Changes in sediment budget and morphology in the floodplains of the braided reach of the lower Yellow River

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January 13, 2021

Abstract

Floodplains provide valuable social and ecological environment functions, and understanding the rates and patterns of floodplain sedimentation/erosion is critical for floodplain management and rehabilitation. The sediment entering the lower Yellow River has been dramatically reduced, and the geomorphology has changed greatly during the operation of the Xiaolangdi (XLD) reservoir since 2000. Utilizing sediment resources is the key to managing the downstream river, and the floodplains not only play the roles of flood mitigation, detention and de-sanding but also provide land to support local residents and economic development; however, the floodplain currently faces competition between land development and protection. This research presents a detailed investigation of changes in the sediment budget and morphology of the braided reach between Huayuankou (HYK) and Gaocun (GC) during 2000-2017 using digital elevation models (DEMs) and the historical bathymetry of the braided reach. During the implementation of the water-sediment regulation scheme (WSRS), the long-term low-concentration flow released from the XLD reservoir leads to a fully scoured long channel, further improving the bank-full discharge and reducing the risk of floods on floodplains. However, the floodplains have gradually changed from sedimentation to erosion due to the continual construction of farm dykes and control works, land use changes and other forms of land disturbance, including water and soil conservation measures and climate change. The cumulative eroded volume was approximately 11.47×108 m3 along the HYK - GC reach between 2000 and 2017, of which 3.08×108 m3 originated from the floodplains, with an average annual erosion rate of 1.3 cm/yr. To develop the economy and guide floodplain construction, we propose a new method of environmental management to reconstruct the floodplain domain into different zones for immigration resettlement areas, agricultural areas and resource development and utilization areas, with the methods of river dredging and floodplain filling.

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Funding information: National Natural Science Foundation of China, Grant/Award numbers: 51979185 and 51879182; National Key R&D Program of China, Grant/Award: 2016YFC0402503

Abstract

Floodplains provide valuable social and ecological environment functions, and understanding the rates and patterns of floodplain sedimentation/erosion is critical for floodplain management and rehabilitation. The sediment entering the lower Yellow River has been dramatically reduced, and the geomorphology has changed greatly during the operation of the Xiaolangdi (XLD) reservoir since 2000. Utilizing sediment resources is the key to managing the downstream river, and the floodplains not only play the roles of flood mitigation, detention and de-sanding but also provide land to support local residents and economic development; however, the floodplain currently faces competition between land development and protection. This research presents a detailed investigation of changes in the sediment budget and morphology of the braided reach between Huayuankou (HYK) and Gaocun (GC) during 2000-2017 using digital elevation models (DEMs) and the historical bathymetry of the braided reach. During the implementation of the water-sediment regulation scheme (WSRS), the long-term low-concentration flow released from the XLD reservoir leads to a fully scoured long channel, further improving the bank-full discharge and reducing the risk of floods on floodplains. However, the floodplains have gradually changed from sedimentation to erosion due to the continual construction of farm dykes and control works, land use changes and other forms of land disturbance, including water and soil conservation measures and climate change. The cumulative eroded volume was approximately 11.47×10^8 m^3 along the HYK - GC reach between 2000 and 2017, of which 3.08×10^8 m^3originated from the floodplains, with an average annual erosion rate of 1.3 cm/yr. To develop the economy and guide floodplain construction, we propose a new method of environmental management to reconstruct the floodplain domain into different zones for immigration resettlement areas, agricultural areas and resource development and utilization areas, with the methods of river dredging and floodplain filling.

KEYWORDS

sediment budget; morphology changes; braided reach; lower Yellow River; erosion rate; floodplain reconstruction

INTRODUCTION

The erosion, transport and deposition of sediment within river basins are among the important processes of geomorphological development and have influenced the evolution of river channels, floodplains and deltas (Peng, Chen, & Dong, 2010). Since the 20th century, the sediment fluxes in the lower reaches of rivers have substantially decreased due to reservoir construction, soil and water conservation measures and land use changes (Syvitski, Vörösmarty, Kettner, & Green, 2005; Vörösmarty et al., 2003; Walling & Fang, 2003); examples include the Mississippi and Colorado Rivers in America and the Yangtze and Yellow Rivers in China (Maren, Yang, & He, 2013; Meade & Parker, 1985; Walling & Fang, 2003; Wang et al., 2007). However, a sediment supply shortage in the lower river reaches directly affects the morphology, stratigraphy, and ecological environment of channels, floodplains and deltas (Edmonds, Slingerland, Best, Parsons, & Smith, 2010; Xia et al., 2016; Xu et al., 2016).

With the development of society and the acceleration of urbanization processes, humans have improved their environmental protection consciousness and gradually realized the importance of river ecosystems (Dong, 2004; Gao, Jiang, & Zhang, 2008; Hill, 1979; Hillman, Aplin, & Brierley, 2003). Floodplains, as prominent parts of a river, play a pivotal role in river ecology. Moreover, floodplains have received considerable attention to date because of the valuable social and ecological functions of these systems, such as flood control, sediment and nutrient retention, recreational opportunities, agricultural production, and wildlife habitat (Pierce & King, 2008), and their land resources have increased in value. To protect these valuable resources from flood inundation, many river control works on both sides of the main channel have been built, which considerably limit the inundation space of large floods and lead to an uneven distribution of sediment deposition areas and a more complex riverbed form (Hudson & Middelkoop, 2015; Parker, 1995; Wu, Wang, Ma, & Zhang, 2005), especially along the lower Yellow River (LYR), which is a typical case of this kind. Owing to the characteristics of “insufficient runoff and excessive sediment loads lacking sufficient coordination” (Hu, Chen, Guo, & Yan, 2017; Wang, Zhou, & Li, 2006), long-term deposition has occurred in the main channel, resulting in the continuous evolution of the river morphology and the well-known phenomenon of a "secondary suspended river" in local reaches. The elevation of the channel bed is usually higher than that of the floodplain, while the elevation of the floodplain is also higher than that of the levee backside (Hu & Zhang, 2006; Li, Chen, & Liu, 2009; Liu, 2012; Zhang, Huang, Carling, & Zhang, 2017). In addition, the floodplain domain on both sides of the channel, where many villages are located, is very wide in the LYR and is the base of survival and development for approximately 1.895 million local inhabitants (YRCC, 2013). Currently, the environmental management of the floodplain mainly faces a competition between land protection and economic construction.

The LYR has experienced two distinct stages: continuous deposition before the operation of the Xiaolangdi (XLD) reservoir and continuous scouring after its operation. In recent years, numerous studies have been conducted to investigate the changes in erosion and deposition of the lower reaches (Chu, 2014; Liu, Shi, Zhou, Gu, & Li, 2019; Xu, 2003; Zhang et al., 2017), changes in river channel morphology (Hu, Chen, Liu, & Dong, 2006; Lu, Chen, & Chen, 2000; Wang & Li, 2011; Wang, Wu, & Shen, 2019; Wang, Xia, Zhou, & Li, 2019; Xie, Huang, Yu, & Zhang, 2018) and bank-full discharge (Li, 2019; Wu, Wang, Xia, Fu, & Zhang, 2008; Wu, Xia, Fu, Zhang, & Wang, 2010; Wu, Xia, & Zhang, 2007; Xia, Wu, Wang, & Wang, 2010; Zhang, Zhong, & Wu, 2013), river ecological water requirements (Shi & Wang, 2002; Xia, Yang, & Wu, 2009) and water-sediment relationships (Li & Sheng, 2011; Miao, Kong, Wu, & Duan, 2016; Wang, Fu, Liang, Liu, & Wang, 2017). However, little research information is available on the changes in sediment budget and morphology or the environmental management of the floodplain, especially during the XLD operation since 2000. At present, the following problems occur in the floodplain: i) the tension between the flood flow, detention and sediment deposition functions and the lives and properties of residents in the floodplain; ii) the competition between the rapid economic deployment along the Yellow River and the severe shortage of land resources; and iii) the contradiction between disordered land development, private construction and green ecological development of the floodplain (Zhang, 2017).

This research examines channel changes and sediment distribution in the braided reach, based on the idea of environmental management of floodplains along the lower Yellow River. This study aims to i) quantify the changes in the temporal-spatial distribution of sediment and the morphology of the braided reach of the LYR during the operation of the XLD reservoir since 2000; ii) evaluate the impact of the decrease in sediment supply on the environmental management of floodplains; and iii) propose different floodplain reconstruction modes in terms of the characteristics of different reaches.

STUDY AREA

2.1 General description of the study area

The Yellow River is the second longest river in China and is well known worldwide for its high sediment load; it has a total length of 5,464 km, and its basin drainage area amounts to 795,000 km^2, as shown in Figure 1. The LYR, with a length of approximately 785.6 km, extends from Mengjin in Henan Province to Lijin in Shandong Province and has been divided into three reaches in terms of geomorphological features, namely, the braided reach, the transitional reach and the meandering reach (see Figure 1). Heavy soil erosion on the Loess Plateau has led to intense sedimentation in the LYR (Miao, Yang, Chen, & Gao, 2012), and the total depositional volume in the LYR was approximately 5.52×10^9m^3 during the period from 1950 to 1999 based on observational data, of which 60% was deposited in the braided reach (Xia et al., 2010). The main effect of the heavy sedimentation in the LYR has been the obvious shrinkage of the main channel accompanied by a sharp decrease in the flood discharge capacity, which has resulted in the phenomenon of a secondary suspended river in certain reaches and a flood risk to the local residents and river management.

