

Variation in reach-averaged bankfull discharge in the Yellow River Estuary in recent years

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Abstract The Yellow River Estuary (YRE) alternatively experienced channel aggradation and degradation during the period 1990–2016. To study the variation in flood discharge capacity during the process of river bed evolution, bankfull characteristic parameters were investigated on the basis of measured hydrological data and surveyed cross-sectional profiles, which was crucial for comprehending the processes and the key factors to cause these rapid changes. A reach-averaged method was presented in this study in order to calculate the characteristic bankfull parameters in the YRE, and this method integrated the geometric mean using the logarithmic transformation with a weighted mean based on the distance between the two successive sections. The reach-averaged bankfull parameters in the tail reach of the Yellow River Estuary (the Lijin-Xihekou reach) during the period 1990–2016 were then calculated. Calculated results indicated that the adoption of a concept of reach-averaged bankfull discharge was much more representative than the cross-sectional bankfull discharge, and the results also indicated that bankfull discharges decreased during the process of channel aggradation, and increased during the process of channel degradation. Finally, an empirical formula and a delayed response function were established between the reach-averaged bankfull discharge and the previous 4-year average fluvial erosion intensity during flood seasons, and both of them were adopted to reproduce the reach-averaged bankfull discharges, and calculated results showed high correlations ($R^2 > 0.8$) of these two methods.

Keywords channel adjustments, reach-averaged bankfull discharge, empirical relation, delayed response equation, Yellow River Estuary

1 Introduction

Fluvial processes of a river estuary usually result from the comprehensive effects of incoming flow-sediment conditions. Over the past few decades, the amount of sediment transported into the seas through many large rivers (e.g., the Yellow River (YR), the Yangtze River, the Pearl River, and the Mississippi River) has declined significantly, thereby aggravating the vulnerabilities of systems of estuarine sedimentary (Tessler et al., 2015; Dai et al. 2016, 2018; Mei et al., 2018). Under the comprehensive influences of natural fluvial processes and human activities, most tail reaches of estuaries face threats represented by the damage of flood and the recession of wetland ecosystems. In an alluvial tail reach of an estuary that is subject to severe aggradation and degradation, bankfull discharge is a significant parameter for assessing the capacity of flood runoff and sediment transport (Zhang and Hu, 2007; Hu and Zhang, 2011). Therefore, as a key reference in an alluvial river, bankfull discharge could help to design stable channel geometry and control flood in the Yellow River Estuary (YRE).

Bankfull discharge symbolizes the condition of early flooding at a cross-section, and it has a significant influence on both the size of the channel and the shape of cross-section. Bankfull discharge is defined as the flow that fills the river channel without overtopping the channel banks (Wolman and Leopold, 1957; Williams, 1978). From a geometric perspective, bankfull discharge is an according discharge with an abrupt variation in width-depth ratio; from a dynamic process perspective, it is the pivot point of modifying the channel-floodplain system (He et al., 2015). Additionally, the magnitude of bankfull discharge may also have an important impact on the dimensions of river channels (Knighton, 1996; Page et al., 2005; Wu et al., 2008b; Xia et al., 2010).

The majority of studies on bankfull discharge mainly concentrated on the changes of bankfull discharge at

specific cross-sections (Wu et al., 2008a; Hu and Zhang, 2011). Section-scale bankfull discharges varied along the reach, due to the lateral or the longitudinal variation in cross-sectional geometry (Zhang and Hu, 2007). From this respect, the concept of reach-average would be more appropriate than the concept of cross-sectional scale in describing the capacity of flood discharge in an alluvial river (Williams, 1978; Xia et al., 2010, 2014). Although the concept of bankfull originally proposed by Williams (1978) can be applied to alluvial rivers in equilibrium, and then it is further extended to a wide range of applications in alluvial rivers in nonequilibrium.

The three steps of how to calculate reach-averaged bankfull discharge in the tail reach of the YRE are listed as follows: (i) identifying the zone of main-channel and bankfull level of the river reach; (ii) calculating the bankfull discharge at each cross-section located in the study reach (section-scale); and (iii) estimating bankfull discharge of the study reach (reach-averaged). The first step is an artificial and empirical process, with strong subjectivity (Williams, 1978; Johnson and Heil, 1996; Navratil et al., 2006; He et al., 2015). Existing methods for identifying the bankfull level include recognizing geomorphological configuration characteristics (Leopold et al., 1964; Williams, 1978; Hupp and Osterkamp, 1996; Knighton, 1996; Castro and Jackson, 2001; Wu et al., 2008a; Harman et al., 2008) and determining the bankfull level by adopting geometric criteria based on the measured topographic data (Wolman, 1955; Leopold et al., 1964; Riley, 1972; Pickup and Warner, 1976). For a specified hydrometric section that is not subject to severe channel evolution, the method currently used in the second step for calculating bankfull discharge is generally appropriate. Xia et al. (2010) made a detailed comparison of four different methods to determine the cross-sectional bankfull discharge, and it was proved that a one-dimensional hydrodynamic model can provide higher accuracy than other three methods (Xia et al., 2010).

Most previous studies adopted an arithmetic or geometric method (Wohl et al., 2004; Liang et al., 2005; Wohl and Wilcox, 2005; Hu et al., 2012). A geometric averaging method based on the logarithmic transformation was proposed by Harman et al. (2008), and it accounted for the flow-continuity condition, which can be used to estimate the reach-averaged bankfull discharge. However, these methods mentioned above cannot satisfy the effect of different spacing between two successive cross-sections in calculating reach-averaged bankfull discharge. Therefore, an appropriate method should be adopted to estimate the magnitude of reach-averaged bankfull discharge. Xia et al. (2010) proposed a coupled method that integrates a geometric mean based on logarithmic transformation with a weighted mean based on continuous two-segment spacing, considering the effect of different cross-sectional spacing on the calculated results.

The investigation into the reach-averaged bankfull

discharge in the tail reach of the YRE from a long time average is meaningful and important in the analysis of fluvial processes. Due to a close connection among bankfull parameters, the changes in the corresponding reach-averaged bankfull geometry should be included in the analysis. Therefore, this investigation is to: (i) estimate the bankfull parameters in the tail reach of the YRE by a reach-averaged method; (ii) analyze the response of bankfull parameters to the changes in flow-sediment conditions entering the tail reach of the YRE; and (iii) establish relationships between the reach-averaged bankfull discharge and the flow-sediment regime entering the tail reach during flood seasons, based on the measured data from 1990 to 2016.

2 Study area

The Yellow River originates in the Qinghai-Tibet Plateau, and it is the second largest river in China, flowing about 5464 km eastwards across the North China Plain to the Bohai Sea, with a drainage area of 742400 km² (Yao et al., 2017) (Fig. 1(a)). As one of the largest contributors of fluvial sediment into the sea, the Yellow River ranked first globally with an average annual sediment concentration of 22.0 kg/m³, and second in terms of the amount of sediment discharged into the sea (10.8×10^8 t/yr) among the rivers with annual water discharge greater than 1000×10^8 m³/yr or sediment load more than 5×10^8 t/yr (Jiang et al., 2017). According to its geographic characteristics, the Yellow River could be divided into four regions: the upper reach, the middle reach, the lower reach, and the YRE (Fig. 1(a)).

The tail reach of the YRE, downstream of the Lijin section, has a length of 106 km (Fig. 1(b)), and it is commonly divided into three different channel-pattern reaches: the meandering reach, the transitional reach, and the estuary reach. The reach between Lijin and Wangjiazhuang is a typical meandering reach, with a length of 10 km. In this reach, the cross-sections have a narrow and deep geometry, and the difference of elevation between the floodplain and the main channel is relatively large, ranging from 4 to 7 m. In addition, the mainstream in the reach between Lijin and Wangjiazhuang generally remains stable during long periods because of the implementation of river revetment works.

