2016). The evolution of anabranching rivers is complex and affected by various factors, such as the upstream flow regime, channel boundaries, and the hydrological regime (Latrubesse, 2008; Kleinhans and van den Berg, 2011). The morphologies of anabranching reaches downstream must adapt to dramatic changes in hydrological conditions imposed by dams (Draut et al., 2011). Investigating channel evolution and its causes in anabranching reaches facilitate river navigation, flood prevention, and river management (Chen et al., 2012; Mendoza et al., 2016).

Anabranching reaches typically transport water and sediments via two or more channels. These rivers display a main channel and one or more channel branches according to their width during low-flow seasons (Eaton et al., 2010; Frias et al., 2015). Main channel–branch channel alteration, which occurs in intervals from several years to hundreds of years and causes severe adjustments in channels and sandbars, is an essential evolutionary feature of anabranching rivers (You, 1984; Abad et al., 2010). Many studies show that hydrological conditions are the main factors that determine fluvial processes (Rodrigues et al., 2006; Smith and Rogers, 2009). The position of flow dynamic axis transfers from one riverbank to another along the vertical flow direction with the increase of flow discharge. This shift in position causes changes in the water diversion ratios of channels and spatial differences in erosion intensity under different discharges (Yu, 1994; Abad et al., 2010). A hydrological process with a suitable variability, which results in erosion in branch channels and prevents the extinction of an island, is the necessary condition for anabranching river maintenance (Fang, 1964; Ni, 1998). Disregarding the relationship between anabranching morphology and hydrological condition negatively affects riverbed prediction (Jain and Sinha, 2004; Zhu et al., 2015). Therefore, dramatic changes in hydrological conditions significantly affect the channel evolution of anabranching reaches. Branch channel shrinkage and island integration after dam construction were documented in the Peace River in Canada, the Spey River in Scotland, and the Han River in China (Church, 1995; Xu, 1997; Gilvear, 2004). However, riverbed evolution not only is dependent on input flow and sediment process but also relates to environmental conditions such as original river channel pattern and riverbed morphology (Brandt, 2000; Grant et al., 2003). Given that the typical characteristics of a river play an important role in fluvial processes, forecasting channel evolution according to research conducted on other rivers is difficult.

The Yangtze River, with a catchment area of 1.8×10^6 km^2, is the longest river in China. The Three Gorges Dam (TGD) is located 40 km upstream from Yichang and started operating in 2003. After the installation of TGD, the total runoff released into the downstream reach of the dam has not changed substantially, although the storage strategy has decreased the frequency of flooding and increased medium discharge (Han et al., 2017). Owing to the replenishment of sediments scoured from the riverbed upstream of Jianli, the amount of coarse sediments in flow diminished slightly at the Jianli, Luoshan, and Hankou stations. Consequently, erosion intensity from the Chenglingji reach to the Hukou reach decreased to a greater extent than that in the upstream reach of Chenglingji (Fig. 1).

Most of the anabranching reaches of the Yangtze River are composed of two or three channels from the Chenglingji reach to the Hukou reach (Fig. 1). The riverbed particles had a median grain size of 0.19 mm over the pre-dam period, and thus the channels displayed limited resistance to erosion (Luo et al., 2012). Many projects such as levees, bank prevents, and waterway regulations have been implemented in these reaches, strengthening the riverbanks and islands and increasing flow dynamics in the channels (Lu and Liu, 2002; Liu, 2008). Over the past decades, many studies have been conducted on riverbed erosion and morphology adjustments in anabranching reaches (Li et al., 2007; Sun et al., 2011; Liu et al., 2016; Zhang et al., 2016). Some researchers suggested that the same adjustments, particularly island integration and shrinkage of branch channels, appearing in other rivers influenced by dams will occur in the Yangtze River (Han and He, 1997). However, some differences exist between observed results and existing viewpoints in terms of the adjustment of anabranching reaches. For instance, the main channel in the Yangtze River has shrunk in the Luxikou reach after 2003 (Chen et al., 2013).