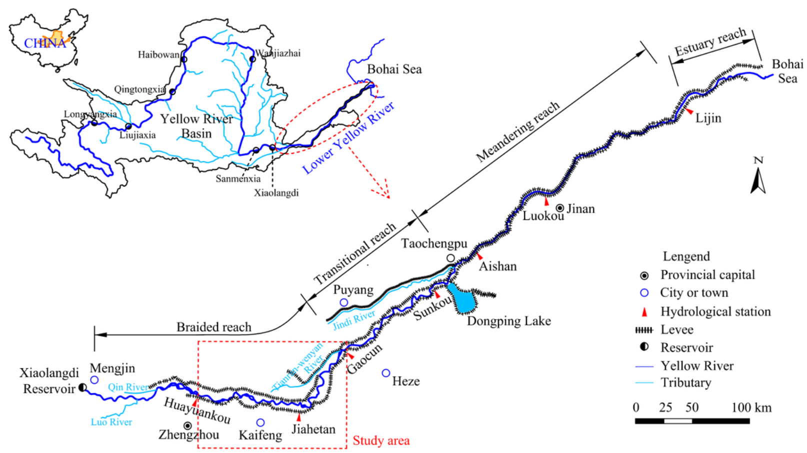

Figure 1 Map of the Yellow River Basin drainage area showing the locations of the major reservoirs and of the lower river reaches showing the locations of the major hydrological stations.

Our study reach is from the Huayuankou (HYK) hydrological station in Zhengzhou city to the Gaocun (GC) hydrological station in Heze city (see Figure 2). This reach is a typical braided reach in the LYR, which has the following characteristics (Qian, Zhou, & Hong, 1961; Wu et al., 2005): i) the river is wide and shallow and does not have a stable channel but often consists of two or more channels divided by rapidly migrating bars; ii) the shape of the cross-section changes greatly along the channel, and the mainstream shifts frequently back and forth and continues eroding the floodplains; and iii) the floodplains on both sides of the channel are very wide, and many villages and farmland are located there.

Along the 186.5 km study reach from HYK to GC, seven reaches of equal length are established, namely, Huayuankou - Huanglianji (HYK - HLJ), Huanglianji - Weicheng (HLJ - WC), Weicheng - Wang'an (WC - WA), Wang'an - Jiahetan (WA - JHT), Jiahetan - Youfangzhai (JHE - YFZ), Youfangzhai - Yangxiaoji (YFZ - YXJ), and Yangxiaoji - Gaocun (YXJ -GC), as shown in Figure 2. Each reach consists of the main channel and the floodplain, and the area of each part is calculated (Table 1). The total surface area of the study reach is approximately 1,710 km^2, of which approximately 356 km^2 marks the main channel, accounting for 21% of the total area, and the remaining 1,353 km^2 consists of floodplains, accounting for 79% of the total area.

Table 1 Divisions and areas of the reach between HYK and GC of the lower Yellow River

Domain	Area (km^2) HYK-HLJ	Area (km^2) HLJ-WC	Area (km^2) WC-WA	Area (km^2) WA-JHT	Area (km^2) JHT-YFZ	Area (km^2) YFZ-YXZ	Area (km^2) YXZ-GC	SUM
Left floodplain	183	115	88	37	81	126	118	749
Main channel	49	83	53	68	43	31	29	356
Right floodplain	42	72	58	119	143	130	40	605

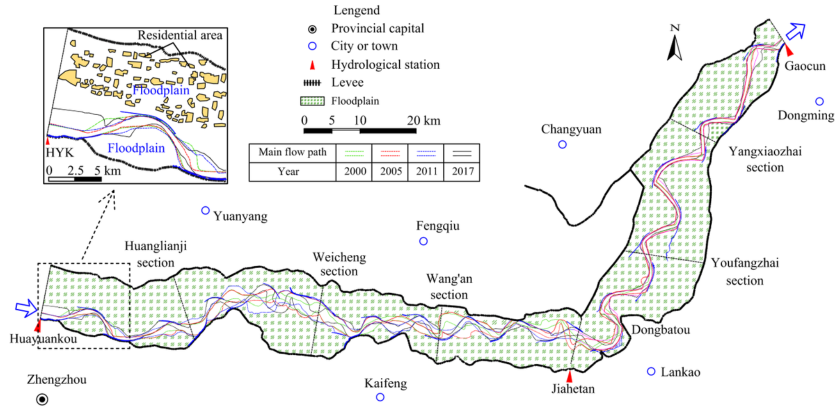

Figure 2 Sketch map of the study area.

2.2 Changes in the runoff and sediment load

The Yellow River Basin has been greatly affected by human activities in recent decades, and the runoff and sediment load in the LYR have notably changed due to regulation works such as reservoirs, water resource utilization and soil conservation (Li, Fu, Wu, & Wu, 2014), especially the operation of the XLD reservoir since 2000. The flow and sediment regimes entering the LYR can be represented by the hydrological data from the HYK and GC gauging stations during the pre-dam period 1960-2000 and the post-dam period 2000-2017 (see Figure 3); these data reveal decreases in the annual runoff and sediment load during the period from 1960 to 2017. From 1960 to 1973, the annual water discharge and sediment load were approximately $455.69\times10^8 m^3$/yr and 11.76×10^8t/yr, respectively. Large-scale soil and water conservation measures and a large number of silt dams were built on the Loess Plateau in the 1970s (Liu, Gao, Ma, & Dong, 2018; Xu, 2005), and the annual sediment load decreased to 10.54×10^8 t/yr, while the annual runoff reached $422.28\times10^8 m^3$/yr during 1974-1985. In the mid-1980s, the Longyangxia reservoir (see Figure 1) was built on the upper Yellow River and came into operation in 1986; the annual water discharge reached approximately $257.86\times10^8 m^3$/yr, and the annual sediment load decreased to 6.18×10^8 t/yr between 1986 and 1999. The XLD reservoir has been in operation since 2000, and by October 2016, the bank-full discharge had increased from 1,800 m^3/s during the pre-flood period in 2002 to 4,000 m^3/s. The annual water discharge of the LYR was maintained at approximately $236.31\times10^8 m^3$/yr, while the annual sediment load amounted to only 1.03×10^8 t/yr during 2000-2017.

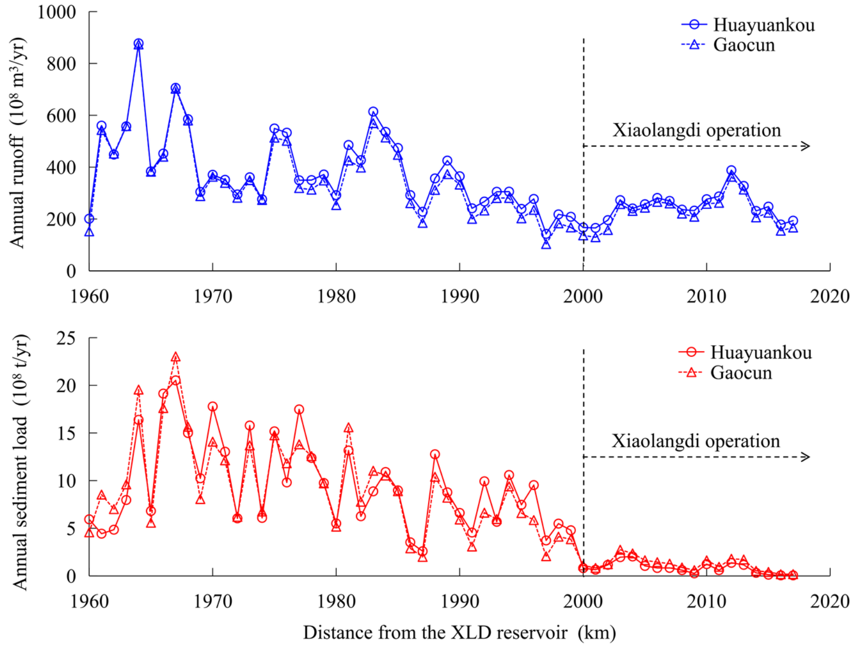

Figure 3 Annual runoff and sediment load of the LYR from 1960 to 2017.

DATA AND METHODS

3.1 Data collection

With the operation of the XLD reservoir, the sediment entering the LYR has dramatically decreased, and the geomorphology of the LYR has changed considerably. To investigate the temporal-spatial distribution of sediment and the geomorphological evolution of the braided reach between HYK and GC, hydrological data from 1960-2017 and bathymetry data sets of various cross-sections from 2000 to 2017 were collected.

The hydrological data on this study reach, including the annual runoff and sediment concentration, were measured at the HYK and GC stations from 1960 to 2017. The cross-sections lie between opposite primary levees of the LYR, with the distance between neighbouring cross-sections ranging from 0.5-5 km along the channel direction. The Beijing 54 geodetic coordinate system was adopted for all the bathymetric data sets to obtain the elevation of the riverbed in reference to a fixed level across the whole region. The Yellow Sea 1985 datum was applied as the reference level in this research.