The reach from Yuwa to the river mouth belongs to a 66 km estuary reach. The geometry of cross-sections in this reach become wide and shallow because of the lack of revetment works in the reach downstream of the Q4 section, which results in severe adjustments of river regime in the estuary reach (Hou et al., 2009). In addition, the elevation difference between the floodplain and the main channel is lower than that of the meandering reach, ranging from 2 to 3 m. The reach located between Wangjiazhuang and Yuwa has a typical transitional channel pattern from meandering to estuary, with a length of 30 km. After the

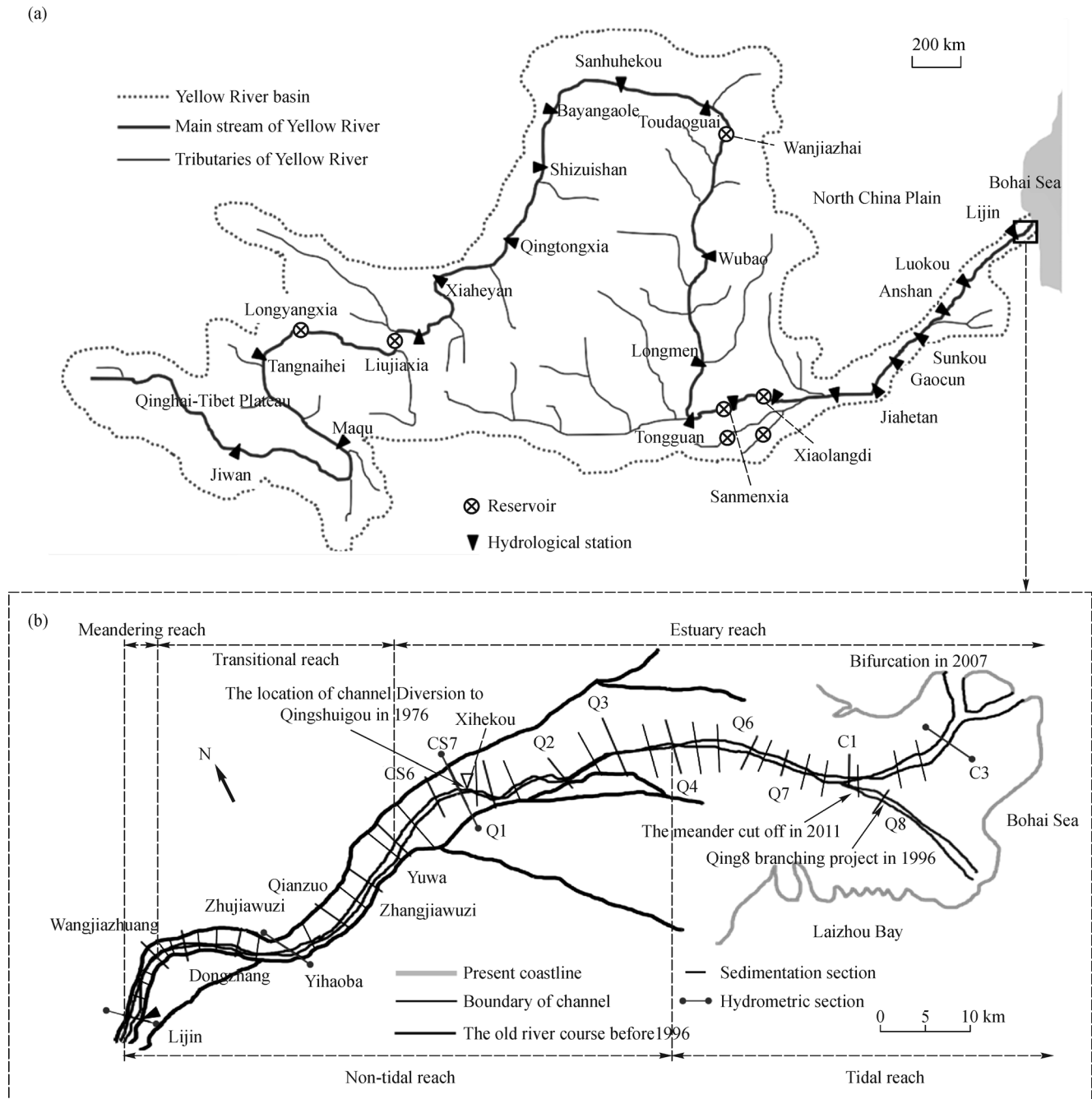


Fig. 1 Sketch images showing (a) the Yellow River basin and (b) the YRE.

flood season in 1999, the difference of elevation between the floodplain and the main river channel in this reach ranges from 4–5 m. Owing to insufficient revetment works at river bends, the riverbed has a high deformation rate, which causes an unstable main channel.

According to the hydrodynamic characteristics in the tail reach of the YRE, it is generally divided into two distinct reaches: the non-tidal reach from Lijin to Q4 and the tidal reach from Q4 to the river mouth (Yu et al., 2016). In general, morphological evolution in the river channel of

the YRE primarily depends on the upstream flow and sediment regime and the oceanic dynamics from the Bohai Sea (Leonardi et al., 2013; Yu et al., 2016). However, the intensity of fluvial dynamics is much higher than that of oceanic dynamics in the YRE (Yu et al., 2016). Therefore, it is unnecessary to consider the effect of oceanic dynamics when studying the channel evolution characteristics of the YRE (Wang et al., 2008), and previous studies show that the tail reach of the YRE upstream of Xihekou is not affected by the oceanic dynamics, because the length of the

tidal reach is within 20 km (Wang et al., 2008). The Lijin-Xihekou reach is chosen as the study reach for investigation of bankfull parameters due to the lack of tidal level data, covering the meandering reach, the transitional reach, and a part of the estuary reach.

2.1 Changes in flow and sediment regime

To meet the increasing demand for the purpose of flood control and water resources utilization, the river flow in the Yellow River has been increasingly regulated. Over 3100 reservoirs were constructed in the Yellow River basin by the year 2000, and among these reservoirs, the Longyangxia and Xiaolangdi reservoirs have played the most profound effect on the flow-sediment regime entering the YRE (Cai and Rosegrant, 2004). The Longyangxia Reservoir started to operate in 1986. Since then, the average annual water and sediment volumes were reduced sharply, and the YRE underwent the period of seasonal desiccation, which lasted until the service of the Xiaolangdi Reservoir ended in 1999 (Zhang and Hu, 2007; Hou et al., 2009; Hu and Zhang, 2011). Because the amount of water and sediment in the YRE is mainly from upstream, and there is no inflow or outflow of tributaries along the YRE with the exception of two tributaries. In addition, at the Lijin station, as the last hydrometric station in the Lower Yellow River (LYR), its measurements can represent the conditions of flow and sediment entering the YRE (Hu and Zhang, 2011). The details of the hydrological characteristics at Lijin are listed in Table 1.

Figure 2 shows the changes in annual water discharge (V_w) and sediment load (V_s) at Lijin. The average annual water volume was $143.9 \times 10^8 \text{ m}^3/\text{yr}$ and about 60% of the total ($86.2 \times 10^8 \text{ m}^3/\text{yr}$) occurred in flood seasons during the period 1990–1999, and the average annual sediment load came up to $3.9 \times 10^8 \text{ t/yr}$, of which $3.4 \times 10^8 \text{ t/yr}$ occurred in flood seasons. The average annual water volume was about $154.8 \times 10^8 \text{ m}^3/\text{yr}$ during the period 1999–2016, and 53% ($81.9 \times 10^8 \text{ m}^3/\text{yr}$) of that was the average flood-season water volume. In addition, the average flood-season sediment load ($0.9 \times 10^8 \text{ t/yr}$) accounted for 75% of the average annual sediment volume ($1.2 \times 10^8 \text{ t/yr}$). In summary, the measurements from 1990 to 2016 indicate that: (i) the transport of flow and sediment was mainly concentrated in flood seasons; (ii) the sediment amount reduced significantly and the water amount declined slightly after 1999; and (iii) the ratio of water and sediment amounts in flood season to those in the whole year decreased after the reservoir operation.

