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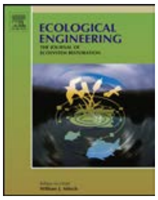

The hydro-environmental response on the lower Yellow River to the water–sediment regulation scheme

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ABSTRACT

Heavy sedimentation has led to the phenomenon of a secondary perched river in the lower Yellow River. The water–sediment regulation scheme (WSRS) using the Xiaolangdi Reservoir was implemented in 2002 to solve this problem. In this study, we analyzed the impact of the WSRS on the lower Yellow River and investigated the mechanism by which the WSRS affects channel erosion. We found that the runoff and sediment load, the sediment grain size, and the river channel of the lower Yellow River have all altered dramatically since the implementation of the WSRS. The variations in runoff and sediment load are no longer synchronized: runoff shows a rising trend, whereas sediment load remains relatively stable. The proportions of runoff and sediment load during the rainy season have decreased, whereas the proportions of runoff and sediment load during the dry season have increased. The median sediment grain size displays a gradually increasing trend top–down along the lower Yellow River. The main river channels in the lower Yellow River have been fully scoured, leading to an increase in channel depth and bankfull discharge. In addition, the sediment load flowing into the estuary reach is relatively stable, with an average value of 158.6×10^6 t, which is sufficient to maintain the dynamic balance of the Yellow River Delta. We found that the degree of channel erosion in the lower Yellow River depends mainly on the incoming sediment concentration.

1. Introduction

Dams, especially large dams, have played a pivotal role in the comprehensive utilization of rivers. The earliest dams were built for the purposes of irrigation, flood control, and water supply. Later, most of the world's large rivers were dammed to generate power to help meet the increasing global demand for renewable energy. Dams were built on almost all of the world's large rivers, e.g., the Three Gorges Dam on the Yangtze River (Guo et al., 2012; Su et al., 2013), the Aswan High Dam on the Nile River (Stanley and Wingerath, 1996; Strzepek et al., 2008), and the Hoover Dam on the Colorado River (Kwak et al., 2014). In addition to the intended effects, the construction and utilization of dams simultaneously results in indirect impacts on the river system. Large dams and reservoirs commonly affect the runoff and sediment load into the sea (Dai et al., 2008; Wang et al., 2006a; Yu et al., 2013) and thereby change the evolution of the river delta (Yang et al., 2011). As the river is the prime source of nutrients for estuaries, the composition of material flowing to the sea (e.g., nitrogen content, phosphorus content, and salinity) can be modified by the variations in material flux (Carriquiry et al., 2010; Jin et al., 2013; Gao et al., 2014a). Downstream fluvial sedimentation also changes the morphology of riverbeds due to the loss of energy in the reduced flow (Dai and Liu, 2013). In addition, dams are widely recognized as having significant negative consequences for the surrounding natural ecosystems and environment (Fu et al., 2010; Gao et al., 2014b). The construction and use of dams may affect the distribution of local vegetation (Kellogg and Zhou, 2014; New and Xie, 2008; Su et al., 2012) and destroy animal habitats (Asaeda and Rashid, 2012; Yi et al., 2014, 2010).

The Yellow River is called "the cradle of Chinese civilization", and it was the most prosperous region in early Chinese history (Yu, 2002). To prevent floods and generate electricity, a cascade of large dams has been built along the mainstream Yellow River in

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recent decades. Currently, the Yellow River Basin is one of the most manipulated fluvial systems in the world, with dozens of large dams. By 2012, there were 29 large reservoirs scattered widely across the river basin with storage capacities exceeding 0.1×10^9 m^3. The Xiaolangdi Dam is located in the mouth of the last gorge in the middle reach of the Yellow River, approximately 40 km north of Luoyang, Henan Province (Fig. 1), and is a key location for the control of flooding and sediment in the lower reaches of the Yellow River. The Xiaolangdi Dam is a multi-purpose project mainly designed for flood control, ice control, and sediment reduction, as well as irrigation, water supply, and power generation. Since the completion of the Xiaolangdi Dam at the end of 2002, a water–sediment regulation scheme (WSRS) has been conducted annually by the Yellow River Conservancy Commission (YRCC) to address downstream flooding, deposition problems, and other issues (Wan et al., 2013).

Most previous studies related to the WSRS focused on changes in the hydraulic characteristics (Yu et al., 2013; Zhang et al., 2009), sediment transportation (Miao et al., 2010; Xu and Si, 2009), and channel adjustment (Xu et al., 2005) of the lower Yellow River, as well as on the evolution of the Yellow River Delta (Wang, 2005; Yao et al., 2012). However, these studies mainly focused on only one or two indices individually. Several studies have attempted to explain the patterns of erosion and sediment deposition in the channel of the lower Yellow River. Some researchers have attributed the channel erosion to the artificially high flow rate during the WSRS (Wan et al., 2013; Xu and Si, 2009), whereas others suggest that the dominant factor is the large volume of water discharged from the Xiaolangdi Reservoir during the WSRS (Qi et al., 2012; Yu et al., 2013). Thus, the mechanism by which the WSRS influences the evolution of the lower Yellow River is still unclear and needs further quantification. In this study, we assess the implementation of the WSRS in detail and comprehensively analyze the effects on runoff, sediment load, sediment grain size, and channel erosion, as well as on the evolution of the estuary delta. In addition, we also investigate the mechanism though which the WSRS affects channel erosion in the lower Yellow River. This exploration of the impact of the WSRS on the lower Yellow River will provide a reference case and a theoretical basis for the management of other rivers.