3.2 Methods

The spatial interpolation method has been an active research topic for many years in various fields. This method has been applied to examine changes in sediment deposition and erosion in different areas, such as the tidal reach of the Yangtze River (Yuan, Lin, & Sun, 2020) or the Yellow River Delta (Fan, 2019; Jiang, Pan, & Chen, 2017). Similarly, the numerical simulation of river hydrodynamics requires spatial interpolation of discrete bathymetric data to determine the elevations at the nodes of the computational grid. There are many spatial interpolation methods for river channel topography, such as the inverse distance weighted, natural neighbour, kriging, spline, and other methods, which have their own advantages, and a reasonable interpolation method should be selected according to different characteristics of the river channel topography.

The braided reach of the LYR contains a broad floodplain with secondary perched compound cross-sections. According to the distribution characteristics of the measured cross-section sets, the floodplain and main channel are treated separately to obtain high-resolution DEMs from the scattered data. Merwade et al. (Merwade, Maidment, & Goff, 2006) showed that in a flow-oriented coordinate system, anisotropic spatial interpolation methods are clearly better than isotropic methods for interpolating river channel bathymetry. In this research, the mesh generator of the MIKE software (Amidror, 2002) was employed for mesh generation and interpolation purposes. A curvilinear grid was constructed covering the main channel, and the distance along the channel direction s was divided by a factor larger than 1 (3 was adopted). An unstructured triangular mesh was applied in the floodplains with natural neighbour interpolation in regard to the bathymetry, as shown in Figure 4.

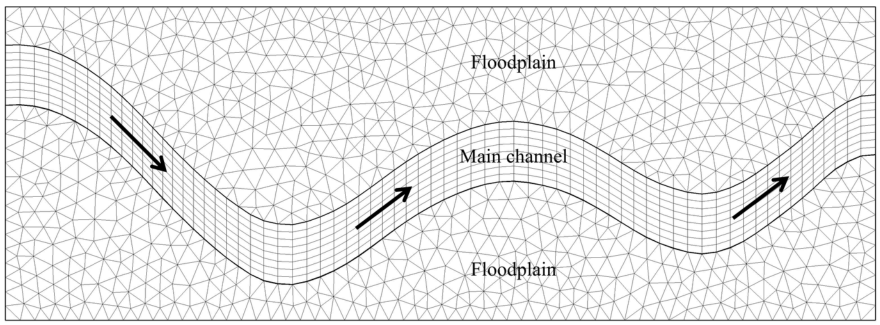

Figure 4 Sketch diagram of meshes for different zones.

RESULTS AND DISCUSSION

4.1 Sediment budget

4.1.1 Channel erosion and deposition

The sediments in the LYR are mainly received from the middle reaches, and long-term deposition in the lower reaches has raised the riverbed above the surrounding ground, which is called a “suspended river”. The LYR generally accumulated deposits prior to 2000, with a cumulative deposition of 83×10^{8} m^{3} between 1950 and 2000. Since the operation of the XLD reservoir began in 2000, the LYR has changed gradually from a sedimentation pattern to an erosion pattern due to the large quantities of sediment trapped by the dam, with a decrease in the cumulative deposition volume, as shown in Figure 5.

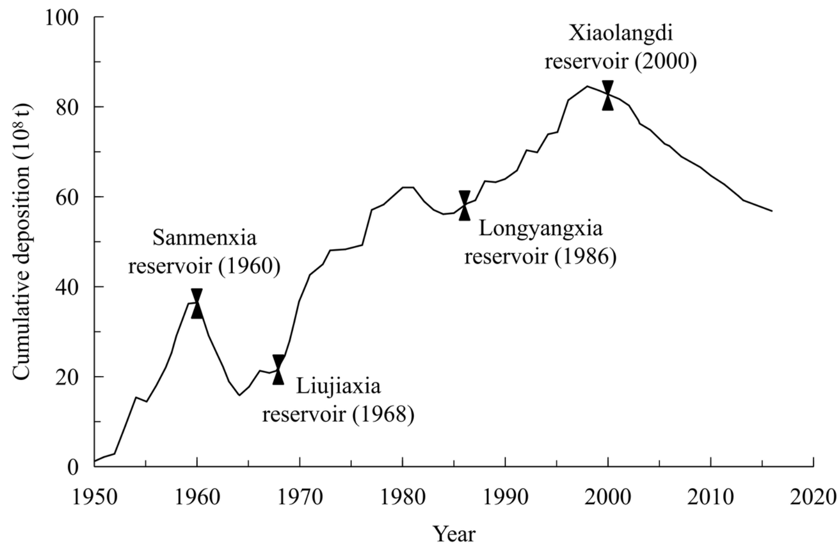

Figure 5 Cumulative deposition in the lower Yellow River.

However, the degrees of erosion are not the same in different segments of the braided reach between HYK and GC. Table 2 lists the segmented erosion and deposition volumes of the braided reach during the different periods. The cumulative erosion volume in the braided reach amounted to approximately $11.470 \times 10^8 m^3$ between 2000 and 2017, of which 64% came from the HYK-JHT reach and 36% came from the JHT-GC reach. This is mainly due to the gradually weakened erosion ability caused by the fading kinetic energy from the runoff (Kong et al., 2015).

Table 2 Sedimentation/erosion volume between HYK and GC from 2000-2017

Time Section	Erosion and sedimentation volume (10^8 m^3) HYK-HLJ	Erosion and sedimentation volume (10^8 m^3) HLJ-WC	Erosion and sedimentation volume (10^8 m^3) WC-WA	Erosion and sedimentation volume (10^8 m^3) WA-JHT	Erosion and sedimentation volume (10^8 m^3) JHT-YFZ	Erosion and sedimentation volume (10^8 m^3) YFZ-YXZ	Erosion and sedimentation volume (10^8 m^3) YXZ-GC	Total
2000-2002	0.124	0.505	0.167	0.515	-0.042	0.237	0.566	2.070
2002-2005	-0.709	-0.804	-0.429	-0.477	-0.735	-0.604	-0.241	-4.000
2005-2007	-0.153	-0.392	-0.446	-0.509	-0.372	-0.128	-0.042	-2.043
2007-2011	-0.303	-0.527	-0.298	-0.152	-0.176	-0.141	-0.173	-1.771
2011-2013	-0.261	-0.080	-0.177	-0.225	-0.206	-0.139	-0.192	-1.281
2013-2015	-0.456	-0.559	-0.657	-0.647	-0.298	-0.507	-0.554	-3.679
2015-2017	-0.149	-0.072	-0.135	-0.025	-0.052	-0.134	-0.200	-0.767

2000-2017	-1.908	-1.930	-1.975	-1.521	-1.882	-1.417	-0.837	-11.470

From 2000 to 2002, the total depositional volume from HYK to GC was approximately 2.07×10^{8} m^{3}, except for the JHT - YXZ reach, and all other reaches displayed depositional patterns. During the trial operation stage of the XLD reservoir from 2000 to 2002, a large amount of sediment released from the reservoir was still transported to the floodplain and deposited in the different regions. After the XLD reservoir achieved full operation in 2002, three water-sediment regulation scheme (WSRS) experiments were conducted by the Yellow River Conservancy (YRCC) during the period from 2002 to 2005: July 4-15, 2002; September 6-18, 2003; and June 19 - July 13, 2004 (Hu et al., 2017). These three WSRS events led to full scouring along the downstream river channel, with a total erosion of 4.0×10^{8}m^{3} of the reach from HYK to GC during 2002-2005. Since 2005, the WSRS has been conducted annually by the YRCC to address downstream flooding, deposition problems, and other issues (Li & Sheng, 2011), and the cumulative erosion of the reach was approximately 9.54×10^{8} m^{3}between 2005 and 2017.

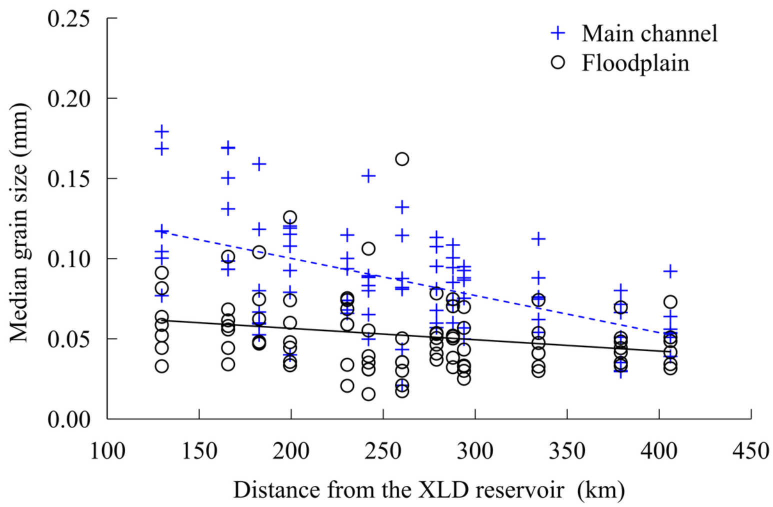

Figure 6 Distribution of the median sediment grain size between HYK and GC in the LYR.

In the braided reach (between HYK and GC), the median grain size of the bed material decreases gradually from HYK to GC, and the grain size of sediment in the main channel is generally larger than that in the floodplain (see Figure 6). The average median particle sizes of the bed material in the main channel and floodplain are approximately 0.1 mm and 0.05 mm, respectively, corresponding to dry bulk densities ranging from 1.233-1.410 t/m^{3}and 1.121-1.249 t/m^{3}, respectively (Shao & Wang, 2005). Considering the characteristics of the fine sediment particle size in the LYR, the dry bulk densities of the bed material in the main channel and floodplain are 1.233 and 1.121 t/m^{3}, respectively. The scouring and silting mass in the braided reach during the period 2000 - 2017 can be calculated.