2.2 Variation in accumulated channel evolution volume

Statistical data show that the channel deformation in the Lijin-Xihekou reach underwent two stages: continuous aggradation (over the period from 1990 to 2000) and continuous degradation stages (over the period from 2000

Table 1 Details of average annual hydrological characteristics at Lijin

Year	Average discharge $/(\text{m}^3 \cdot \text{s}^{-1})$	Average sediment concentration/ $(\text{kg} \cdot \text{m}^{-3})$	Average water level/m
1990	862.9	17.57	12.04
1991	472.3	17.79	11.18
1992	347.3	41.03	8.79
1993	569.7	23.61	10.21
1994	677.4	32.13	10.09
1995	497.6	38.53	8.33
1996	476.8	28.41	7.91
1997	124.5	7.88	5.2
1998	316.2	36.43	6.58
1999	218.2	27.94	10.17
2000	120.1	3.86	11.49
2001	188.6	5.96	11.82
2002	141.4	12.56	11.29
2003	417.7	22.3	11.44
2004	788.8	13.33	11.67
2005	583.5	9.86	11.4
2006	683.9	7.38	11.53
2007	596.2	7.46	11.2
2008	496.7	5.3	11.17
2009	406.6	4.28	10.81
2010	646.2	8.33	10.94
2011	449.8	5.71	10.6
2012	947.1	6.29	11.33
2013	820.1	6.9	11.3
2014	351.8	2.69	10.52
2015	454.7	2.26	10.52
2016	245	1.32	10.14

to 2016) (Zhang et al., 2018). As Fig. 3 shows, about $0.399 \times 10^8 \text{ m}^3$ of sediment was deposited in the channel of the Lijin-Xihekou reach during the period from 1990 to 2000. Since the reservoir started operating in 1999 the accumulated amount of channel scour has gradually increased to $0.401 \times 10^8 \text{ m}^3$ during the period 2000–2015. The largest volume of annual channel scour was about $0.168 \times 10^8 \text{ m}^3$ in 2003 because of the occurrence of five hyperconcentrated flood events.

3 Data and methods

3.1 Data collection

Since the Xiaolangdi Reservoir started operating, the amount of sediment entering the YRE has decreased dramatically, and the YRE channel underwent severe

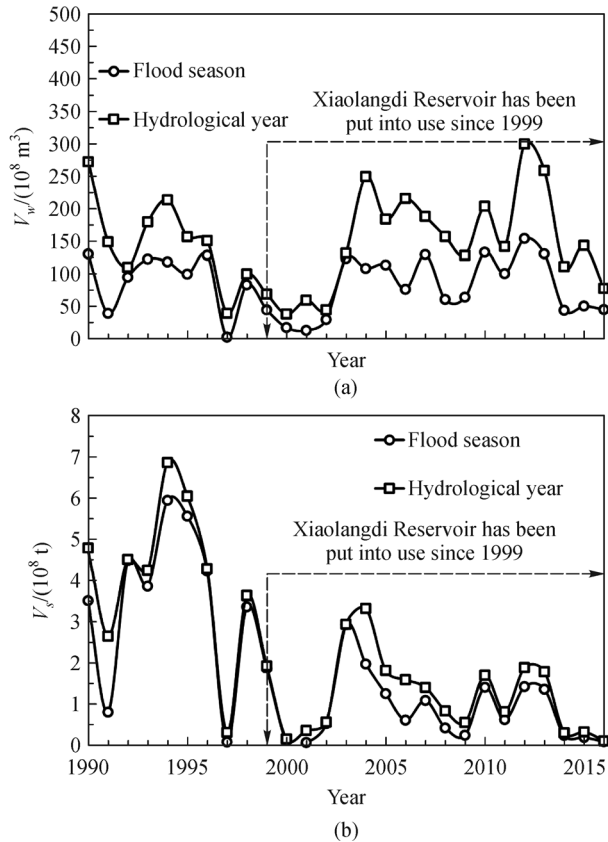


Fig. 2 (a) Temporary variations in water and (b) sediment discharges entering the YRE.

degradation because of the flows with low sediment concentrations regulated by the Xiaolangdi Reservoir.

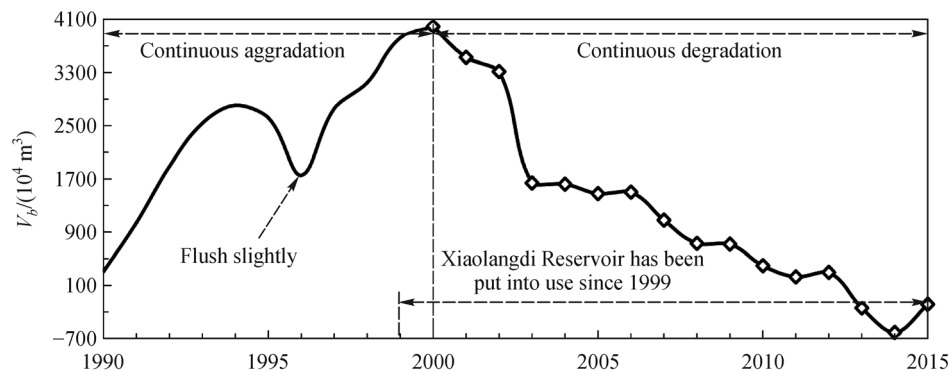


Fig. 3 Temporary variations in accumulated volume of channel deformation in the Lijin-Xihekou reach.

Field measurements collected for this study include hydrological data and cross-sectional profiles surveyed by the Yellow River Conservation Commission (YRCC).

Measured hydrological data usually cover water and sediment discharges at the specific sections, while the channel evolution volume in the tail reach of the YRE is calculated by the data of sedimentation cross-sections which are measured regularly. In addition, daily mean water levels and discharges at stations of Lijin, Yihaoba and Xihekou were collected during the period from 1990 to 2016. It should be noted that the quantity of sedimentation cross-sections in Lijin-Xihekou reach changed during different periods. It was 10 from 1990 to 2000, with a mean distance of 5.5 km between two consecutive cross-sections. The quantity of sedimentation cross-sections increased gradually after the operation of the Xiaolangdi Reservoir, and the total number of sedimentation sections was 11, with a mean distance of 5.1 km during the period 2001–2003. Finally, the number of sedimentation sections reached 22 after 2004, with a mean distance of 2.4 km. The locations of these 22 sections are shown in Fig. 1(b), and other specific information is shown in Table 2.

3.2 Procedure for calculating bankfull discharge

In order to calculate bankfull parameters in the tail reach of the YRE, a procedure is briefly introduced in this section. First, adopt a method to identify the bankfull level. Second, introduce a step which is used to calculate the bankfull discharge at each cross-section (section-scale) herein, and more details are outlined in Xia et al. (2010). Finally, a reach-averaged method is used to calculate the bankfull characteristic parameters in the Lijin-Xihekou reach,

Table 2 Specification of the measurements used in this study

Data type	Station	Period of record	Sources
Daily discharge	Lijin	1990–2016	YRCC
Daily water level	Lijin, Yihaoba, Xihekou	1990–2016	YRCC
Surveyed profiles	10–22 cross-sections	1990–2016	YRCC

including bankfull area and bankfull discharge. It should be noted that the study river reach should include more than 2 cross-sections, thus ensuring the measured data used in 1D hydrodynamic model proposed by Xia et al. (2010) can be adopted to specify the boundary conditions.

3.2.1 Determination of bankfull level

In general, bankfull discharge means the flow at which water just fills the main channel of a river without overtopping the banks of the floodplain. Therefore, the bankfull level at a section in terms of flood control usually means the level of lip top of an active floodplain, and the main area between the both lips on two sides is functionally called the main channel (Xia et al., 2010). The width between both lips of the active floodplains on two sides of the cross-section is named as the bankfull channel width ($= B_{bf}$), and the corresponding main channel area under the bankfull level is named as the bankfull cross-sectional area ($= A_{bf}$). Finally, the mean bankfull channel depth ($= H_{bf}$) is usually evaluated by the ratio of the A_{bf} to B_{bf} ($H_{bf} = A_{bf} / B_{bf}$).

The key step of calculating the cross-sectional bankfull parameters is to determine the bankfull level, because the bankfull level is of great importance, which directly influences the magnitude of bankfull discharge at a section (He et al., 2015). The identification of bankfull channel dimensions at 2 typical sections (Lijin and Xihekou) in 1990 is shown in Fig. 4. Taking Lijin as an example, the bankfull channel width was 511.8 m, and the bankfull cross-sectional area was 1546.9 m², with the mean bankfull channel depth of 3.02 m. The determination of post-flood bankfull level at each section follows these principles:

1) If it is easy to identify the lips of the floodplains on two sides, the elevation of the lip at a lower side is usually regarded as the bankfull level at this cross-section. For example, the bankfull level was 13.82 m at Lijin (Fig. 4(a)) and it was 8.83 m at Xihekou (Fig. 4(b)).

2) In the case where the bankfull indicators are not obvious between the main channel and floodplains, the determination of bankfull level needs to refer to the levels of the floodplains at two consecutive sections as well as the levels of floodplain at other measurement times, in order to ensure a slight variation in bankfull level along the channel.