2. Study area and data collection

2.1. General description of the study area

The Yellow River is the second largest river in China, with a drainage area of 795,000 km^2 and a length of 5464 km. The mean annual natural runoff of the Yellow River is normally 58×10^9 m^3, and the mean annual suspended sediment load is 1.6×10^9 t, ranking it first in all of the world's rivers in terms of sediment load (Wu et al., 2008a,b). In general, the lower Yellow River is defined as the reach between Mengjin in Henan province and Lijin in

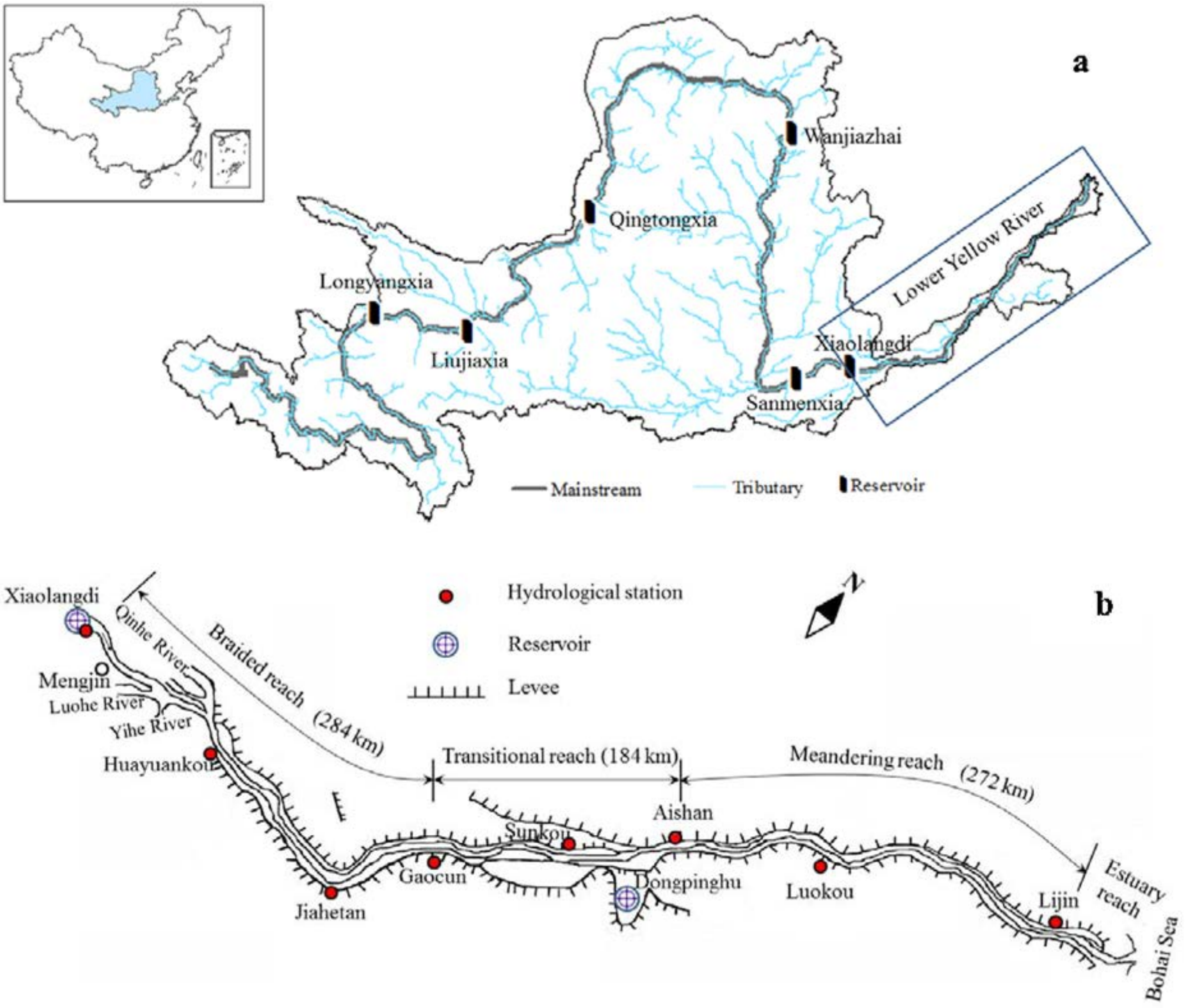

Fig. 1. Map of the Yellow River drainage basin showing the locations of the major reservoirs (a) and the study area showing the locations of the major hydrological stations (b).

Table 1
The modes of operation of the water–sediment regulation scheme (WSRS) in the Yellow River.