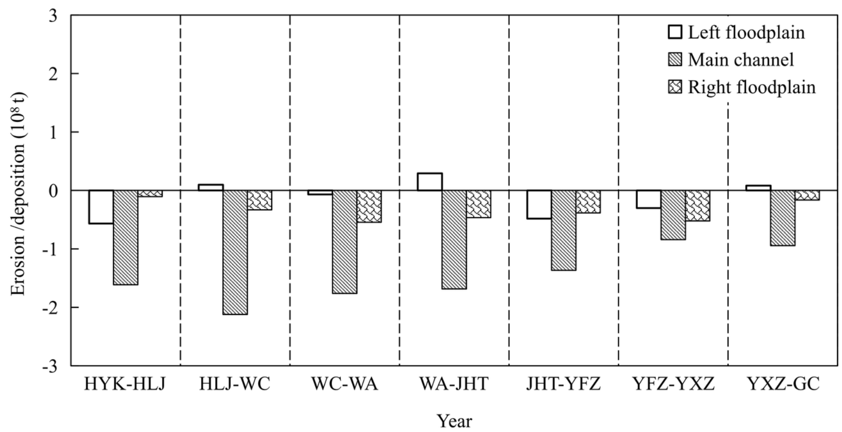

Figure 7 Erosion/deposition masses for the main channel and floodplain of the LYR during 2000-2017.

Here, we illustrate the change in the masses of erosion and deposition in the main channel and the floodplain for the different reaches (see Figure 7). During the period from 2000-2017, the mass of eroded sediment in the main channel was approximately 10.33×10^8 t, with an average annual erosion rate of 0.61×10^8 t/yr, while the mass of eroded sediment in the floodplain reached approximately 3.46×10^8 t, with an average annual erosion rate of 0.20×10^8 t/yr. The main channel erosion has been caused mainly by low sediment flow, and floodplain erosion may have been caused by human activities such as sand mining and land use.

4.1.2 Floodplain erosion and deposition

The total area of floodplains in the braided reach (between HYK and GC) is nearly four times that of the main channel, but the intensity of topographic adjustment of floodplains is lower than that of the main channel. Figure 8 shows the annual deposition and erosion volumes of the main channel and floodplains between 2000 and 2017. The main channel was fully scoured, with a total erosion volume of $8.38\times10^8 m^3$ and an average annual erosion volume of 49×10^8 m^3/yr. However, sedimentation was the main mode in the floodplain before 2002, and the floodplain was dominated by erosion after 2002, with the exception of a few areas where sediment deposition occurred; the other areas of floodplains were scoured.

During the period from 2000 to 2002, the cumulative depositional volume in the floodplain between HYK and GC was approximately 2.65×10^8 m^3, with an average annual deposition of 1.32×10^8 m^3/yr. In addition, the average annual deposition of each reach was approximately 0.09×10^8 m^3/yr; the right floodplain deposition rate ($0.12\times10^8 m^3$/yr) was larger than that of the left floodplain (0.07 $\times10^8 m^3$/yr). During the operation of the XLD reservoir and the implementation of the WSRS, the cumulative erosion was 5.73 $\times10^8 m^3$ in the floodplain between 2002 and 2017, with an average annual erosion value of 0.34 $\times10^8 m^3$/yr, of which 0.11 $\times10^8 m^3$/yr occurred in the left floodplain and 0.23 $\times10^8$ m^3/yr in the right floodplain.

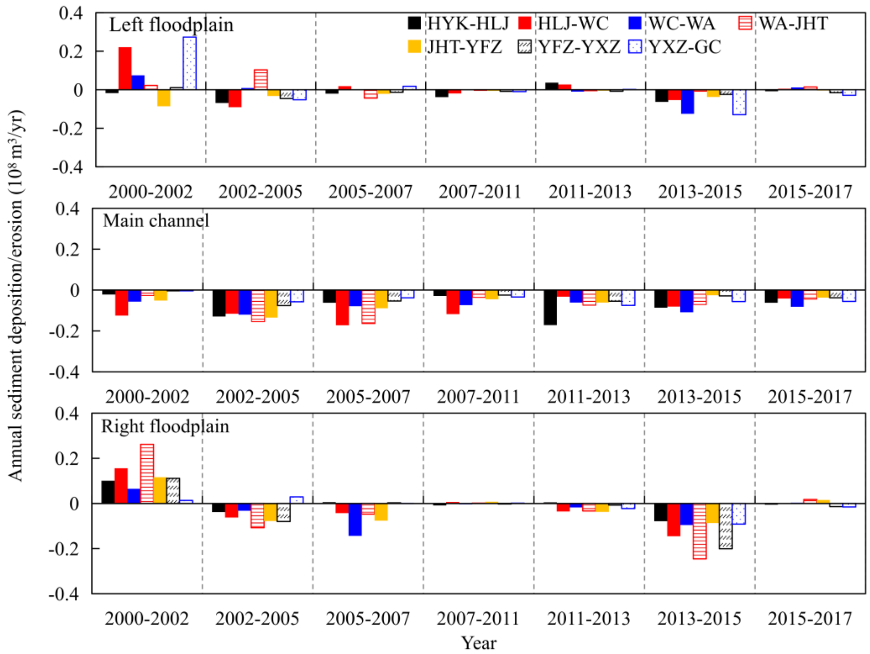

Figure 8 Annual sediment deposition and erosion between the HYK and GC stations during different periods (positive values indicate deposition, and negative values indicate erosion).

Table 3 shows the rates of erosion and deposition in the floodplains (including the left floodplain and right floodplain) of the various reaches in different periods. Before the operation of the XLD reservoir, the deposition rates ranged from 1.6-3.7 cm/yr in the floodplain of the braided reach (between HYK and GC) during 1965-1999 (Zhang et al., 2017). However, the floodplain gradually changed from a sedimentation pattern to an erosion pattern since the operation of the XLD reservoir, with an average erosion rate of 1.3 cm/yr between 2000 and 2017.

Table 3 Erosion/deposition rates in the floodplains of the different reaches

Time Section	Erosion/deposition rate (cm/yr) HYK-HLJ	Erosion/deposition rate (cm/yr) HLJ-WC	Erosion/deposition rate (cm/yr) WC-WA	Erosion/deposition rate (cm/yr) WA-JHT	Erosion/deposition rate (cm/yr) JHT-YFZ	Erosion/deposition rate (cm/yr) YFZ-YXZ	Erosion/deposition rate (cm/yr) YXZ-GC	Average
2000-2002	11.54	20.35	9.88	13.98	-1.19	4.72	13.36	10.38
2002-2005	-6.42	-8.23	-2.20	9.37	-4.74	-4.87	1.39	-2.24
2005-2007	0.12	-2.13	-12.36	-7.85	-3.97	-0.41	0.66	-3.70
2007-2011	-2.11	-0.46	-0.18	-0.36	-0.13	-0.42	-0.37	-0.57
2011-2013	1.52	-1.23	-2.11	-2.02	-1.60	-0.59	-2.76	-1.26
2013-2015	-11.13	-12.38	-15.25	-11.25	-5.32	-8.68	-16.92	-11.56
2015-2017	-0.88	0.26	0.93	2.66	0.29	-1.13	-3.19	-0.15

2000-2017	-1.05	-0.55	-3.04	0.65	-2.38	-1.63	-1.12	-1.30

Floodplains are an important part of the LYR, and the reasons for floodplain erosion can be summarized as follows. (a) Human activities, which affect fluvial systems in many ways (Xu, 2003). i) In recent decades, with increasing population and rapid urbanization, economic construction and land use have entered a period of rapid development, including agricultural production and building construction. ii) The residents of the floodplain domain have constructed many farm dykes on both sides of the main channel to allow agricultural production and to prevent small to moderate floods. iii) The construction of reservoirs has played an important role in blocking sediment, especially the operation of the XLD reservoir since 2000, and the sediment entering the LYR has dramatically decreased with an average annual sediment load of 1.03×10^{8} t/yr during 2000-2017, which is 83% lower than that from 1986 to 1999 (see Figure 3). Additionally, the XLD reservoir has efficiently controlled large-scale floods, which has reduced the risk of flooding in the floodplains. (b) Climate changes. A change in the rainfall regime may change the erosion and transport capability of storm runoff (Xu, 2003), especially extreme rainfall events, which are a determining factor in hydrological soil erosion (Nunes, Seixas, Keizer, & Ferreira, 2010). Owing to the thick layer and short depositional time of sediments in the floodplains of the LYR, loose sediment particles are vulnerable to erosion by rainfall and runoff, resulting in a decrease in the surface elevation.

4.2 Morphology changes

The morphology of natural river channels can be divided into the cross-sectional form, longitudinal profile and plan form. The quantitative characteristics of the cross-sectional form include the width, depth, area, wetted perimeter and width-to-depth ratio. The longitudinal profile is mainly reflected in the changes in the riverbed slope along the channel, while the quantitative features of the plan form include the bending coefficient, curvature radius, bending distance and swing amplitude. In this research, we mainly consider adjustment regulation of the riverbed morphology from three aspects: the longitudinal profile, the horizontal migration of the thalweg and the cross-sectional forms.