3.2.2 Calculation of section-scale bankfull discharge

The section-scale bankfull discharge is equal to multiplying the wetted area of a sedimentation cross-section by the corresponding average flow velocity when the water stage of a cross-section just comes up to the bankfull level. Xia et al. (2010) compared the advantages and disadvantages of 4 different methods used to estimate section-scale bankfull discharges, including the mean daily discharge

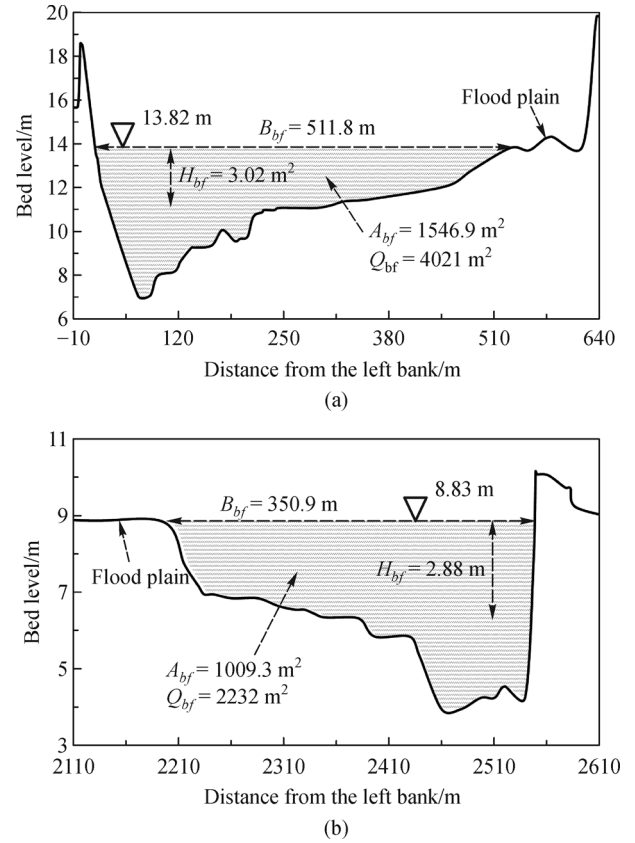


Fig. 4 Identification of bankfull channel dimensions at typical sections of (a) Lijin and (b) Xihekou.

and water stage relation, the observed discharge and water stage relation, the water stage-velocity-discharge relation and the simulated discharge and water stage relation using a 1D hydrodynamic model. A comparison of calculated results based on the four different methods showed that the section-scale bankfull discharge computed by the 1D hydrodynamic model is more accurate than other three methods. In this study, water stages at different magnitude of discharges of each cross-section in Lijin-Xihekou reach were calculated by the 1D hydrodynamic model developed by Xia et al. (2010), and the post-flood cross-sectional profiles are taken as the condition of river channel boundary. In general, the governing equations of the 1D hydrodynamic model can be written as follows:

$$\frac{dQ}{dx} = 0, \quad (1)$$

$$\frac{d}{dx} \left(\alpha_f \frac{Q^2}{A} \right) + gA \frac{dZ}{dx} + gA(J_f + J_l) = 0, \quad (2)$$

where Q = cross-sectional discharge; Z = cross-sectional average water stage; A = cross-sectional area; α_f = momentum correction coefficient; J_f = cross-sectional energy slope, expressed by $J_f = Q^2/K^2$ (K = discharge

modulus); J_l = local loss; x = longitudinal distance; g = gravitational acceleration ($g = 9.81\text{m/s}^2$). In this method, the continuity equation and the momentum equation are solved using the finite-difference scheme, and each cross-sectional water stage is then calculated by the method of bisection. The specific procedure for calculating bankfull discharges at section-scale is presented as follows:

1) The hydrograph of discharge at Lijin measured during the period 1990–2016 was adopted as the upstream boundary condition, with the measured hydrograph of water stage at Xihekou being used to specify the downstream boundary condition. The post-flood cross-sectional profiles at 10 to 22 sections measured in 1990–2016 were adopted as the initial topography. Different discharge levels were specified based on the observed discharge data at the upstream boundary, without taking the lateral inflow and outflow processes along the river into consideration. At the downstream boundary, the measured stage-discharge relation was taken as the boundary condition, and the corresponding water stage can be determined by the measured stage-discharge curve for a given discharge. For example, based on the measured stage-discharge relation at Xihekou in 2007, the corresponding water stage was equal to 8.17 m at a given discharge of $2260\text{ m}^3/\text{s}$ (Fig. 5(a)).

2) As a key parameter in the one-dimensional hydrodynamic model, the appropriate Manning roughness coefficient (n) is of significance, which influences the accuracy of the results directly (Xia et al., 2010). However, it is difficult to determine the n using a suitable formula in view of the complexity of river bed in the YRE. In this method, the value of n at any section can be spatially interpolated from the functional relationships between n and discharge at specified stations. The Manning roughness coefficients under different magnitude of discharge need to be slightly adjusted according to measured data during the computational process, until the simulated stage-discharge relations fit well with measurements at the hydrometric stations (Figs. 5(b) and 5(c)). In addition, according to the previous research, the variation range of n in the tail reach of the YRE was 0.009–0.025 for the main-channel zone (Cao et al., 2005). Therefore, the calibrated values of n should be within this range. The range of roughness coefficients for the floodplain zone used in this study is 0.015–0.020.

3) After obtaining the stage-discharge relation at each cross-section estimated by the above-mentioned method, the section-scale bankfull discharge is equal to the corresponding discharge under the bankfull level from the stage-discharge curve. For instance, the calculated section-scale bankfull discharge in 1990 was $1547\text{ m}^3/\text{s}$ at Lijin and $1009\text{ m}^3/\text{s}$ at Xihekou (Fig. 4).

3.2.3 Calculation of reach-averaged bankfull parameters

Xia et al. (2014) made an improvement of a method for calculating the reach-averaged bankfull parameters devel-

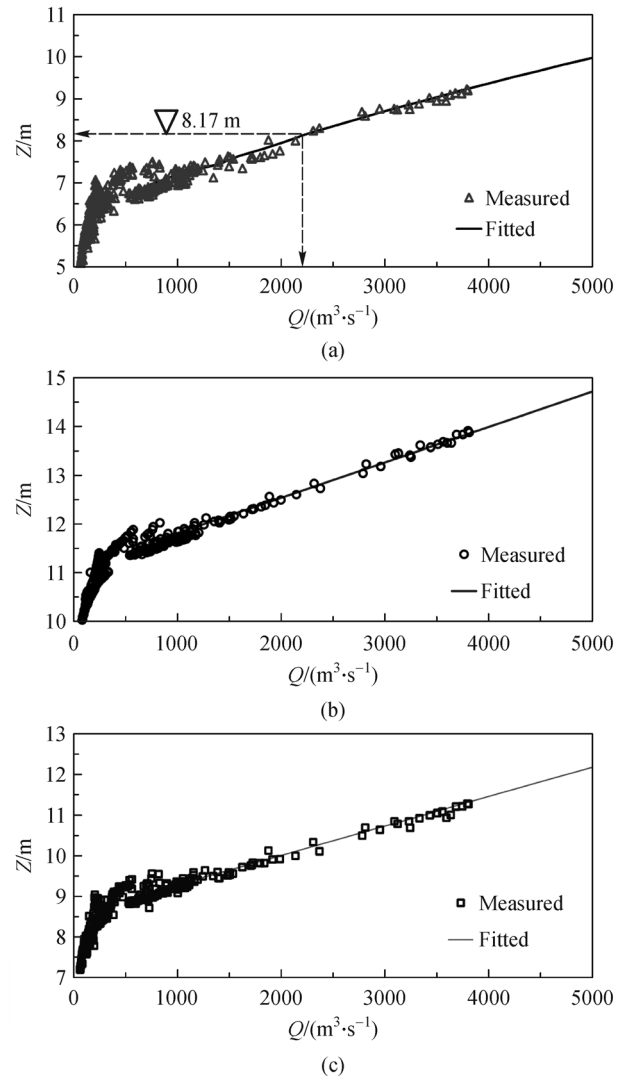


Fig. 5 Calculated and measured rating curves between stage and discharge at different sections (a) Xihekou, (b) Lijin and (c) Yihaoba.