Mode	Description	Operation time
1	Xiaolangdi Reservoir operation	2002
2	Multiple-reservoir joint operation	2003 (before the flood caused by "Autumn rain of West China"); 2007 (during the flood season); 2010 (during the flood season, the second WSR for the year)
3	Multiple-reservoir joint operation and artificial stirring	2004–2012 (before the flood season); 2010 (during the flood season, the third WSR for the year)

Shandong province, with a length of approximately 740 km flowing across the North China plain with a drainage area of 22,000 km^2, as shown in Fig. 1. The lower Yellow River is usually divided into three distinct reaches according to their geomorphological characteristics (Wu et al., 2005; Xia et al., 2014a). The reach upstream of Gaocun, with a typical braided channel pattern, is called the braided reach, with a length of 284 km. The reach lying approximately between Gaocun and Aishan with a channel pattern transitioning from braided to meandering is called the transitional reach, with a length of 184 km, and the reach roughly between Aishan and Lijin with a stable and well-restricted meandering channel pattern is called the meandering reach, with a length of 272 km. The key hydrological stations along the mainstream include Xiaolangdi (XLD), Huayuankou (HYK), Jiahetan (JHT), Gaocun (GC), Sunkou (SK), Aishan (AS), Luokou (LK), and Lijin (LJ).

Heavy soil erosion on the Loess Plateau led to intensive sedimentation in the lower Yellow River channel (Miao et al., 2012b). According to observed data, the total deposition volume in the lower Yellow River was approximately $5.52 \times 10^9\,m^3$ during the period from 1950 to 1999, of which 60% was deposited in the braided reach (Li, 2003; Xia et al., 2010). One effect of the heavy sedimentation in the lower Yellow River was an obvious shrinkage of the main channel accompanied by a sharp decrease in the flood discharge capacity, which markedly influenced the management of the river for flood control. The heavy sedimentation also led to the phenomenon of a secondary perched river in local reaches of the lower Yellow River, which poses a huge flood risk to the local residents.

2.2. Data sources

The annual water discharge and sediment load data during the period from 1950 to 2012 were supplied by the YRCC. The median sediment grain size data for the lower Yellow River Basin during the periods from 1970 to 1989 and from 2003 to 2012 were obtained from the Hydrological Yearbooks of the People's Republic of China. Statistical data on deposition volumes in the lower Yellow River during the period from 1951 to 2000 were taken from the Chinese River Sediment Bulletins published by the Ministry of Water Resources of the People's Republic of China. The data on segmented erosion and deposition in the lower Yellow River from October 2000 to October 2012 were collected from the Yellow River Sediment Bulletin.

3. Implementation of the WSRS

The WSRS in the Yellow River is performed to regulate and control flow and sediment transport in the lower reaches of the river through reservoirs on the mainstreams and tributaries (Li and Sheng, 2011). Briefly, the WSRS uses the Xiaolangdi Reservoir, with the assistance of other reservoirs on the mainstream and tributaries. The WSRS process is very complex and can be divided into three modes, as shown in Table 1. Through three WSRS experiments between 2002 and 2004, three effective modes for regulation were explored and then used in subsequent production runs (Table 2). Among the three modes, the mainstream multiple-

Table 2
Information about the Yellow River WSRS from 2002 to 2012.[a]

Year	Duration	Water volume at Xiaolangdi Reservoir $(10^9\,m^3)$	Control indicators		Outflow from Xiaolangdi Reservoir		River flux into the sea		Riverbed scoured sediment $(10^6\,t)$
			Water discharge $(m^3\,s^{-1})$	Suspended sediment concentration $(kg\,m^{-3})$	Water volume $(10^9\,m^3)$	Sediment load $(10^6\,t)$	Water volume $(10^9\,m^3)$	Sediment load $(10^6\,t)$	
2002	July 7–21	4.341	2600	20	2.61	32	2.29	66.4	36.2
2003	September 6–18	5.61	2400	30	1.81	73.3	2.72	120.7	45.6
2004	June 19–July 13	6.65	2700	40	4.46	4.4	4.80	69.7	66.5
2005	Jun. 15–30	6.16	3500	40	3.80	2.3	4.20	61.3	64.7
2006	June 15–July 3	6.89	3700	40	5.50	8.4	4.81	64.8	60.1
2007	June 19–July 7	4.35	4000	40	3.97	26.1	3.63	52.4	28.8
2007	July 29–August 7	1.66	4000	40	1.73	45.9	2.55	44.9	30.0
2008	June 19–July 3	4.06	4000	40	4.28	47.6	4.08	59.8	20.1
2009	June 19–July 8	4.70	4000	40	5.00	3.7	3.49	34.5	34.3
2010	June 19–July 7	4.85	4000	40	3.95	55.9	4.56	70.1	24.2
2010	July 24–August 3	0.88	3000	40	/	26.1	/	31.1	10.1
2010	August 11–21	1.14	2600	40	/	48.7	/	43.4	11.8
2011	June 19–July 12	/	4000	40	4.92	35	3.74	41.2	/
2012	June19–July 9	3.38	4000	40	5.64	72.8	/	/	/

[a] The symbol '/' indicates that the data are deficient.