4.2.1 Changes in the longitudinal profile and the thalweg point

The longitudinal profile, which is a graph of height (H) against distance downstream (L) expressed by $H = f\ (L\ )$, is an important element of river geomorphology. From 1986 to 1999, the longitudinal profile of the LYR displayed a trend of continuously rising riverbed elevation, in which the average riverbed elevation of the HYK-JHT reach increased by approximately 2.6 m, and the average riverbed elevation of the JHT-GC reach increased by approximately 3.0 m (Shen, Zhang, Li, Shang, & Pan, 2000). Since 2000, the river channel in the LYR has experienced continuous scouring. Figure 9(a) shows the longitudinal profiles of the riverbed in the HYK-GC reach for different years (2000, 2005, 2011 and 2017) by using the mean riverbed elevation points of the channel. The average riverbed gradient basically remained at approximately 0.18longitudinal profile of the riverbed underwent parallel downcutting during scouring. The average bed elevation during the pre-flood season in 2017 was 2.78 m lower than that during the pre-flood season in 2000.

The reach between HYK and GC in the LYR is a typical braided reach, with complex changes in the river regime, and it is easily affected by the water discharge and sediment load from upstream. In addition, the main flows swing frequently and continually erode the floodplains, which results in frequent shifts between the main channel and the floodplain and places certain pressure on flood control works (Hu, 2003). Here, selecting the thalweg points during the pre-flood season in May 2000 as reference positions, the horizontal migration distances of the thalweg points in different years are calculated (see Figure 9b). A negative value indicates that thalweg points moved towards the left bank, and a positive value indicates that thalweg points moved towards the right bank. From a comparison of the different periods, large variations are observed to occur in the thalweg migration amplitude in the different years. Among them, the average annual migration rates along the three hydrological sections are 1,480 m, 1,300 m and 343 m. Moreover, we find that the average annual migration rates of thalweg points in the HYK and JHT cross-sections are four times higher than that in the GC cross-section. The amplitude of thalweg migration gradually decreases in the downstream direction, and the limiting effect of the channel form on thalweg migration is strengthened.

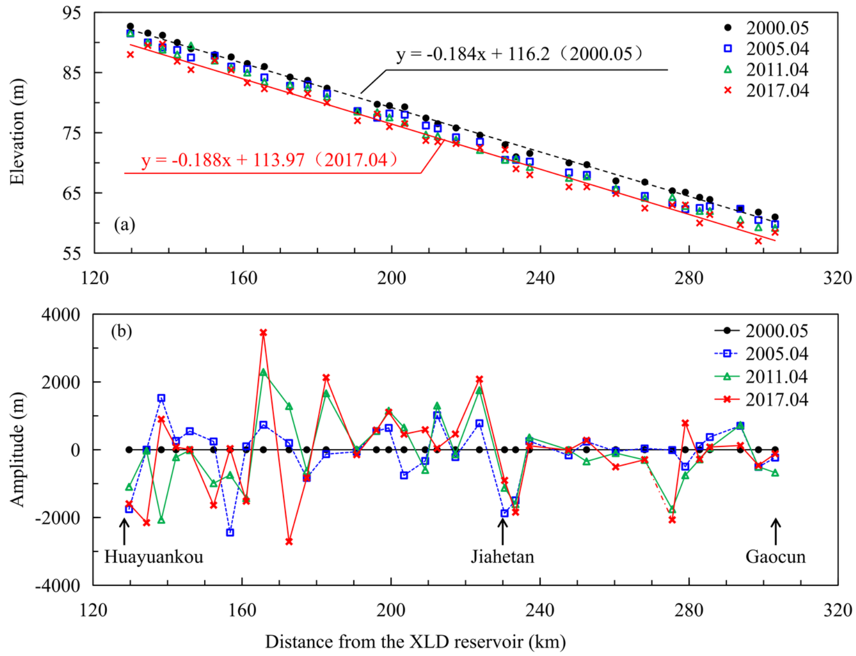

Figure 9 Variations in the riverbed slope (a) and changes in thalweg migration from HYK to GC (b).

4.2.1 Changes in the cross-sectional form

Changes in both the discharge and the sediment load not only affect the channel longitudinal profile but also have a strong influence on the evolution of the cross-sectional form. The cross-sectional form of the braided reach in the LYR shows high complexity. Figure 10 shows a set of typical cross-sectional geometries, represented by the sections at Weicheng (WC) and Yangxiaozhai (YXZ) in different years. Among them, WL is a representative section of the suspended river in the HYK-DBT reach, and YXZ is a typical section of the secondary suspended river in the DBT-GC reach.

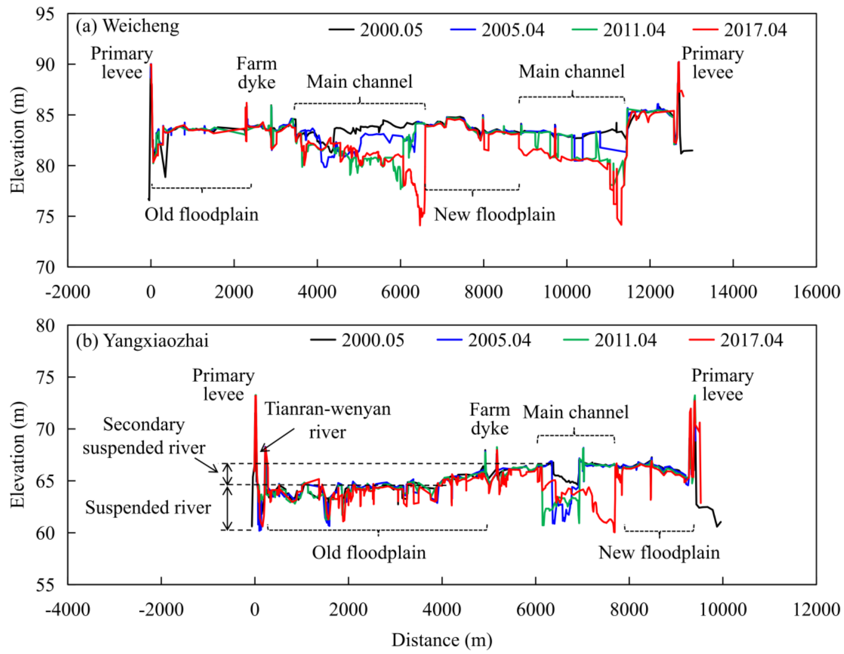

Figure 10 Typical cross-sectional profiles of the LYR at (a) Weicheng section and (b) Yangxiaozhai section.

During the period 1986-1999, the river channel seriously shrank and deposited sediment; the width of the main channel was obviously reduced with decreases ranging from 300 to 2000 m, and the capacity of flood discharge also decreased (Shen et al., 2000). During the operation of the XLD reservoir and the implementation of the WSRS, low-sediment concentration flows were released from the reservoir, which continuously scoured the riverbed and gradually widened and deepened the main channel. The width of the main channel increased by 2600 m at the WC section and 780 m at the YXZ section from 2000 to 2017.

We measured the changes in the widths of the main channel and the floodplains during 2000-2017, as shown in Figure 11. Width changes in the main channel vary greatly from HYK to GC; taking the DBT section as the boundary, the widths of the main channel from HYK to DBT are between 400-2300 m, and the widths of the main channel are concentrated the range from 500-1000 m in the DBT - GC reach. Width changes in the floodplain can be divided into three parts: i) the width of the HYK - WC reach increases gradually downstream, ii) the width of the WC - DBT reach is relatively stable and shows little change along the river, and iii) the width of the DBT - GC reach decreases gradually along the river.

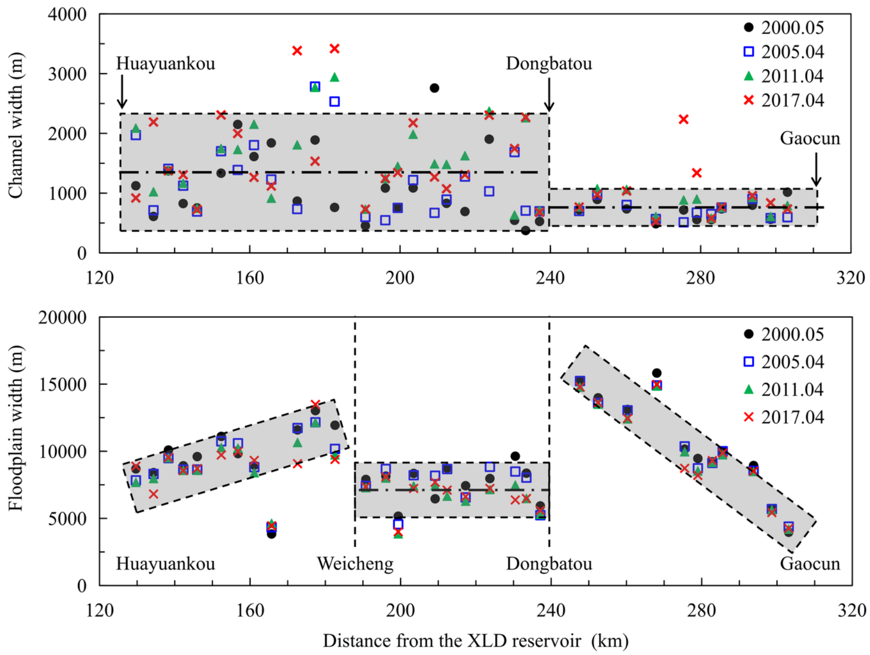

Figure 11 Width changes in the main channel and floodplains in the different reaches.