Previous studies mainly focused on the morphological evolution of individual anabranching reaches, and the universal features of these adjustments and their relationships with changing hydrologic conditions in the anabranching reaches of the Yangtze River remain

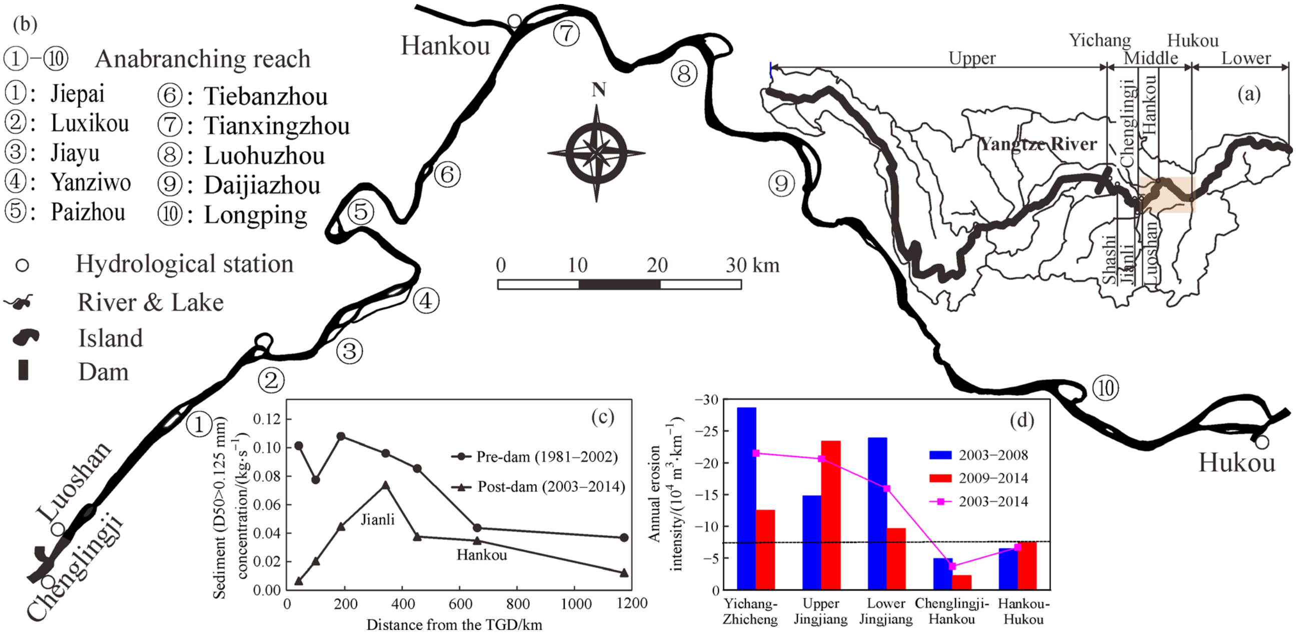

Fig. 1 The Yangtze River basin and the study area. (a) Map of the Yangtze River basin indicating the locations of the TGD, hydrological stations, and study area. (b) Map of the study area showing anabranching reaches. (c) Coarse sediment concentrations measured in the downstream reach of the TGD. (d) Annual erosion intensity of the middle Yangtze River during the post-dam period.

unidentified. The responding mechanisms of channel adjustments to changing hydrological conditions must be investigated, and methods for the forecasting of channel evolution must be explored. The objectives of this study are to (i) unify the morphological adjustments of anabranching reaches, (ii) identify the mechanisms by which riverbeds respond to hydrological conditions, and (iii) elucidate implications for future evolution. The results will benefit riverbed deformation estimation, river management strategies, and river protection in the reaches downstream of dams.

2 Materials and methods

2.1 Data sources

Daily discharge and sediment concentration data measured at the Luoshan and Hankou hydrological stations were obtained from the Changjiang Water Resources Commission (CWRC), China. The study periods are 1955–2002 (the pre-TGD period) and 2003–2014 (the post-TGD period). The topographic data (DEM) of the 10 anabranching reaches (Fig. 1) were also collected from the CWRC. These data, with a scale of 1:10,000, were measured in October 2001, October 2008, and October 2013. Changes in the channel were explored by using the diversion ratios from 1955 to 2015 of eight of these anabranching reaches (Paizhou and Longping were excluded). The diversion ratios were obtained from the CWRC.

2.2 Investigation of channel evolution

According to topographic data recorded in October 2001, October 2008, and October 2013, erosion amounts of main and branch channels in the 2001–2008 and 2008–2013 periods were quantified by the topographic change method. The total erosion amount for the 2001–2008 period was reflected by using the difference in channel storage volume between October 2001 and October 2008 according to Eqs. (1) and (2). A similar comparison was conducted to obtain the erosion amount for 2008–2013. The volume for a certain stage between adjacent sections was calculated in accordance with Eq. (3).