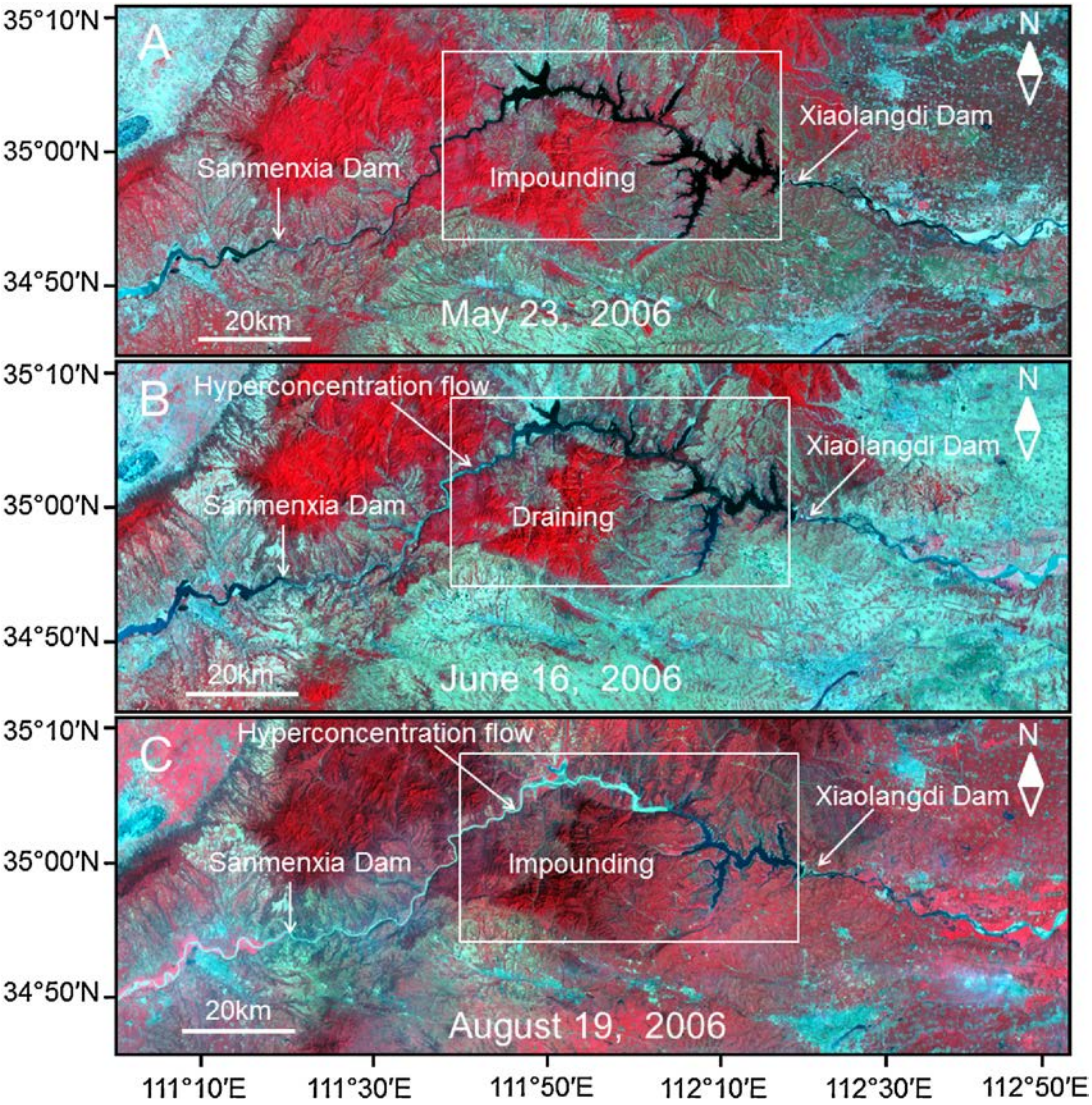

Fig. 2. Remote sensing images showing the changes in the Xiaolangdi Reservoir before (a), during (b), and after (c) the 2006 WSRS. The images were obtained from the Earth Resources Observation and Science (EROS) Center (http://glovis.usgs.gov/).

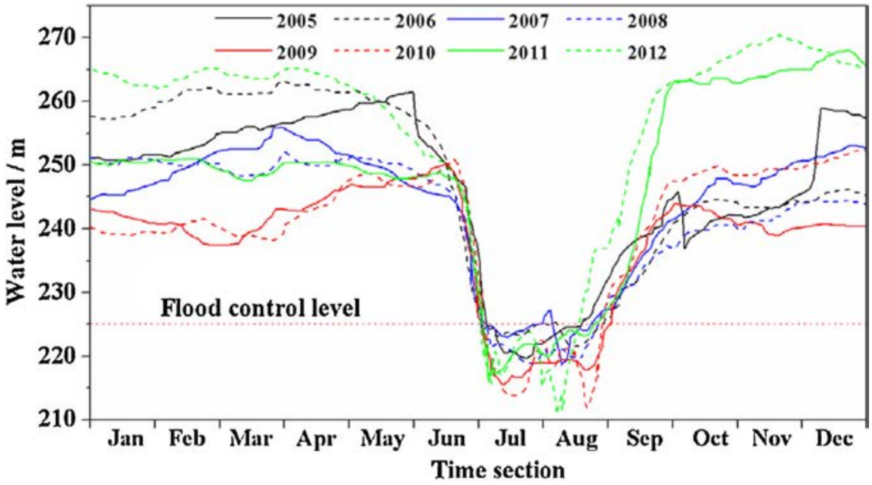

Fig. 3. The dam water-level process map for Xiaolangdi Reservoir from 2005 to 2012. Data were collected from the Yellow River Sediment Bulletin (YRSB) published by the Yellow River Conservancy Commission (YRCC).