4.3 Mode of environmental management in floodplain

During the operation of the XLD reservoir, the riverbed elevation in the LYR has been effectively controlled by the implementation of the WSRS, resulting in an increase in the bank-full discharge and sediment transport capacity of the main channel, which has reduced the probability of large-scale floods and ensured life and property safety on the floodplain. However, sediment resources on the floodplain have been decreasing since 2000, and the unfavourable phenomenon of a secondary suspended river still exists in local reaches. Moreover, the impact on floodplain environmental management is negative because of the shortage of sediment resources. Sediment is the primary source of a sustainable agro-ecosystem in the LYR, which not only influences riverbed morphology development but also may counteract floodplain subsidence and soil erosion. How to optimize sediment resource allocation in the lower reaches of the Yellow River to achieve positive outcomes for both environmental management and economic development has become an urgent problem.

Under the new requirements of water control and ecological urban construction, we propose a new design idea for floodplain environmental management; some floodplains of the LYR can be reconstructed by measures such as pipeline sediment transport and river dredging. From the levee to the main channel, the floodplain can be sequentially reconstructed into different regions (see Figure 12), including the “high floodplain”, “secondary floodplain” and “new floodplain”; among these regions, the new floodplain together with the main channel could perform the tasks of flood control and sediment transport in the LYR. Through reconstruction of the floodplain domain and in coordination with environmental management measures, different functional zones (such as residential areas, efficient agricultural areas and ecological wetland areas) can be formed. This mode of floodplain reconstruction can solve the unfavourable morphology of the secondary suspended river in local reaches and guarantee flood control safety in the LYR, promote the development of floodplain areas and achieve positive results both in river management and in benefits to people.

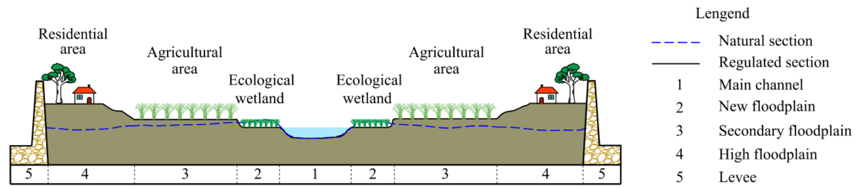

Figure 12 Sketch of environmental reconstruction and management in floodplains

Due to the geomorphic features of various reaches of the lower Yellow River, different reaches should adopt diverse management methods according to the local conditions, as shown in Figure 13. The HYK-GC reach can be divided into two sections according to the characteristics of the river morphology. i) The HYK-DBT reach, with a wide floodplain area and high elevation and slight development of the secondary suspended river, is recommended to adopt the management mode of "high floodplain, secondary floodplain and new floodplain". ii) The DBT-GC reach, also called the low floodplain, which has a high probability of overbank flooding and serious development of the secondary suspended river, is the key management area on the floodplain of the LYR; in this region, it is advisable to adopt the management mode of "high floodplain, secondary floodplain and new floodplain" or "secondary floodplain and new floodplain".

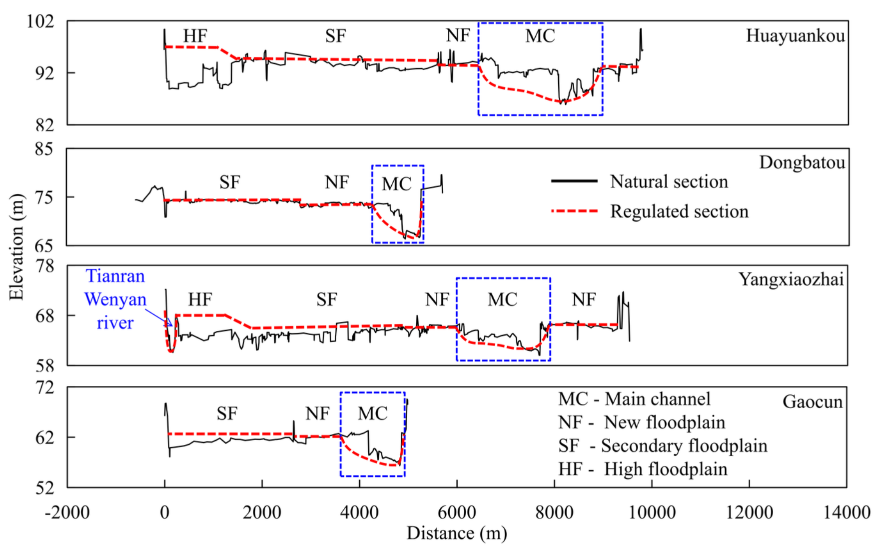

Figure 13 Floodplain management of different reaches along the LYR.

The floodplain reconstruction scheme of the lower reaches could realize the optimal allocation of sediment resources downstream, which would be conducive to flood control and sediment transport in the LYR. This scheme, together with the XLD reservoir operation mode and flood control works in the lower reaches, could realize long-term stability in the LYR. In addition, through environmental management of the floodplains, the construction of environmental landscapes and economic belts along the Yellow River could provide ecological spaces for the cities, which could improve the quality and competitiveness of urban development and provide an impetus for the sustainable development of the regional economy.

CONCLUSIONS

Since the operation of the XLD reservoir began in 2000, the objective of mitigating riverbed elevation increases in the LYR has been achieved. With the proposal of the new goals for environmental protection and high-quality development of the Yellow River Basin, the environmental management and rehabilitation of floodplains have received increasing attention from people in all walks of life. Our research investigated the changes in the sediment budget and morphology of the braided reach between HYK and GC in the LYR, and the main findings are as follows:

During the operation of the XLD reservoir from 2000 to 2017, the total eroded volume of the braided reach (between HYK and GC) was approximately 11.47×10^8 m^3, of which approximately 8.38×10^8 m^3 occurred along the main channel and $3.09\times10^8 m^3$ in the floodplains. The main channel was fully scoured, with an average erosion rate of 14.16 cm/yr, leading to increases in channel depth and bank-full discharge. The floodplains gradually changed from a sedimentation pattern to an erosion pattern, with an average erosion rate of 1.30 cm/yr, due to the implementation of the WSRS, continual construction and reinforcement of control works along the channel and other human activities.

Sediment is the primary source of a sustainable agro-ecosystem in the lower Yellow River, which influences morphological development and may counteract floodplain subsidence and soil erosion. The shortage of sediment resources is unfavourable to the environmental management of floodplains. We propose a new management mode for the floodplains in the LYR. Some floodplains in local reaches are rebuilt into high floodplain, second floodplain and new floodplain areas, with some mechanical measures such as pipeline sediment transport and floodplain filling. This mode could eliminate the unfavourable form of a secondary suspended river and optimize the allocation of sediment resources downstream, which lays a good foundation for the environmental management of the lower Yellow River and the economic development of the floodplain region.

ACKNWLEDGEMENTS

The project is funded by the National Natural Science Foundation of China (51979185 and 51879182) and the National Key R&D Program of China (2016YFC0402503).