$$E = S_1 - S_2, \tag{1}$$

$$S_j = \sum\nolimits_1^n V_i \qquad (j = 1,2), \tag{2}$$

$$V_i = \frac{1}{3}\left(A_i + A_{i+1} + \sqrt{A_i \times A_{i+1}}\right) \times \Delta L_i, \tag{3}$$

where E is the erosion amount, S_1 and S_2 are the storage volumes of the channel during two adjacent measurements, V_i is the channel storage volume between transects i and $i+1$, A_i and A_{i+1} are the cross-sectional areas of transects i and $i+1$, respectively, and ΔL_i is the distance between transects i and $i+1$. These cross-sections, each with consistent intervals of 100 m, were extracted from the DEM using the Kriging interpolation method (Sanders and Chrysikopoulos, 2004). Calculated water level defined to be at bankfull level was obtained according to the measured water surface profile along the river.

2.3 Classification of anabranching reaches

To integrate the channel morphology and the flow process, we presented a new method for classifying anabranching reaches, basing on the observed changes in the diversion ratio associated with different discharges (Fig. 2).

Step 1. The two channels of an anabranching reach are numbered C1 and C2. For reaches with three anabranching structures, such as Luoxikou and Luohuzhou, the third-order channel and its adjacent channel are regarded as a whole because of the weak transport capacity of water and sediment in the third-order channel.

Step 2. The diversion ratio of each channel is plotted against the flow discharges measured in the main stream. A regression line that characterizes the relationship between the diversion ratios and the discharges is established for each channel.

$$\theta_1 = k_1{*}Q + b_1, \tag{4}$$

$$\theta_2 = k_2{*}Q + b_2, \tag{5}$$

where θ_1 and θ_2 are the diversion ratios of C1 and C2, respectively, Q is the discharge in the main stream, and k_1 (k_2) and b_1 (b_2) are the slope and intercept of the regression lines for C1 (C2), respectively.

In terms of specific discharge, for which $\theta_1 + \theta_2 = 1$, two equations are established.

$$b_1 = 1 - b_2, \tag{6}$$

$$k_1 = -k_2. \tag{7}$$

Step 3. Each channel is characterized by the slope and intercept of the linear regression equations. If $k_1 > 0$ (or $k_1 = 0$ and $b_1 \geqslant b_2$), C1 and C2 are defined as the flood trend channel (FTC) and low-flow trend channel (LTC), respectively. Otherwise, C1 and C2 are defined as the LTC and the FTC, respectively.

Step 4. Based on the correspondence between the FTC (LTC) and the main channel (branch channel), anabranching reaches can be classified into two types, namely T1 and T2. Type T1 is characterized by the correspondence between LTC and the main channel, whereas type T2 is characterized by the correspondence between FTC and the main channel. The classification scheme for the 10 anabranching reaches surveyed in this paper is shown in Fig. 2.

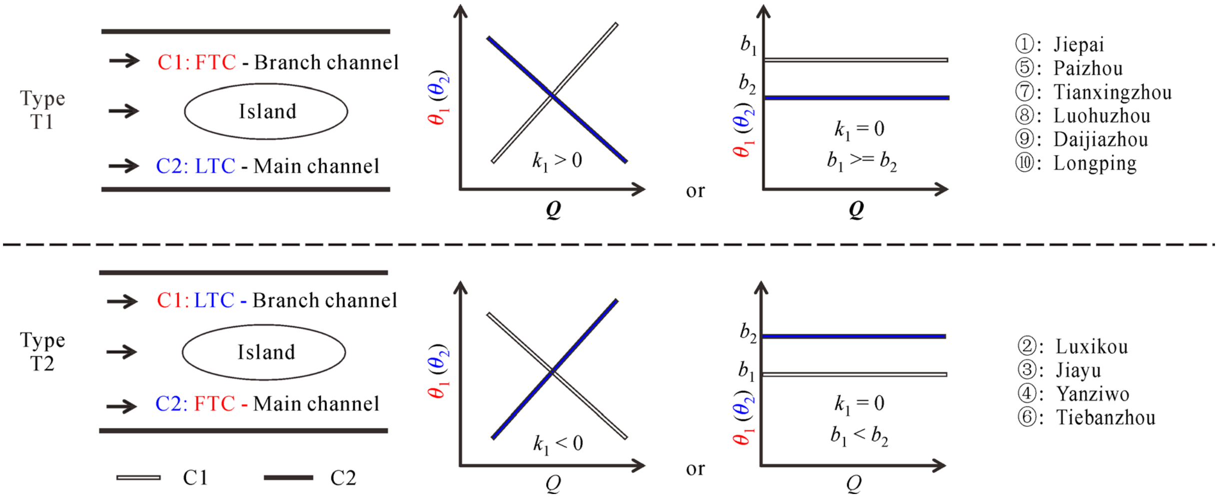

Fig. 2 Sketch of the classification of anabranching reaches.