oped by Harman et al. (2008), and this improved reach-averaged method is used to calculate the reach-averaged bankfull parameters. In this method, the length of study reach is assumed to be L , which covers more than 2 cross-sections. In addition, a 1D hydrodynamic model can be adopted to calculate the bankfull parameters at the i th cross-section. Therefore, the corresponding reach-averaged bankfull channel geometry ($=\bar{G}_{bf}$) covering \bar{B}_{bf} , \bar{H}_{bf} and \bar{A}_{bf} can be written as: and the reach-averaged bankfull discharge (\bar{Q}_{bf}) is expressed as: where x_i is equal to the longitudinal length at the i th cross-section downstream of the Xiaolangdi Dam; G_{bf}^i represents the section-scale bankfull channel dimensions (B_{bf}^i , H_{bf}^i and A_{bf}^i); N is equal to the quantity of cross-sections in the study reach; and the value of $(x_{i+1} - x_i)$ is equal to the distance between two consecutive sections. Eq. (3) can also be written as: it

indicates that \bar{G}_{bf} calculated by this method can satisfy the continuity of the channel dimensions, which means that it makes $\bar{A}_{bf} = \bar{B}_{bf} \times \bar{H}_{bf}$ always true using this improved method. In addition, the reach-averaged geomorphic coefficient ($=\bar{\zeta}_{bf}$) is calculated by: it should be particularly noted that although this reach-averaged method does not have the drawbacks of previous calculation methods, the accuracy of results calculated by the current method is associated closely with the quantity of cross-sections included in the study reach. Namely, the calculated bankfull parameters will be more accurate with a larger quantity of cross-sections included in the calculation:

$$\bar{G}_{bf} = \exp \left[\frac{1}{2L} \sum_{i=1}^{N-1} (\ln G_{bf}^{i+1} + \ln G_{bf}^i) \times (x_{i+1} - x_i) \right], \quad (3)$$

$$\bar{Q}_{bf} = \exp \left(\frac{1}{2L} \sum_{i=1}^{N-1} (\ln Q_{bf}^{i+1} + \ln Q_{bf}^i) \times (x_{i+1} - x_i) \right), \quad (4)$$

$$\begin{aligned} \bar{A}_{bf} &= \exp \left[\frac{1}{2L} \sum_{i=1}^{N-1} (\ln A_{bf}^{i+1} + \ln A_{bf}^i) \times (x_{i+1} - x_i) \right] \\ &= \exp \left[\frac{1}{2L} \sum_{i=1}^{N-1} (\ln W_{bf}^{i+1} H_{bf}^{i+1} + \ln W_{bf}^i H_{bf}^i) \times (x_{i+1} - x_i) \right], \end{aligned} \quad (5)$$

$$\bar{\zeta}_{bf} = \sqrt{\bar{B}_{bf} / \bar{H}_{bf}}. \quad (6)$$

4 Results and discussion

4.1 Section-scale and reach-averaged bankfull discharges

Longitudinal variation in the bankfull parameters along the Lijin-Xihekou reach is shown in Fig. 6, which includes the cross-sectional areas ($=A_{bf}$) and section-scale bankfull discharges ($=Q_{bf}$) in 1990 and 2016. It can be seen from Figure 6 that: (i) the values of Q_{bf} and A_{bf} changed greatly along the study reach, and the values of Q_{bf} at specific sections were relatively small in the transitional reach and the estuary reach after the 1990 flood season, with the values less than 3000 m³/s (Fig. 6(a)), which was caused by the continuous channel aggradation and the corresponding main channel shrinkage after 1986; (ii) by contrast, the longitudinal variation in the Q_{bf} demonstrated an increasing trend along the reach after the 2016 flood season, and the Q_{bf} increased to more than 3000 m³/s in 2016 (Fig. 6 (b)), which indicates that the flood discharge capacity in the tail reach of the YRE recovered to a certain extent because of the continuous channel degradation. Why

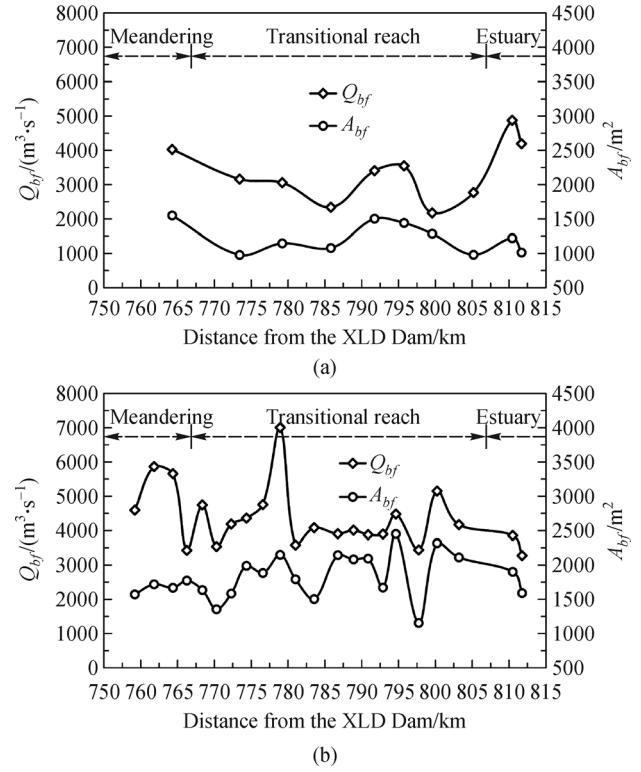


Fig. 6 Longitudinal variations in the section-scale bankfull discharges and areas in the Lijin-Xihekou reach in the years of (a) 1990; (b) 2016.

section-scale bankfull discharges and areas in the Lijin-Xihekou reach had such a significant variation over the past years can be explained as follows: it was because the water-sediment regulation of the Xiaolangdi Reservoir after 1999 caused reshaping of the withered tail reach of the YRE; (iii) the magnitude of A_{bf} varies dramatically with different channel patterns along the river, which caused a similar variation trend in the Q_{bf} . For instance, the maximum Q_{bf} was larger than 7000 m³/s in the transitional reach, while the minimum Q_{bf} was only 3275 m³/s in the estuary reach (Fig. 6(b)).

It also should be noted that the maximum bankfull discharge ($Q_{bf} = 7000 m^3/s$) was too large at a section which is 779 km from the Xiaolangdi dam. According to the equation of flow continuity, there always exists a relationship at any section: $Q_{bf} = A_{bf} \cdot U_{bf}$, where A_{bf} and U_{bf} refer to the bankfull wetted area and flow velocity (Xia et al., 2010). Therefore, $Q_{bf} = 7000 m^3/s$ at the section was caused by relatively large wetted area and flow velocity ($A_{bf} = 2149.3 m^2$, $U_{bf} = 3.26 m/s$).

Figure 7 shows the temporal variations in Q_{bf} at Lijin, Yihaoba and Xihekou, as well as the variation in \bar{Q}_{bf} in the Lijin-Xihekou reach. From Figure 7, the values of Q_{bf} and \bar{Q}_{bf} decreased slightly and then increased progressively over the past 26 years; however, the ranges of variation in

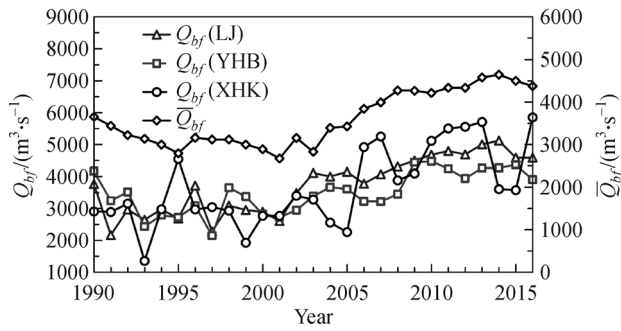


Fig. 7 Temporal variations in the section- and reach-scales bankfull discharges in the YRE.