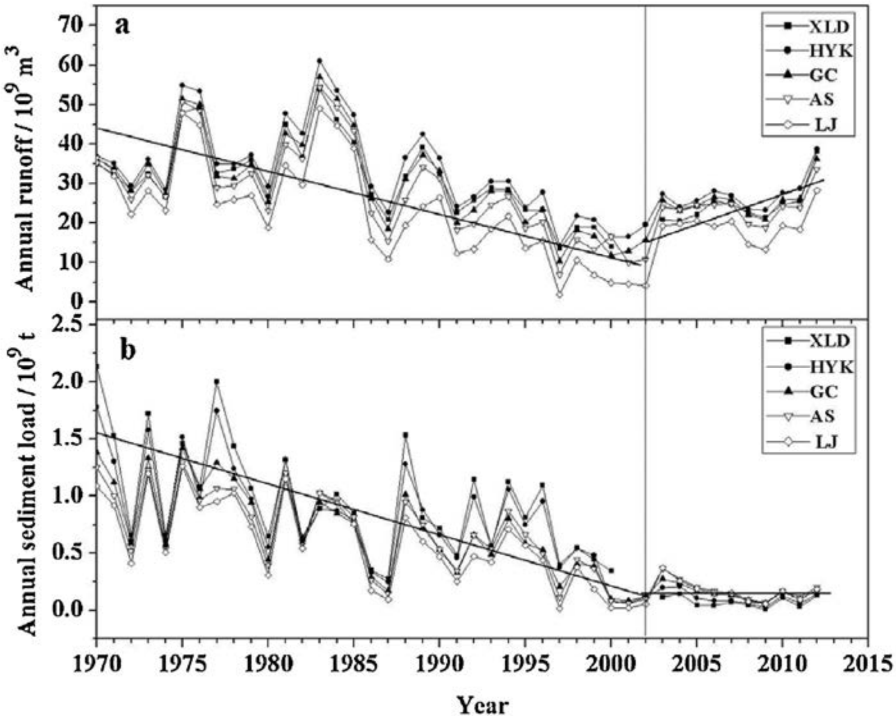

Fig. 4. Annual water discharge (a) and sediment load (b) for the lower Yellow River from 1970 to 2012.

reservoir joint operation is the one most commonly used before the flood season.

To systematically describe the operation of the WSRS, we will take the WSRS from 2006 as an example (Fig. 2). The most important prerequisite of the WSRS is that a certain level of water must be stored above the flood limit level. Generally, the multiple mainstream reservoirs start to impound at the end of the last flood season (Fig. 3). By June 1, 2006, the total water stored above the flood limit level of the Wanjiazai Reservoir, the Sanmenxia Reservoir, and the Xiaolangdi Reservoir was up to $5.37 \times 10^9\,\mathrm{m}^3$, and that of the Xiaolangdi Reservoir alone was $4.88 \times 10^9\,\mathrm{m}^3$. Both levels reached the required condition for implementation of the WSRS. The WSRS process can be divided into two stages: the draining stage and the desilting stage. During the draining stage, the discharge rate of the Xiaolangdi Dam increased from $2600\,\mathrm{m}^3\,\mathrm{s}^{-1}$ to $3700\,\mathrm{m}^3\,\mathrm{s}^{-1}$. During the desilting stage, artificial stirring was conducted to scour the hyperconcentrated flow in the tail section of the Xiaolangdi Reservoir by increasing the volume discharged from the Sanmenxia Reservoir. In this stage, the suspended sediment concentration at the Xiaolangdi Station reached $59.0\,\mathrm{kg\,m}^{-3}$. After the WSRS, the water level sharply decreased to below the flood limit level, as shown in Fig. 3.

4. Effect of the WSRS on the lower Yellow River

4.1. Variations in runoff and sediment load

Typically, downstream runoff and sediment loads are heavily affected by dams and reservoirs, and the effects are very complex because of the artificial regulation of discharge. In this study, we used a multi-scale analysis to investigate the effect of the WSRS on the runoff and sediment load in the lower Yellow River. The annual water discharge and sediment load for the lower Yellow River are shown in Fig. 4.

It can be observed from Fig. 4 that there was an obvious downward trend in annual runoff and sediment load between 1970 and 2002. The synchronous changes in runoff and sediment load suggest that they were basically unaffected by artificial regulation. Since 2002, after the first WSRS experiments, the variations in runoff and sediment load were no longer synchronized. As shown in Fig. 4, the runoff began to rise, whereas the sediment load remained relatively stable. The rising runoff after 2008 was mainly because ecological targets of the estuarine delta were taken into consideration in the WSRS, and a corresponding water distribution plan was devised to protect the wetland ecosystem of the Yellow River Delta (Li and Sheng, 2011). There are two main factors that account for the stable sediment load. One is that the sediment flowing into the lower Yellow River from upstream was reduced by the soil and water conservation policy in the middle reaches of the Yellow River (Zhao et al., 2014). The other factor is that the sediment flowing into the lower Yellow River was controlled by the Xiaolangdi Dam and, in particular, by the WSRS.