3 Channel evolution of anabranching reaches after the TGD operation

From 2001 to 2008, the main channels eroded and the branch channels silted up within the T1 reaches, except the Tianxingzhou and Luohuzhou (Fig. 3). The erosion amount in the main channels exceeded that in the branch channels in these two reaches, and the corresponding difference values were -28.27×10^{6} and -50.31×10^{6} m^{3}, respectively. All T1 reaches displayed erosion in their main channels and silt branch channels from 2008 to 2013. Changing patterns were also reflected by the diversion ratios in Fig. 4. In the Tianxingzhou reach, the diversion ratios of branch channels experienced a 5% decrease in the 2002–2006 and 2007–2014 periods and were close to zero in March 2014. The ratios decreased by 18% and 11% under low-flow discharges in the Jiepai and Daijiazhou reaches, respectively.

In the T2 reaches, branch channels tended to erode whereas main channels displayed deposition or weaker erosion. From 2008 to 2013, the difference values between the main channel and branch channels were 41.71×10^{6} m^{3},

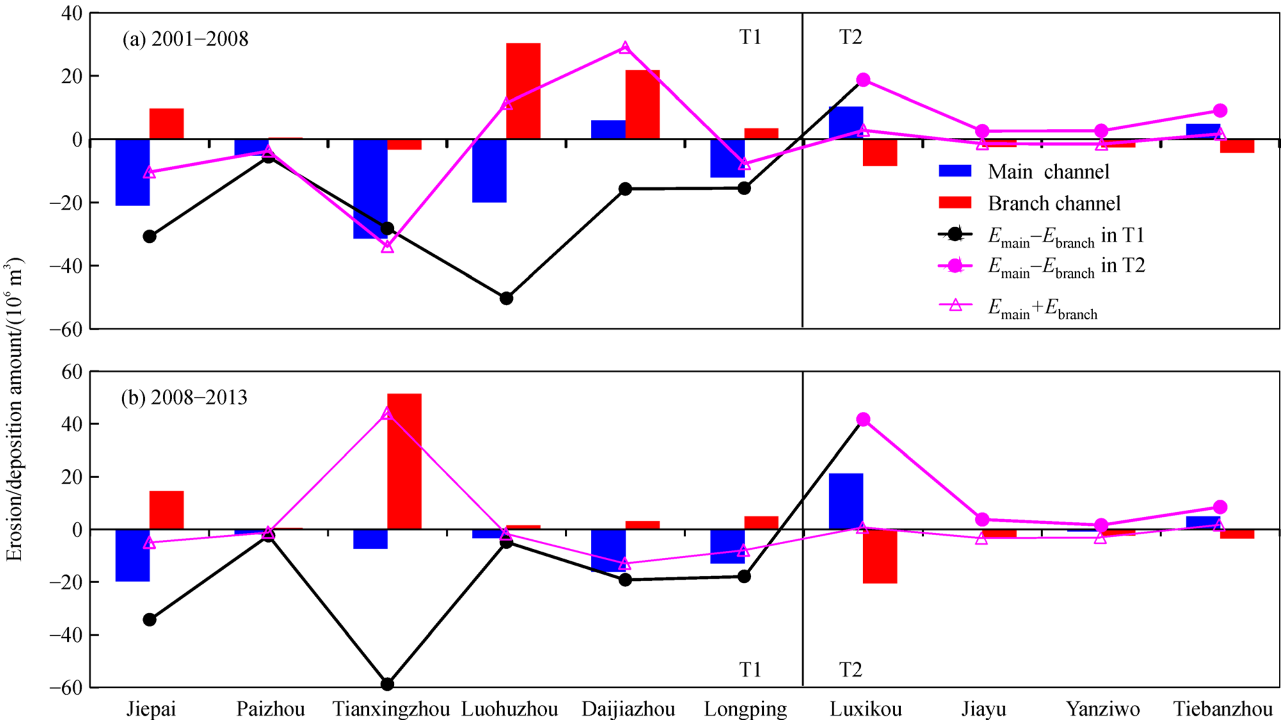

Fig. 3 Comparison of erosion between the main and branch channels in the anabranching reaches.