Q_{bf} at these cross-sections were much greater than that of \bar{Q}_{bf} . Taking the Q_{bf} at Xihekou as an example, the minimum Q_{bf} was about 1360 m³/s, with the maximum value > 5500 m³/s. The \bar{Q}_{bf} increased gradually from 3654 to 4377 m³/s over this period. The reach-averaged method for estimating the value of \bar{Q}_{bf} , satisfies not only the effect of different Q_{bf} , but also the effect of various distance between two consecutive sections. However, the

magnitude of Q_{bf} at a particular cross-section usually varies significantly in response to the varied flow-sediment regimes. Hence, as compared with that of Q_{bf} , the variation range of \bar{Q}_{bf} is smaller in terms of reach-scale. The adoption of \bar{Q}_{bf} seems to be more representative, in terms of describing the flood discharge capacity and the sediment transport capacity in the tail reach of the YRE that is subject to the continuous channel aggradation and degradation due to the operation of the reservoir.

The variation in bankfull discharge is caused by the change in bankfull channel dimensions, which is influenced directly by channel evolution due to the non-equilibrium sediment transport in the river channel. The relation between the cumulative channel evolution volume (= V_b) and the bankfull discharges (section-scale and reach-averaged) in the Lijin-Xihekou reach is shown in Fig. 8. The correlation (= R^2) between \bar{Q}_{bf} and V_b is equal to 0.81, which is relatively higher, as compared with the values of Q_{bf} at Lijin, Yihaoba and Xihekou ($R^2= 0.63, 0.60, 0.32$, respectively). It also can be seen from Figure 8 that the value of bankfull discharge in the study reach would generally decrease with an increase in V_b .

To summarise, the calculated values of \bar{Q}_{bf} in the

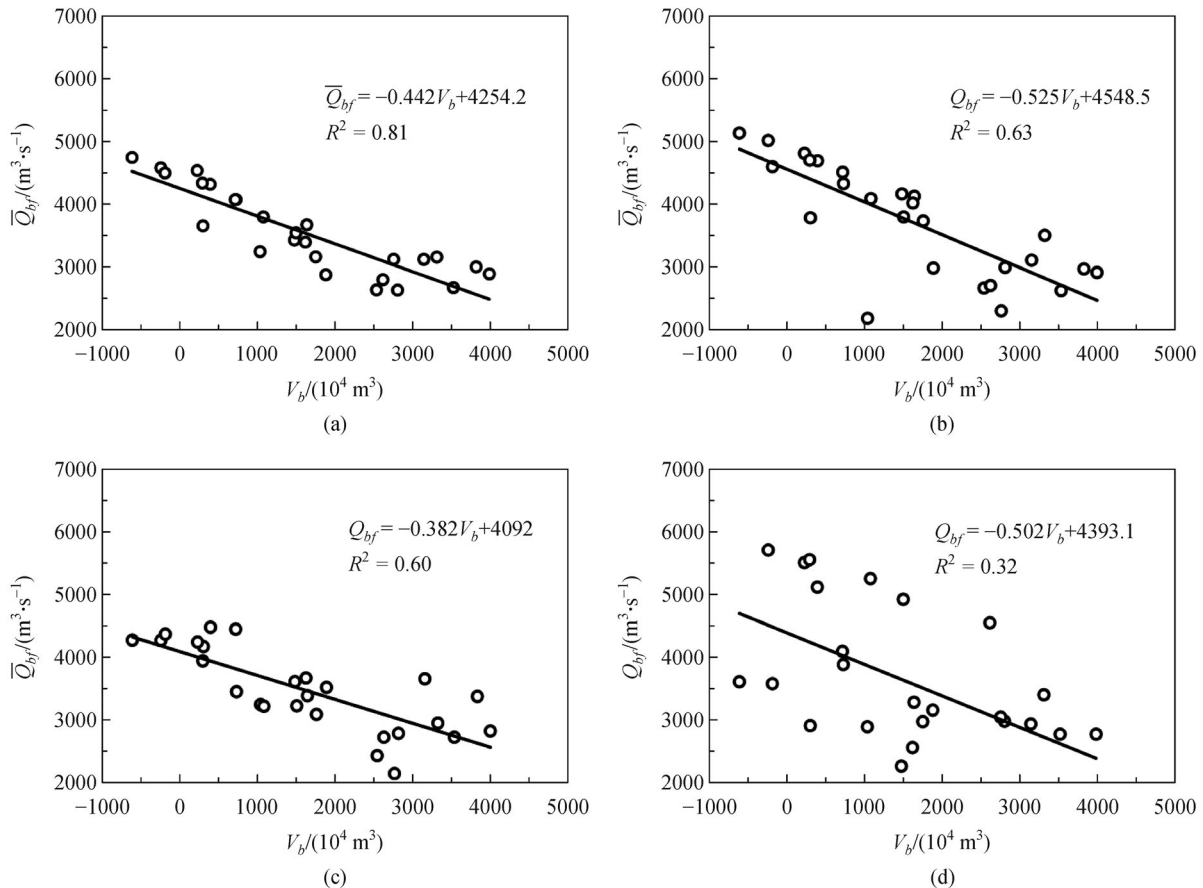


Fig. 8 Linear regression between the cumulative channel evolution volume (V_b) in the Lijin-Xihekou reach and the bankfull discharges (a) in the Lijin-Xihekou reach; (b) at Lijin; (c) at Yihaoba; and (d) at Xihekou.

Lijin-Xihekou reach had a smaller range of variation, but had a higher correlation degree with the flow and sediment regime entering the YRE. Therefore, it further suggests that \bar{Q}_{bf} is more representative than Q_{bf} when describing flood discharge capacity in the tail reach of the YRE.

4.2 Adjustments in reach-averaged bankfull geometry

The post-flood cross-sectional profiles at 10–22 sedimentation sections in the Lijin-Xihekou reach were surveyed annually over the period from 1990 to 2016. With continuous channel degradation after the Xiaolangdi Reservoir operation, the values of \bar{G}_{bf} (\bar{B}_{bf} , \bar{H}_{bf} , \bar{A}_{bf} and $\bar{\zeta}_{bf}$) changed significantly over this period. The values of \bar{G}_{bf} in the Lijin-Xihekou reach were calculated using Eq. (3) and Eq. (6), with these parameters and the corresponding variation ranges being indicated in Table 2. It can be seen from Table 3 that: the values of \bar{B}_{bf} , \bar{H}_{bf} and \bar{A}_{bf} increased by 3.00%, 3.98% and 11.23%, respectively, while the value of $\bar{\zeta}_{bf}$ decreased by 12.52%.

Figure 9(a) presents the temporal variation in \bar{G}_{bf} in the tail reach of the YRE, and it indicates that the values of \bar{A}_{bf} and \bar{H}_{bf} had a larger variation range than \bar{B}_{bf} . Besides, the variation of \bar{A}_{bf} had a similar trend with \bar{H}_{bf} during the period from 1990 to 2016. The value of \bar{H}_{bf} increased from 2.3 m in 2003 to 3.4 m in 2005, with a significant increase of 47.8%, and then increased to 3.9 m in 2009. During the period from 2009 to 2016, the value of \bar{H}_{bf} remained at 3.9–4.0 m. The variation in \bar{A}_{bf} showed a significant increasing trend, ranging from 1139.9 m² in 2003 to 1865.4 m² in 2009, with an increase of \bar{A}_{bf} by as much as 63.6%. The value of \bar{B}_{bf} increased gradually from 466 to 481 m during the period from 1990 to 2016 with a slight fluctuation. Figure 9(b) shows the temporal variation in $\bar{\zeta}_{bf}$ in the study reach. As Fig. 9(b) shows, $\bar{\zeta}_{bf}$ increased with a dramatic fluctuation during the period from 1990 to 2003 and decreased significantly from 2003 to 2016. The adjustment in $\bar{\zeta}_{bf}$ was mainly influenced by channel widening and incision. During the period 2003–2016, both channel widening and incision occurred in the reach, and continuous downward erosion occurred after 2003, which caused the profiles of cross-sections in the Lijin-Xihekou reach to develop toward a deep geometry.