In addition, the changes in runoff and sediment load at different hydrological stations were also no longer synchronized after 2002, as shown in Fig. 5. It can be observed from Fig. 5a that, for every time period, the runoff at Huayuankou was higher than at Xiaolangdi, which can be attributed to the water recharge from the Qinhe River, Luohe River, and Yihe River tributaries between the two stations. Due to high water consumption by humans and industry and less recharge, the runoff gradually reduced between Huayuankou and Lijin, regardless of the time period: the 1970s, 1980s, 1990s or 2002–2012 (Fig. 5a). The sediment load presented the same trend in the 1970s, 1980s, and 1990s. However, that trend has been basically reversed since the first WSRS implementation in 2002. Apart from a small reduction at Lijin, the sediment load gradually increased between Xiaolangdi and Aishan (Fig. 5b), which indicates that the main river channel in the lower reaches has been scoured since the implementation of the WSRS.

The monsoon-dominated rainfall causes strong seasonality in both runoff and sediment load because runoff is the carrier of sediment load. In the Yellow River Basin, runoff and sediment load are generally concentrated within the rainy season, which runs from July to October each year. However, the distribution of monthly runoff and sediment load on the mainstream have changed significantly since a large number of reservoirs, including the Liujiaxia, Longyanxia, and Sanmenxia Reservoirs, went into operation in the upper and middle reaches of the Yellow River Basin (Zhao et al., 2014). During the period 1986 to 1997, runoff at the Huayuankou station during the rainy season (July to October) comprised 47% of the annual average runoff, with the maximum monthly runoff in August being 3.6 times the minimum in January (Ren et al., 2002). In the 1990s, the sediment load at Lijin station during the rainy season (July to October) was 86.4%, with August having the maximum monthly sediment load (Liu et al., 2014). Fig. 6 shows the distributions of the observed monthly runoff and sediment load at the Xiaolangdi, Huayuankou, Gaocun, Aishan, and Lijin stations from 2002 to 2012, and Table 3 shows the percentages of runoff and sediment load in the wet and dry seasons for the same period. The proportions of runoff and sediment load in the period 2002 to 2012 are lower during the rainy season and higher during the dry season, compared with the previous time periods. As shown in Fig. 6 and Table 3, the percentage of runoff at Huayuankou in the wet season decreased to 39.3% because of the operation of the Xiaolangdi Reservoir, and the maximum monthly runoff occurred in June rather than August (Table 3). The percentage of sediment load at Lijin in the wet season also decreased to 71.5%, and the month with the maximum sediment load changed from August to July. These changes in the distributions of the observed monthly runoff and sediment load were caused by the WSRS, which usually led to the release of floodwaters in late June, prior to the rainy season (Table 2). This led directly to the advances in the months of maximum runoff and sediment load. Furthermore, the new monthly distribution for sediment load does not entirely match that for runoff. This is because of the asynchronous nature of runoff and sediment regulation at the Xiaolangdi Reservoir. As described in Section 3, the WSRS process was divided into a draining stage and a desilting stage, with the draining stage usually occurring prior to the desilting stage.

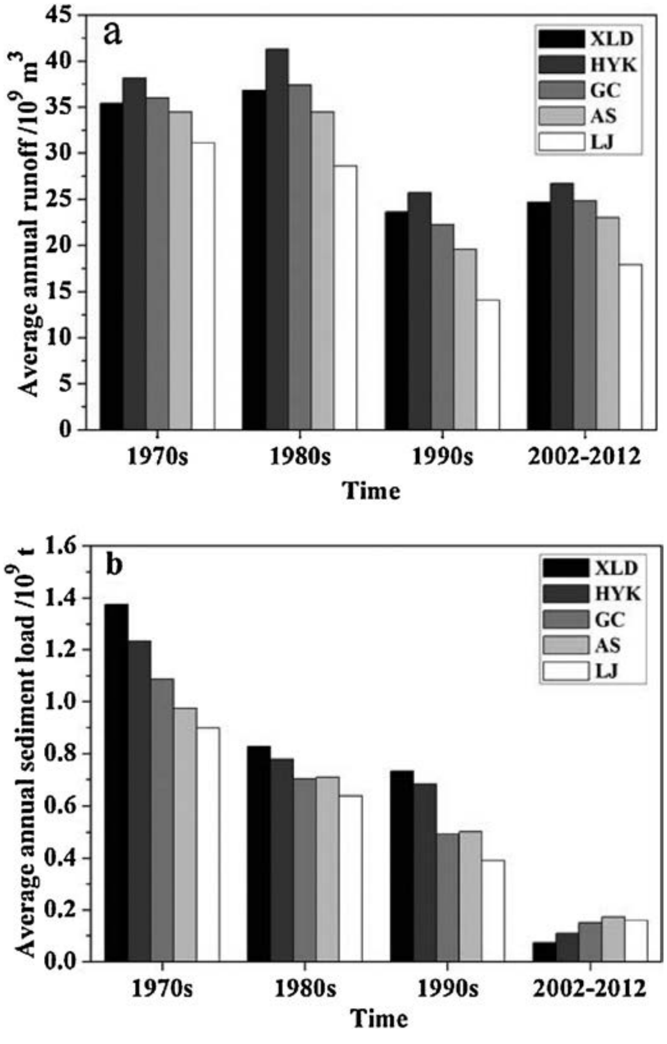

Fig. 5. Average annual runoff and sediment load in the lower Yellow River.