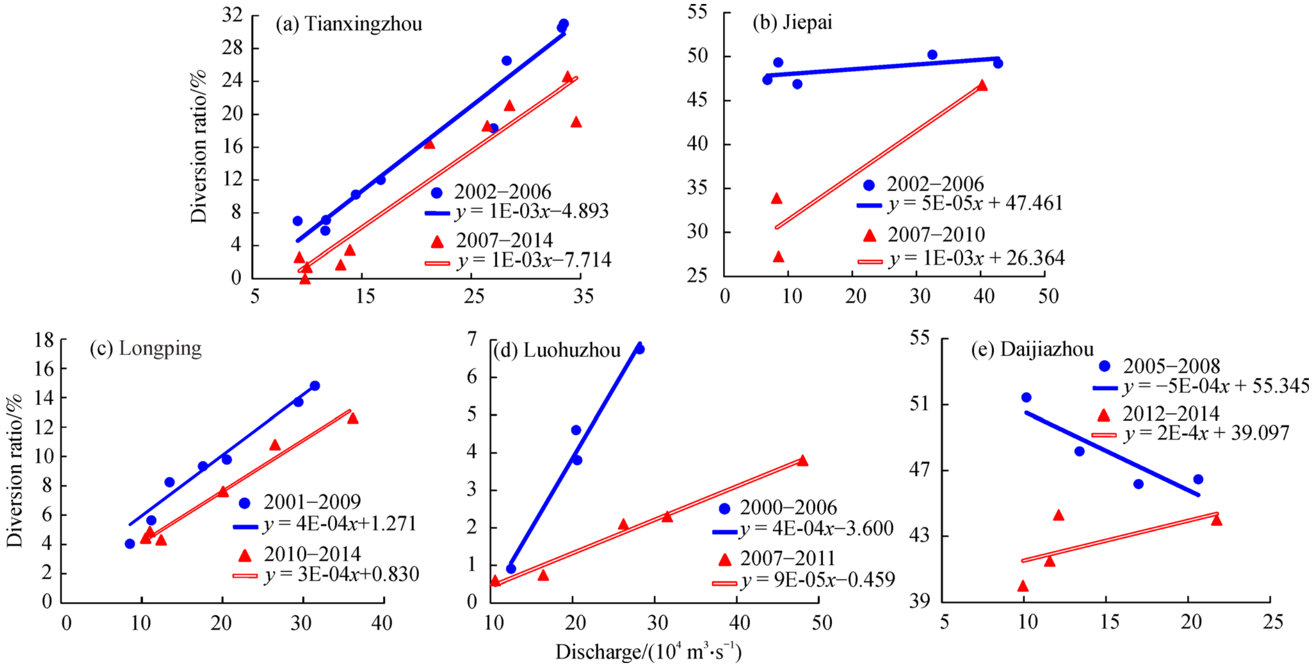

Fig. 4 Changes in the water diversion of branch channels in T1 reaches.

3.77×10^6 m^3, 1.60×10^6 m^3, and 8.50×10^6 m^3 in Luxikou, Tiebanzhou, Jiayu, and Yanziwo, respectively. The diversion ratios of the branch channels displayed an increasing trend in the T2 reaches (Fig. 5). The main channel–branch channel alternation occurred in the Luxikou reach.

In the T1 reaches, the main channels expanded whereas the branch channels shrunk. The T2 reaches showed an opposite changing trend. On the basis of the correspondence between the main (branch) channel and FTC (LTC), these differences in evolution can be explained in terms of LTC expansion and the FTC shrinkage in all anabranching reaches.

4 Morphological responses of channels to the changing hydrological processes

4.1 Relationship between channel evolution and natural hydrological processes

The high-velocity zone of flow migrates from the LTC to the island and then to the FTC as discharge and increases at the entrance of the anabranching reach (Fig. 6; Liu et al., 2014; Li et al., 2016). In cases where a critical discharge Q_1 is present, flood discharges above Q_1 accelerate the expansion of FT. LTC develops under low and moderate