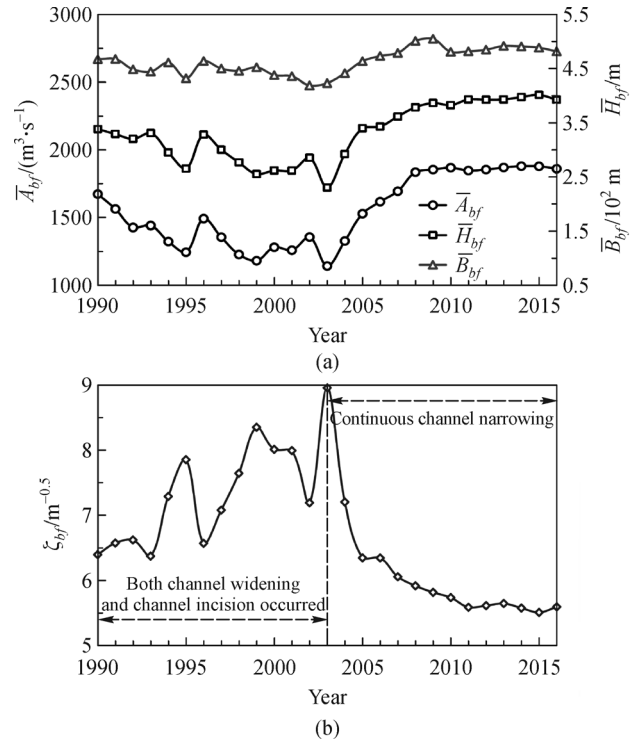


Fig. 9 Temporal variations in the reach-scale bankfull channel dimensions in the Lijin-Xihekou reach: (a) \bar{A}_{bf} , \bar{H}_{bf} and \bar{B}_{bf} ; (b) $\bar{\zeta}_{bf}$.

4.3 Response of reach-averaged bankfull discharges to incoming flow and sediment regime

The above analysis indicates that the recent channel evolution in the tail reach of the YRE mainly occurred in flood seasons, and therefore, the intensity of channel evolution during non-flood seasons can be neglected in this investigation. Previous investigations indicate that the magnitude of the bankfull discharge in the Lower Yellow River is an empirical formula of the previous years' conditions of flow and sediment during flood seasons (Wu et al., 2008a, 2008b). In this study, it is assumed that \bar{Q}_{bf} also can be predicted using similar relations in the YRE with a further calibration process. Hence, an empirical formula was developed between \bar{Q}_{bf} and the previous 4 years' average discharge and incoming sediment coefficient in the tail reach of the YRE. In an alluvial river, the flow and sediment conditions are usually represented by the fluvial erosion intensity, which is expressed as:

Table 3 Reach-scale bankfull channel dimensions in the Lijin-Xihekou reach in 1990 and 2016

Year	$\bar{B}_{bf} / (10^2 \text{ m})$	\bar{H}_{bf} / m	$\bar{A}_{bf} / \text{m}^2$	$\bar{\zeta}_{bf} / \text{m}^{-1/2}$
1990	4.67	3.77	1669.72	6.39
2016	4.81	3.92	1857.25	5.59
variation rate	3%	3.98%	11.23%	12.52%↓

$$F_{fi} = \left(\frac{\bar{Q}_{fi}^2}{\bar{S}_{fi}} \right) / 10^4, \quad (7)$$

where F_{fi} is the fluvial erosion intensity in the i th year; and \bar{Q}_{bf} and \bar{S}_{fi} are the average discharge (m^3/s) and the corresponding sediment concentration (kg/m^3) in the i th flood season at Lijin, respectively. In an alluvial river, there is an empirical relationship between water discharge (Q) and sediment discharge (Q_s) at a hydrometric station under the state of quasi-equilibrium, which can be written as $Q_s = a(Q)^b$, where a and b represent coefficient and exponent, respectively. Based on the hydrological data measured at Lijin and Yihaoba before 1999, the calibrated parameter b was approximately equal to 2.0 ($R^2 = 0.866$, $P = 0.934$) (Fig. 10). Therefore, \bar{Q}_{fi}^2 at a hydrometric station can be regarded as the index of the sediment transport capacity, and $\bar{Q}_{fi}^2/\bar{S}_{fi}$ represents the fluvial erosion intensity, namely, the ratio of sediment transport capacity to the incoming sediment concentration at a given discharge.

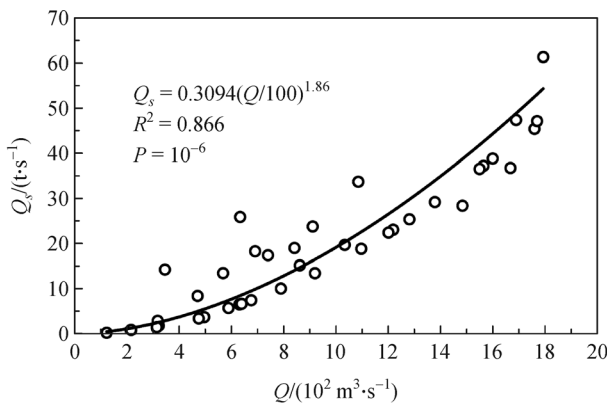


Fig. 10 Sediment rating curve under quasi-equilibrium at Lijin.

4.3.1 Empirical relationship for predicting the reach-averaged bankfull discharges

A delayed response during non-equilibrium adjustment processes is a significant characteristic of fluvial systems. In this study, the x years' average fluvial erosion intensity ($=\bar{F}_{xf}$) during flood seasons can be expressed by:

$$\bar{F}_{xf} = \frac{1}{x} \sum_{i=1}^x \bar{F}_{fi}, \quad (8)$$

where x is the number of years for the moving average; \bar{F}_{xf} is the mean fluvial erosion intensity during the flood season for the i th year. As Fig. 11 shows, it is confirmed that the corresponding correlation ($=R^2$) reached their maximum ($x = 4$), with the optimal value of correlation coefficient ($R^2 = 0.83$). The selection of $x = 4$ illustrates that the fluvial system of the YRE had a memory of 4 years in the variation of \bar{Q}_{bf} , and it also indicates that the variation in

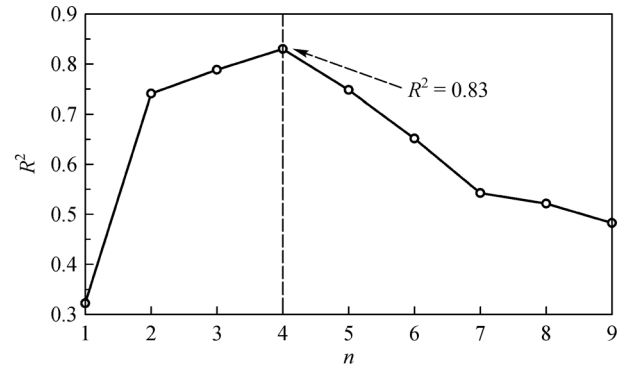


Fig. 11 Variation in the value of R_2 with an increasing value of n .

\bar{Q}_{bf} was caused by the accumulative impacts of discharge-sediment concentration for several successive years. In addition, it is found that \bar{Q}_{bf} and the previous 4-year average fluvial erosion intensity ($=\bar{F}_{4f}$) in flood seasons have the highest correlation. Therefore, the empirical relationship between \bar{F}_{4f} and \bar{Q}_{bf} can be expressed by the following form:

$$\bar{Q}_{bf} = \alpha(\bar{F}_{4f})^\beta, \quad (9)$$

where α is a coefficient; and β is an exponent.

In Eq. (9), the value of \bar{F}_{4f} was adopted to reproduce the bankfull discharges in the tail reach of the YRE. On the basis of the measured hydrological data from 1990 to 2016, α and β in Eq. (9) for the study reach were calibrated by the method of logarithmic transformation and regression analysis, and these calibrated parameters are shown in Table 3. Figure 12(a) implies that the value of \bar{Q}_{bf} in the Lijin-Xihekou reach estimated using the established empirical relation (Eq. (9)) basically fit well with the calculation by Eq. (4); and the variation range of \bar{Q}_{bf} calculated by Eq. (4) is similar to that by Eq. (9). Figure 12 (b) shows that the correlation coefficient between \bar{Q}_{bf} and \bar{F}_{4f} is higher ($R^2 = 0.83$, $P = 0.951$). Therefore, it indicates that the empirical relation developed in this study can be used to predict the variation in \bar{Q}_{bf} in the tail reach of the YRE.