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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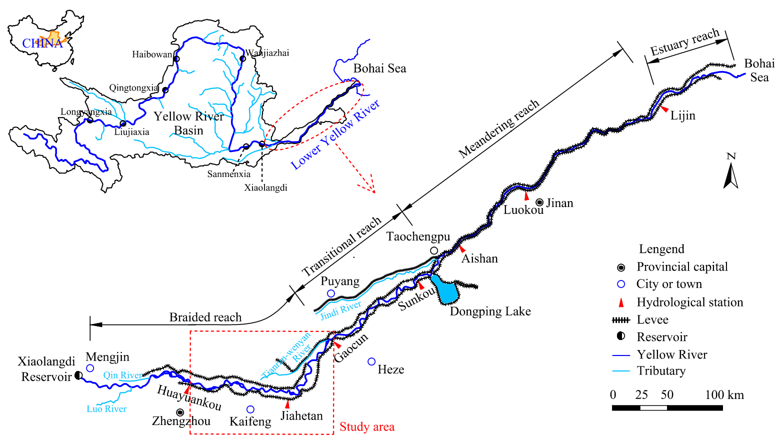
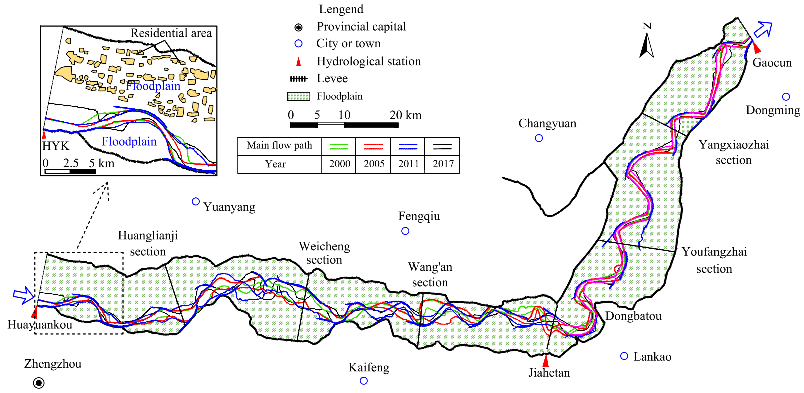
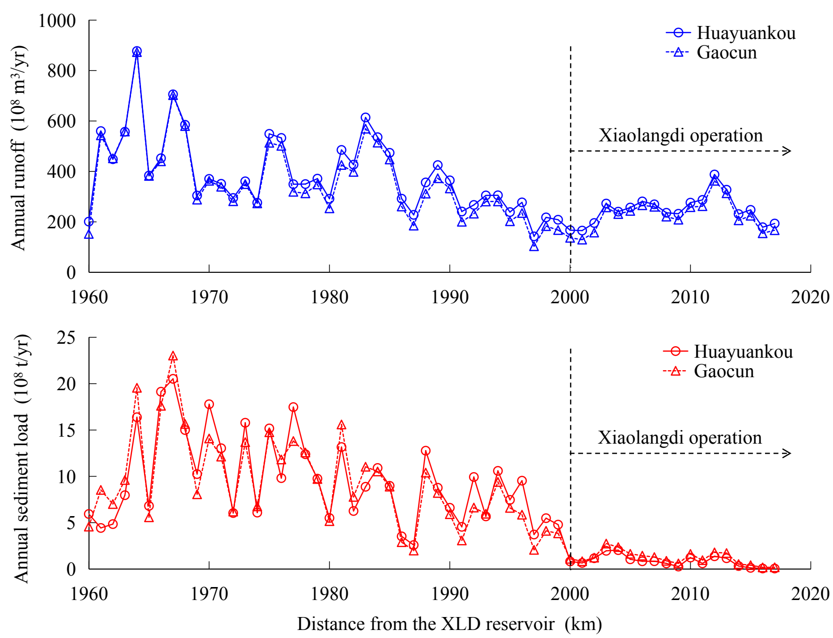
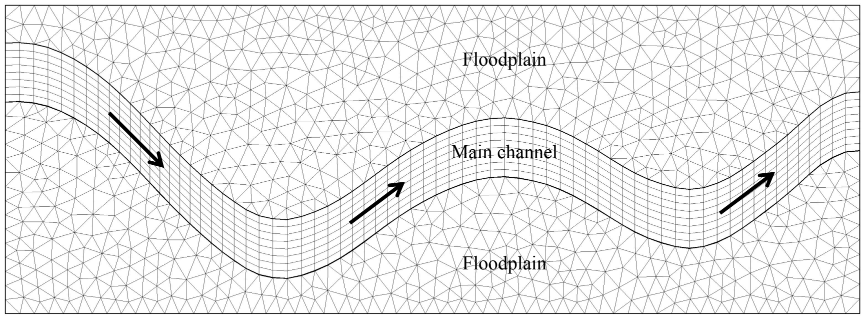
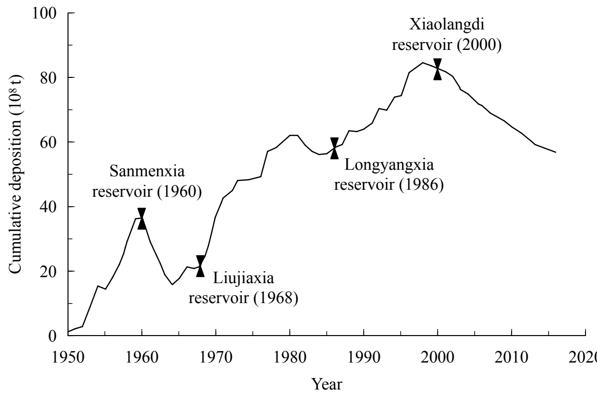
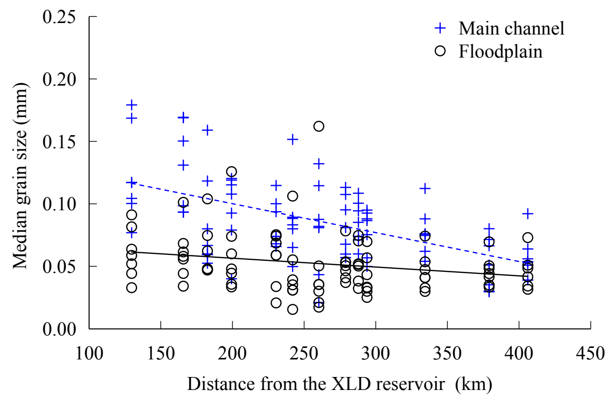


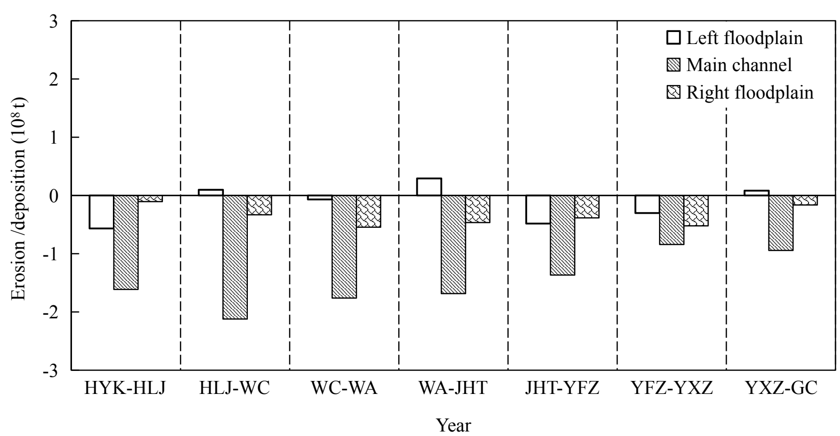

Lengend
Provincial capital
City or town
Hydrological station
Levee
Floodplain
0 5 10 20 km
Main flow path
Year
2000
2005
2011
2017
Residential area
Floodplain
Floodplain
HYK
0 2.5 5 km
N
Gaocun
Dongming
Changyuan
Yangxiaozhai section
Yuanyang
Fengqiu
Huanglianji section
Weicheng section
Wang'an section
Youfangzhai section
Dongbatou
Huayuankou
Zhengzhou
Kaifeng
Jiahetan
Lankao

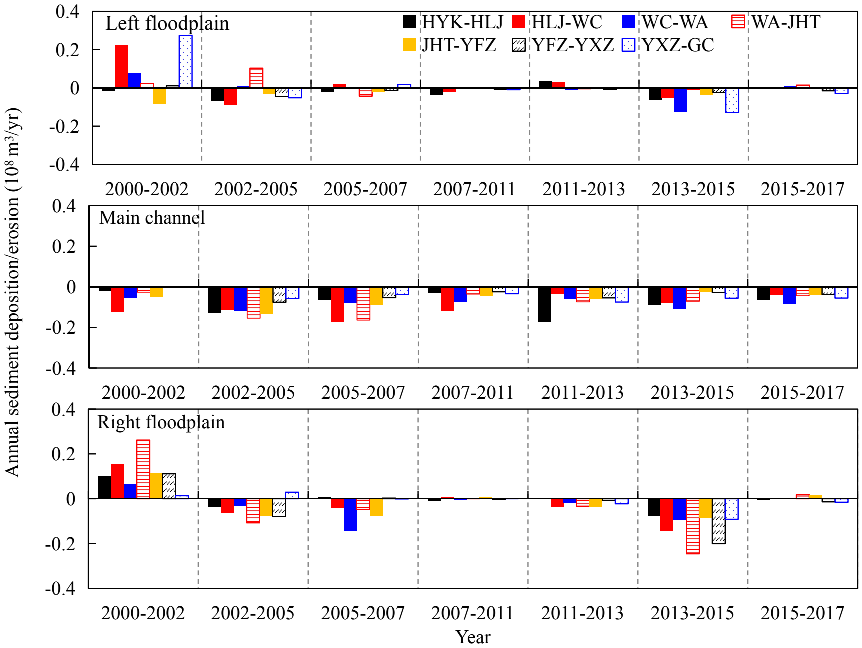

Annual runoff (10^8 m^3/yr)
1000
800
600
400
200
0
1960
1970
1980
1990
2000
2010
2020
Huayuankou
Gaocun
Xiaolangdi operation
Annual sediment load (10^8 t/yr)
25
20
15
10
5
0
Huayuankou
Gaocun
Xiaolangdi operation
Distance from the XLD reservoir (km)