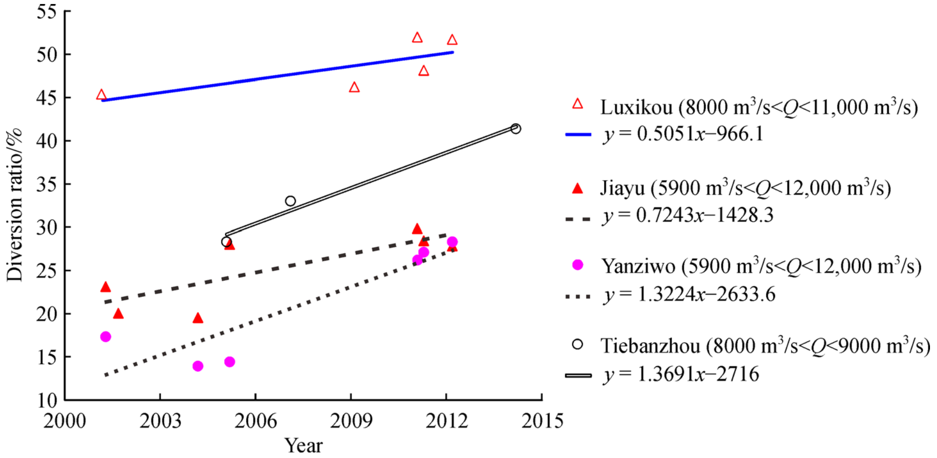

Fig. 5 Changes in the water diversion of branch channels in T2 reaches.

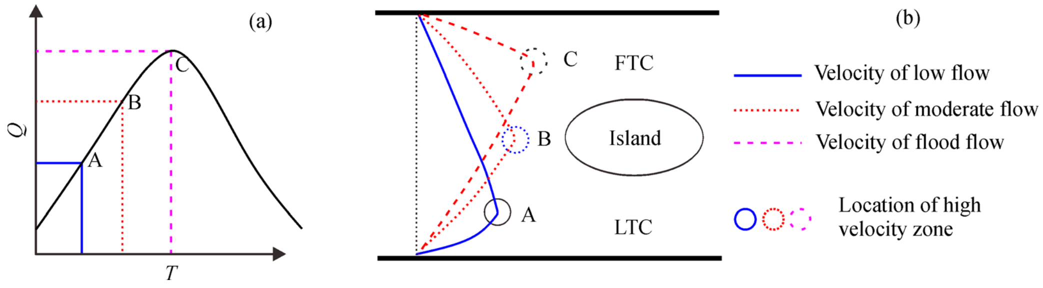

Fig. 6 Changes in flow dynamics at different discharges. (a) Sketch showing the flow process. (b) Sketch showing the transformation of high-velocity zone at different flows.

discharges below Q_1, rendering Q_1 close to the bankfull discharge (Han et al., 2013, 2014). The bankfull discharges of the reaches upstream and downstream of Hankou are 36,500 and 40,500 m^3/s, respectively (Huang et al., 2014).

Changes in the diversion ratio were consistent with the changes in the duration of flood discharges within the anabranching reaches (Fig. 7). In the Jiepai reach, the diversion ratios of the FTCs and the five-year average durations of discharges that were greater than the bankfull discharge increased at first and then decreased; the maximum value was noted to be approximately 2000. A decreasing trend was found to have existed in the diversion ratio of FTC and flood discharge duration in Luohuzhou since 1955. In addition, the riverbed processes of the three typical reaches showed the FTCs to be scouring in the flood season and depositing in the dry season (Fig. 8). Given that the flood season has greater discharge than the dry season, increase in the durations of flood discharge result in the expansion of FTCs, whereas increase in the duration of low flow accelerates erosion in LTCs.