4.3.2 Prediction of reach-averaged bankfull discharges by the delayed response equation

Bankfull discharge in an alluvial river usually adjusts more slowly than external disruptions (e.g., water discharge and sediment load increase or decrease suddenly in a river reach) (Wu et al., 2008a), and such an adjustment rule is also supposed to apply to the variation in \bar{Q}_{bf} in this study, and the corresponding equilibrium value can be described as a function of the incoming sediment coefficient and average discharge in flood seasons. Because of the frequent

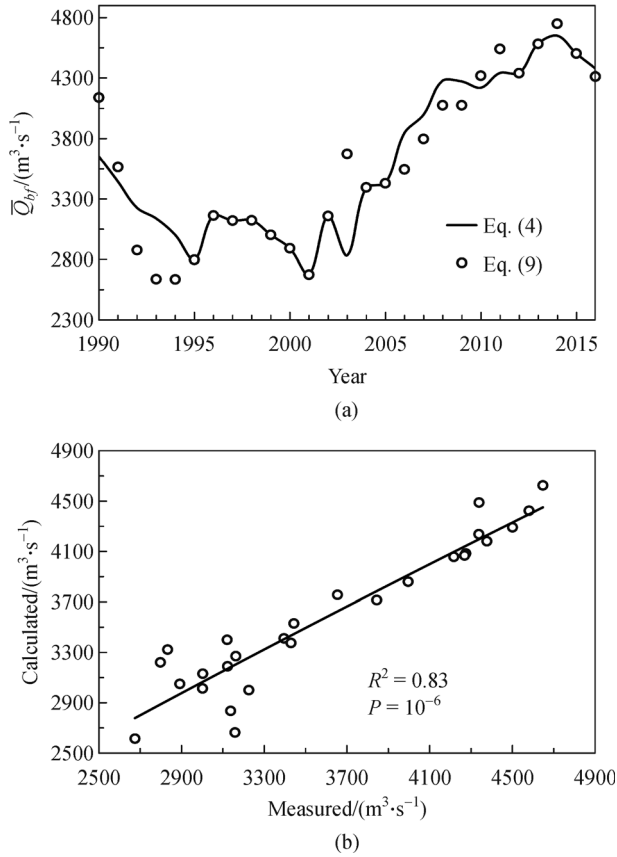


Fig. 12 Comparison between the measured reach-scale bankfull discharge and the calculations using the empirical relation: (a) temporal variations in the calculated and measured values; (b) correlation degree between them.

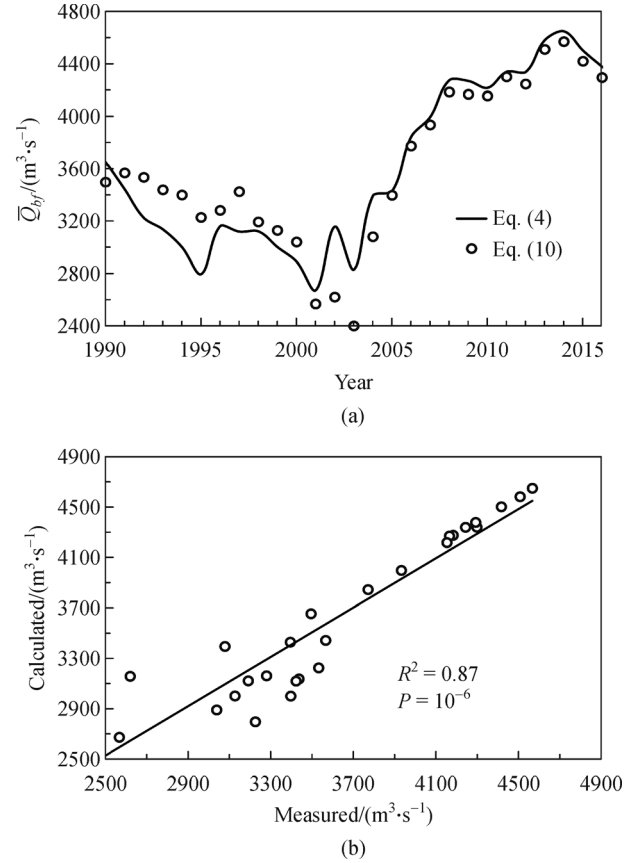


Fig. 13 Comparison of the measured reach-scale bankfull discharge and the calculations using the delayed response equation: (a) temporal variations in the calculated and measured values; (b) correlation degree between them.

changes in flow-sediment regime entering the tail reach of the YRE, \bar{Q}_{bf} may be under non-equilibrium within a limited period of time. As a result, the current value of \bar{Q}_{bf} is related to the values in earlier years during the processes of equilibrium adjustment, namely, the earlier average fluvial erosion intensity, which is expressed as an iterative relation:

$$Q_{bfy} = K(1 - e^{-\beta\Delta t}) \sum_{i=1}^y \left(e^{-(y-i)\beta\Delta t} \bar{F}_{fi}^a \right), \quad (10)$$

where y is the delayed time steps; i denotes the i th year accounted from the initial year interval ($i = 1, 2, \dots, y$); time interval Δt is set to 1 here; β is the approaching speed of \bar{Q}_{bf} towards equilibrium; K and a represent the coefficient and exponent, respectively. The parameters, K , a and β in Eq. (10), need to be calibrated by measurements.

In this study, the delayed time period was assumed to be 4 years ($y = 4$). \bar{Q}_{bf} was calculated by Eq. (10), and a , β and K were calibrated by linear regression on the basis of the discharge and sediment measurements (Table 3). As shown in Fig. 13(a), the values of \bar{Q}_{bf} in the study reach estimated

by Eq. (10) are largely consistent with the results calculated by Eq. (4). Additionally, Fig. 13(b) shows that the correlation between \bar{Q}_{bf} and the results calculated using Eq. (10) is relatively higher ($R^2 = 0.87$, $P = 0.929$) than that using Eq. (9). Therefore, it is concluded that \bar{Q}_{bf} in the tail reach of the YRE can also be predicted by the delayed response equation (Eq. (10)) of Wu et al. (2008a).

From Table 4, it can also be obtained that: (i) using the calibrated parameters a and β calculated by the delayed response equation, the attribute weights in the previous 4 years were estimated annually by $(1 - e^{-\beta\Delta t})e^{-(n-i)\beta\Delta t}$, and they were equal to 0.0124, 0.0125, 0.0127, and 0.0129 in the first to 4th year, respectively; (ii) due to the rational allocation of attribute weight in each year in Eq. (10), the correlation ($= R^2$) between the calculated values \bar{Q}_{bf} using Eq. (10) and the measurements is relatively higher than that of Eq. (9) in the study reach, and however, the form of Eq. (10) is more complicated than that of Eq. (9).

The Lijin-Xihekou reach, which is not affected by ocean dynamics, is chosen as the study reach for investigation due to limited measurements. However, it is obvious that different relationship will be applied to the river reach with

Table 4 Calibrated coefficients and exponents in different methods and correlation coefficients between calculated and measured reach-scale bankfull discharges

Calibration of different methods	α	K	β	R^2
Eq. (9)	2832.4	—	0.158	0.83
Eq. (10)	-0.173	2805.18	0.013	0.87

the influence of the tide, because the tide also plays an important role in the estuarine channel evolution (Xiong and Zeng, 2008). Therefore, a further investigation into the influence of tide should be conducted in the future.

5 Conclusions

Due to the Xiaolangdi Reservoir operation after 1999, the flow and sediment regime entering the YRE has been changed dramatically, which caused the process of continuous channel aggradation and degradation in the tail reach of the YRE since 1990. This study investigated the variation in \bar{Q}_{bf} in the tail reach of the YRE, and the main findings in this study are summarized as follows:

1) \bar{Q}_{bf} in the Lijin-Xihekou reach was calculated by a reach-averaged method, which can satisfy both the flow-continuity condition and the effect of different spacing on the value of \bar{Q}_{bf} .

2) The annual value of \bar{Q}_{bf} in the Lijin-Xihekou reach during the period 1990–2016 were calculated by the reach-averaged method. The results indicate that the changing range of reach-averaged discharges in the tail reach of the YRE was much smaller than that of Q_{bf} ; the value of \bar{Q}_{bf} was more relevant to the cumulative channel evolution volume with the correlation coefficient of 0.81 between these variables, and the magnitude of bankfull discharge decreased during the process of channel aggradation and increased during the process of channel degradation.

3) An empirical formula for the Lijin-Xihekou reach of the YRE was developed between \bar{Q}_{bf} and \bar{F}_{4f} during flood seasons, and a delayed response function with a relaxation time of 4 years was also adopted to predict the variation in \bar{Q}_{bf} . The encouraging results ($R^2 > 0.8$) obtained from these two methods indicate that both methods can be used to calculate the values of \bar{Q}_{bf} in the tail reach of the YRE.

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