The WSRS procedures can not only adjust the water supply to meet water consumption in the lower Yellow River in different seasons, but can also effectively solve the problem of the river drying up during the dry season. There was an overall decline in annual precipitation in the Yellow River Basin between 1956 and 2008, and the annual temperature increased significantly against the backdrop of global warming (Miao et al., 2011, 2012a). In addition, the population along the Yellow River Basin swelled, causing uncontrolled expansion of water consumption by humans and industry (Peng and Chen, 2010). A direct result of the reduced precipitation and increased water intake is the drying up of the Yellow River (Fig. 7). Hydrological records from the Lijin hydrological station indicate that the river seasonally ran dry for a total of 940 days between 1982 and 2000, including for 901 days during the 1990s. The most serious period of drying up in the Yellow River occurred in 1997, when the river ran dry for 226 days (Fig. 7). Although the total runoff in the lower Yellow River from 2002 to 2012 is approximately the same as during the 1990s (Figs. 4a and 5a), the river has not run dry since the implementation of the WSRS (Fig. 7).

4.2. Sediment grain size

The sediment transport capacity of rivers depends on many factors, including runoff velocity, sediment grain size, and the specific gravity of sediment particles in a particular river (Yang, 2005). The sediment in the Yellow River comes mainly from the middle reaches (Xu, 2002, 2003), so the specific gravity of sediment particles in the lower reaches can be considered to be basically constant. Moreover, sediment grain size has a close relationship with runoff velocity. If the runoff velocity is low, deposition of coarse sediment particles is fast and sediment transport capacity is therefore low, and vice versa. When runoff velocity exceeds a certain value, not only do large sediment particles display little deposition but the river channel may also be scoured, which further increases the concentration of suspended sediment and the average sediment grain size in the runoff. Thus, the sediment grain size can reflect the sediment transport capacity of the river.

Fig. 8 shows the median sediment grain size measured at the Xiaolangdi, Huayuankou, and Lijin stations. In the 1970s and 1980s, the median grain size gradually decreased from Xiaolangdi to Lijin, indicating serious sedimentation in the lower Yellow River. However, between 2003 and 2012, although the runoff was lower than during the 1970s and 1980s, the median grain size increased from Xiaolangdi to Lijin (except in 2009), indicating that the downstream river channel was scoured during the WSRS. The large increase in median grain size between Xiaolangdi and Huayuankou in 2009 indicates that the erosion of the river channel in this section was severe. With a decline in the scouring action, slight deposition occurred between Huayuankou and Lijin. Nevertheless, the median grain size at Lijin was still significantly larger than that at Xiaolangdi, illustrating that, on the whole, the lower Yellow River channel was scoured in 2009.

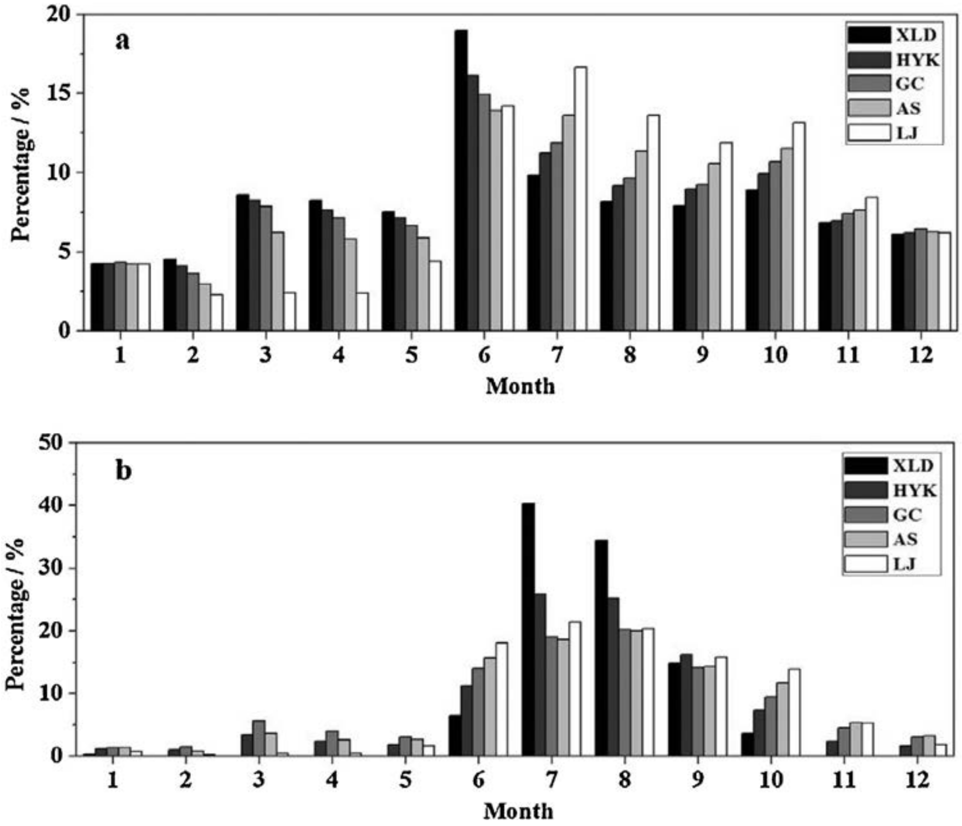

Fig. 6. Distributions of observed monthly runoff (a) and sediment load (b) in the lower Yellow River from 2002 to 2012.