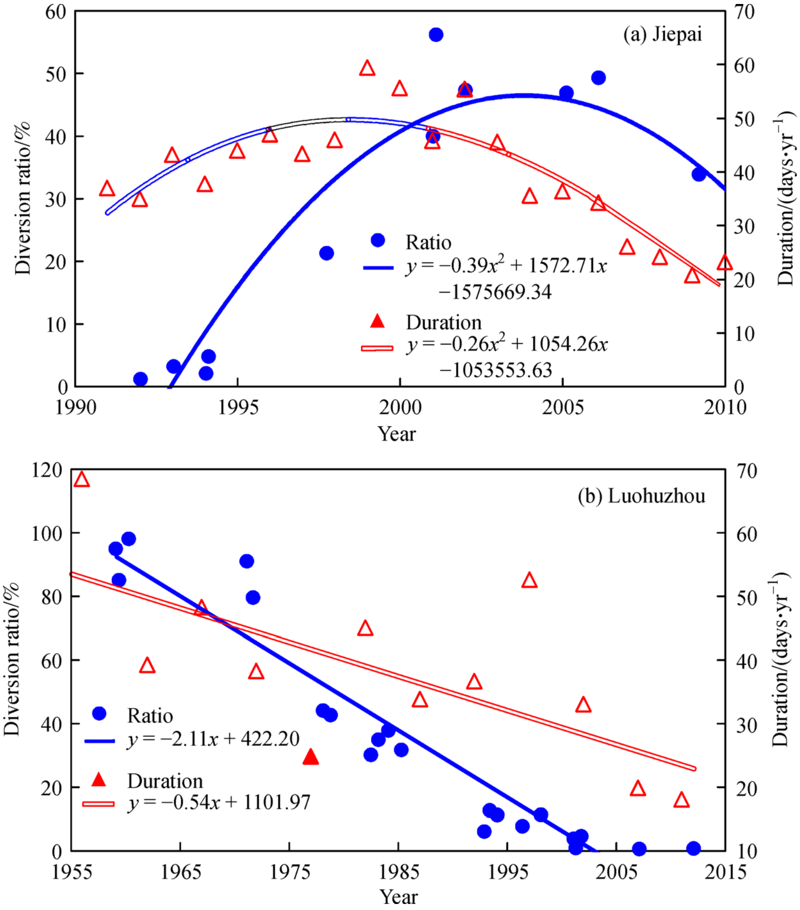

Fig. 7 Relationship between the diversion ratios of the FTCs and flood discharge duration, which greater than the bankfull discharge duration. (a) Corresponding discharge of diversion ratio ranging from 8000 m^3/s to 16,000 m^3/s. (b) Corresponding discharge of diversion ratio ranging from 10,000 m^3/s to 20,000 m^3/s.

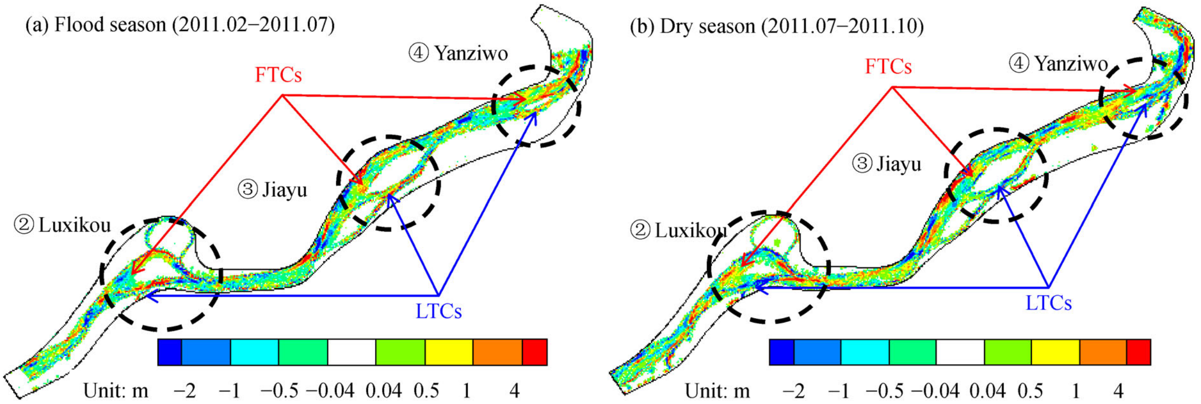

Fig. 8 Erosion/deposition ranges of three typical reaches during flood and dry seasons. (a) Flood season (2011.02–2011.07); (b) dry season (2011.07–2011.10).

4.2 Channel evolution responding to changing flow processes

Substantial differences in deformation amplitudes exist between FTCs and LTCs because of their differences in duration and erosion intensity. According to flow processes during the pre- and post-dam periods, the proportion of flows greater than bankfull discharge decreased by 6.7% and 6.3% at the Luoshan and Hankou stations, respectively. In addition, the medium flow frequencies, which ranged from mean annual discharge to bankfull discharge, increased by 8.6% and 8.0% at the same two stations, respectively (Fig. 9). The decrease in the duration of flood discharge reduced erosion time in FTCs and increased erosion time in LTCs, causing FTCs to shrink and LTCs to expand (Fig. 10).

Suitable hydrological variability in flow processes is a necessary condition for the maintenance of anabranching reach patterns. Minimal variability in flow processes leads to a stable flow dynamic axis, which is conducive to the development of a branching river pattern and meandering pattern (You, 1984; Abad et al., 2010). During the post-dam period, the flow process variability decreased and then led to the stable distribution pattern of the main and the branch channels in the T1 reaches. For the T2 reaches, the distribution pattern deviated from its original state because of the deposition of the main channels and the erosion of the branch channels. However, the T2 reaches were converted into T1 reaches when the diversion ratios of the branch channels were greater than 50%, indicating that the distribution pattern of T2 reaches developed with a steady trend. Therefore, the channel evolution in the T1 and T2 reaches is adaptive to the changing flow process.