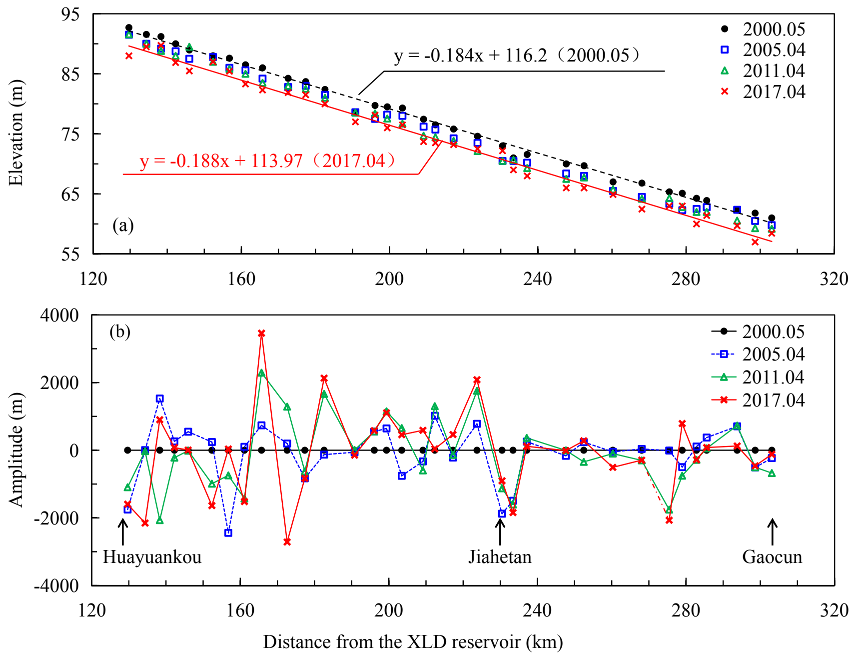

Floodplain
Main channel
Floodplain

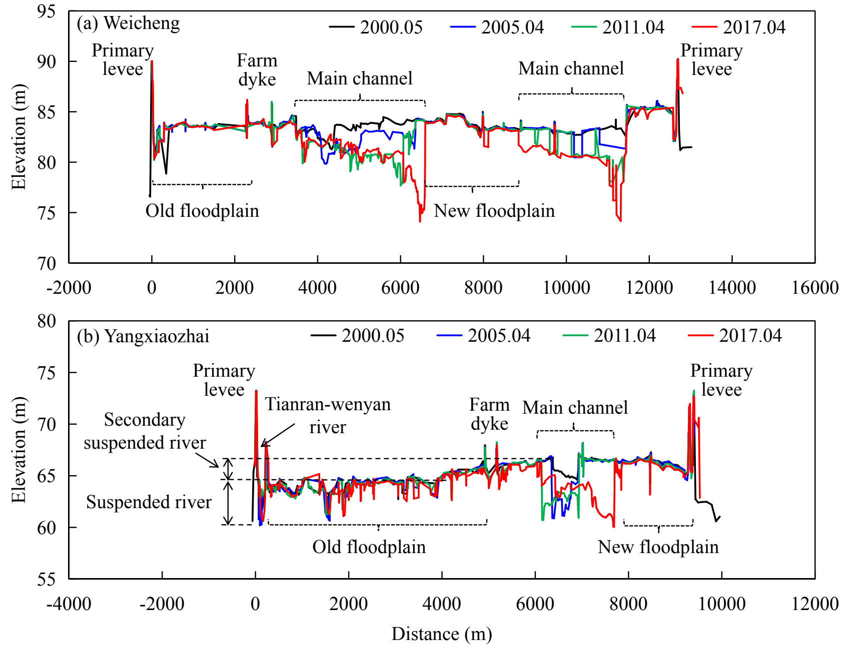

Xiaolangdi
reservoir (2000)
Sanmenxia
reservoir (1960)
Longyangxia
reservoir (1986)
Liujiaxia
reservoir (1968)
Cumulative deposition (10⁸ t)
Year
0
20
40
60
80
100
1950
1960
1970
1980
1990
2000
2010
2020

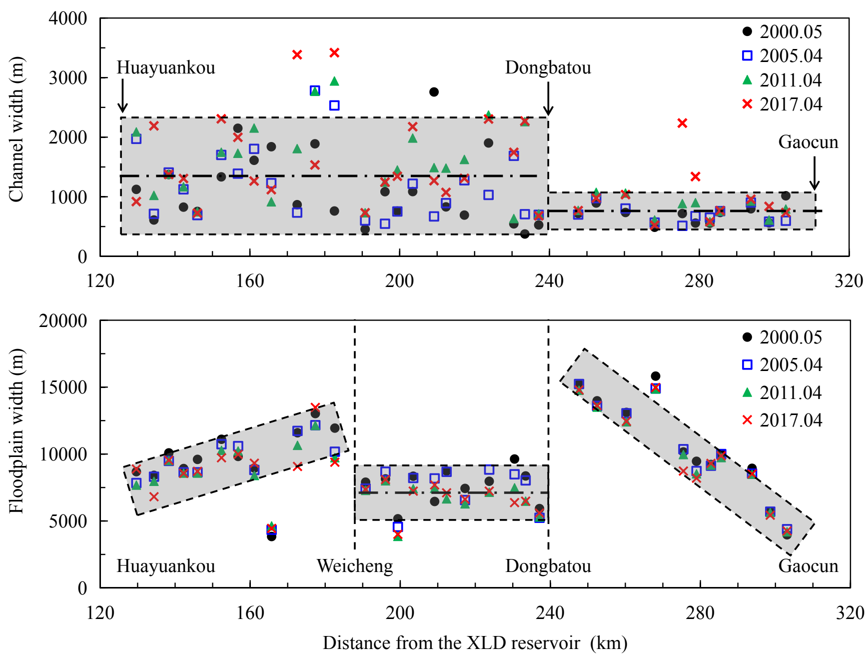

Main channel
Floodplain
Median grain size (mm)
Distance from the XLD reservoir (km)
0.25
0.20
0.15
0.10
0.05
0.00
100
150
200
250
300
350
400
450

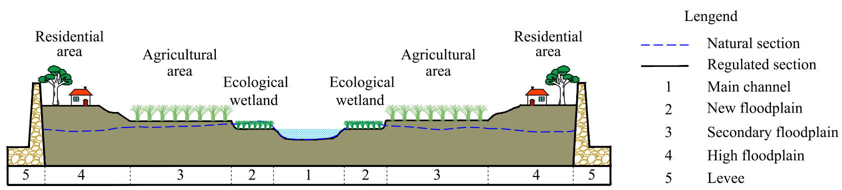

Left floodplain
Main channel
Right floodplain
Erosion /deposition (10^8 t)
3
2
1
0
-1
-2
-3
HYK-HLJ
HLJ-WC
WC-WA
WA-JHT
JHT-YFZ
YFZ-YXZ
YXZ-GC
Year

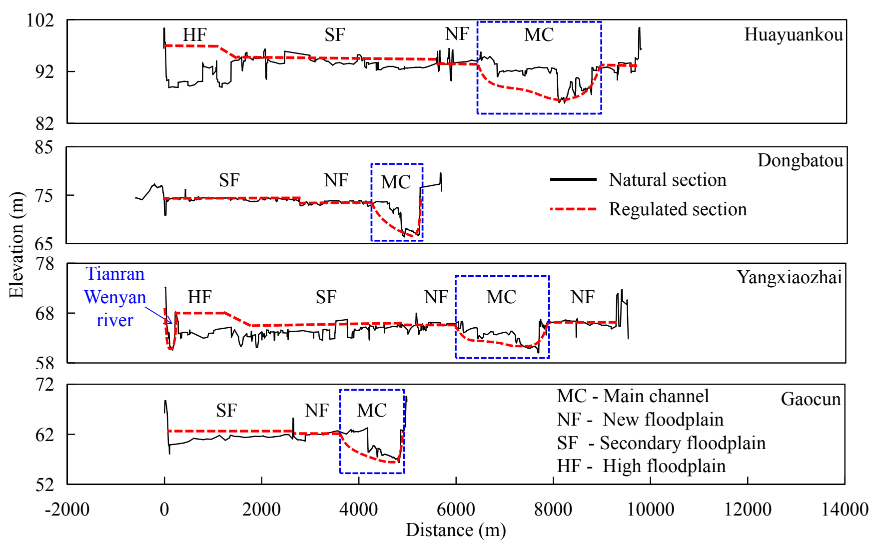

Left floodplain
Main channel
Right floodplain
HYK-HLJ
HLJ-WC
WC-WA
WA-JHT
JHT-YFZ
YFZ-YXZ
YXZ-GC
0.4
0.2
0
-0.2
-0.4
2000-2002
2002-2005
2005-2007
2007-2011
2011-2013
2013-2015
2015-2017
Annual sediment deposition/erosion (10^8 m^3/yr)
Year


95
85
75
65
55
Elevation (m)
y = -0.184x + 116.2（2000.05）
y = -0.188x + 113.97（2017.04）
2000.05
2005.04
2011.04
2017.04
(a)
120
160
200
240
280
320
4000
2000
0
-2000
-4000
Amplitude (m)
(b)
Huayuankou
Jiahetan
Gaocun
Distance from the XLD reservoir (km)


(a) Weicheng
2000.05
2005.04
2011.04
2017.04
Primary levee
Farm dyke
Main channel
Main channel
Primary levee
Old floodplain
New floodplain
Elevation (m)
(b) Yangxiaozhai
Primary levee
Tianran-wenyan river
Farm dyke
Main channel
Primary levee
Secondary suspended river
Suspended river
Old floodplain
New floodplain
Distance (m)


Channel width (m)
Huayuankou
Dongbatou
Gaocun
2000.05
2005.04
2011.04
2017.04
Floodplain width (m)
Huayuankou
Weicheng
Dongbatou
Gaocun
Distance from the XLD reservoir (km)


Residential area
Agricultural area
Ecological wetland
Ecological wetland
Agricultural area
Residential area
Lengend
Natural section
Regulated section
1 Main channel
2 New floodplain
3 Secondary floodplain
4 High floodplain
5 Levee


Huayuankou
Dongbatou
Yangxiaozhai
Gaocun
HF
SF
NF
MC
Natural section
Regulated section
Tianran Wenyan river
MC - Main channel
NF - New floodplain
SF - Secondary floodplain
HF - High floodplain
Elevation (m)
Distance (m)