5 Implications for future evolution

The present studies indicate that morphological adjustments are largely determined by the flow processes. The decreased frequency of flood discharge and increased frequency of medium discharge will likely persist if the operation strategy of the TGD remains unchanged. The FLCs will shrink under the continuous effects of the TGD, and the LTCs will expand gradually. The differences between the diversion ratios of the main and branch channels will increase in the T1 reaches and decrease in the T2 reaches. Once the diversion ratio of the branch channel is greater than that of the main channel, the T2 reaches will convert themselves into T1 reaches. The morphology will adapt to the flow to a great degree, with a low coefficient of variation, indicating that the period of main channel–branch channel alternations will increase in the anabranch-

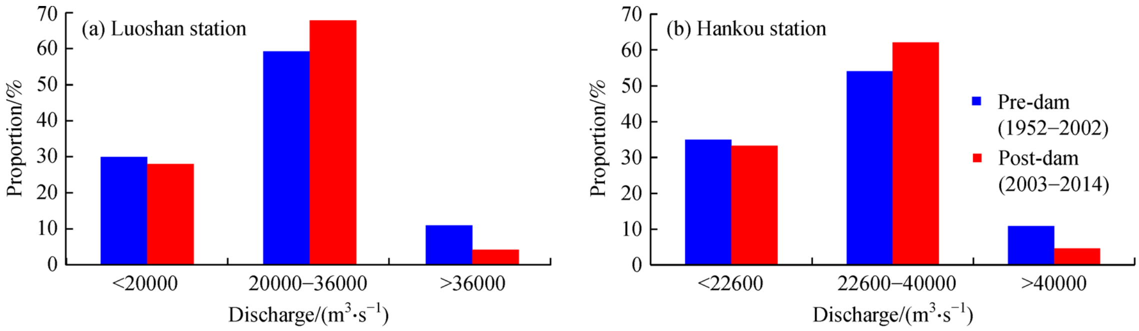

Fig. 9 Changes in flow process observed at the Luoshan and Hankou stations.

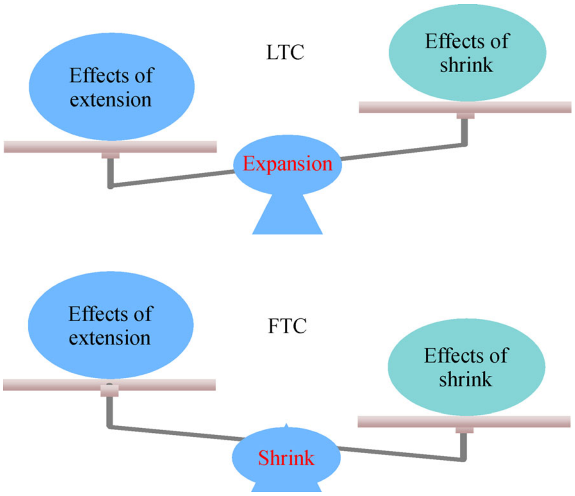

Fig. 10 Mechanism underlying the channel evolution under the changing flow process.

ing reaches downstream of the TGD.

However, sediment fluxes will diminish with the movement of the main scour zone from the upstream to the downstream reaches (Yang et al., 2007; Xu and Yan, 2010). Determining whether the anabranching reaches in the middle Yangtze River will convert into a single pattern in the next few decades is difficult. Therefore, more research on river pattern adjustments should be conducted in the future.

6 Conclusions

We provided a unified explanation of the channel adjustments of anabranching reaches under changing hydrological conditions influenced by the TGD. The channels of specific anabranching reaches were defined as FTCs or LTCs on the basis of changes in the diversion ratio as the discharge increased. The anabranching reaches were classified either as type T1, characterized by the correspondence between the LTC and the main channel, or as type T2, characterized by the correspondence between the FTC and the main channel. The expansion of LTCs and shrinkage of FTCs occurred in all anabranching reaches. Significant reductions in the duration of flood and the increased duration of low and moderate flow discharge increased the erosion duration of LTCs and drove channel evolution during the post-dam period. Over the past decades, the regulation of the TGD and cascade dams further increased the low and medium discharge frequencies and reduced flood discharge frequency. Accordingly, the pattern of evolution will be maintained, and the T2 reaches will convert themselves into T1 reaches once the diversion ratios of branch channels are greater than 50%. The implications for future evolution indicate that the channels will adapt to the flow to a great degree and have a low coefficient of variation, and the period of main channel–branch channel alternations will increase. Thus, additional long-term and in-depth studies of river pattern adjustments are imperative.

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