4.3. Channel erosion and deposition

Because of the large sediment content in the Yellow River received from the middle reaches, long-term deposition in the lower river formed a world-famous “hanging river”. According to statistical data in the Bulletins of Chinese River Sediment published by the Ministry of Water Resources of the People’s Republic of China, the total deposition volume in the lower Yellow River was approximately $5.44 \times 10^9\,m^3$ during the period from October 1951 to October 2000, with an average annual sediment deposition of $0.11 \times 10^9\,m^3$. During centuries of levee construction, excessive sediment deposits have raised the riverbed several meters above the surrounding ground. At Kaifeng, Henan Province, the Yellow River is approximately 10 m above ground level.

During the implementation of the WSRS, sediment deposition in the lower Yellow River was gradually alleviated. Fig. 9 shows the annual sediment deposition and erosion between the Huayuankou and Lijin stations between 1970 and 2012. It can be seen from the figure that sediment deposition between Huayuankou and Lijin was generally significantly greater than channel erosion prior to 2002, with slight erosion present in 1983 and 1984. Since 2003, the situation has reversed, with an average annual erosion of 60×10^6 t.

However, the degree of erosion is not the same in different reaches that have varying channel characteristics. Table 4 lists the segmented erosion and deposition values for the lower Yellow River. It can be seen that the main river channel in the lower reaches was fully scoured between October 2000 and October 2012, with a total erosion volume of $1.64 \times 10^9\,m^3$ and an average annual erosion volume of $136 \times 10^6\,m^3$. From the total erosion volume, 67.36% comes from the reach upstream of Gaocun. In addition, 16.95% comes from the transitional reach, and the last 15.69% comes from the meandering reach. This is mainly due to the gradually weakened erosion ability caused by the fading kinetic energy from the runoff. In addition, the distribution of erosion volume in the three reaches of the lower Yellow River also corresponds to the previous deposition distribution (Li, 2003; Xia et al., 2010).

Since the lower Yellow River channel was fully scoured, the depth of the channel also changed accordingly. Fig. 10 shows the difference in water levels for 2009 and 2012, relative to levels in

Table 3
Percentages of runoff and sediment load in the wet and dry seasons at different stations in the lower Yellow River from 2002 to 2012.

Station	Runoff			Sediment		
	Wet season (%)	Dry season (%)	Maximum month	Wet season (%)	Dry season (%)	Maximum month
Xiaolangdi	34.9	65.1	June	93.1	6.9	July
Huayuankou	39.3	60.7	June	74.6	25.4	July
Gaocun	41.5	58.5	June	62.9	37.1	August
Aishan	47.1	52.9	June	64.7	35.3	July
Lijin	55.3	44.7	July	71.5	28.5	July

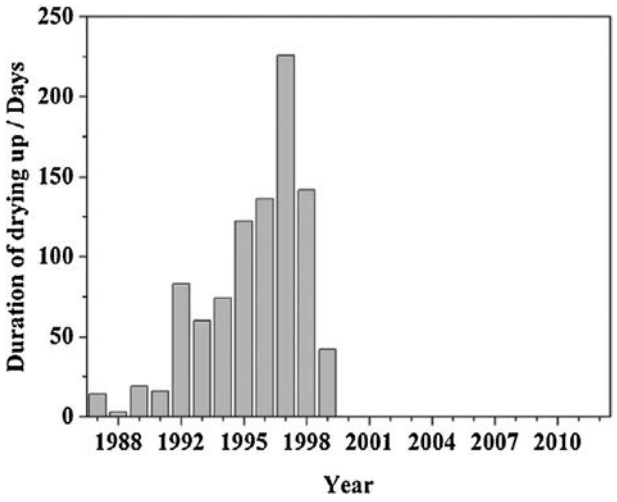

Fig. 7. Seasonal drying-up of the Yellow River between 1987 and 2012.

2000 when the water flow was 2000 $m^3 s^{-1}$. As the water flow was the same in all years, the difference in water levels indicates the change in the average channel depth. During the operation of the Xiaolangdi Reservoir and the implementation of the WSRS, the lower Yellow River channel became noticeably deeper than in 2000. In 2012, the average channel depth at Huayuankou increased by 1.88 m, whereas at Lijin it increased by 1.25 m. It can also be seen that the greatest change occurred in the braided reach, followed by the transitional reach and then the meandering reach (Fig. 10), which is consistent with the results of the above analysis.

A direct result of these channel adjustments is variation in the bankfull discharge in the lower Yellow River. In the lower Yellow River, bankfull discharge often results in flow such that water just fills a channel without overtopping the banks of the flood plain or the top of farm dikes, which are inner embankments adjacent to the main channel constructed by local inhabitants (Xia et al., 2014a, b). Bankfull discharge is an important indicator to measure the flood discharge capacity of a river. Fig. 11 shows the bankfull discharge of the lower Yellow River in different years. The bankfull discharge in the braided reach is clearly higher than that in the transitional reach and in the meandering reach. The river channel at Sunkou has the lowest bankfull discharge among all the observation stations, whereas the channel at Huayuankou has the highest discharge. Since the operation of the Xiaolangdi Reservoir and the implementation of the WSRS, the bankfull discharge of the lower Yellow River has significantly increased across the whole channel, indicating that flood discharge capacity has been improved. In 2012, the bankfull discharge at Huayuankou was 6900 $m^3 s^{-1}$, which is 1.86 times the bankfull discharge in 2000.

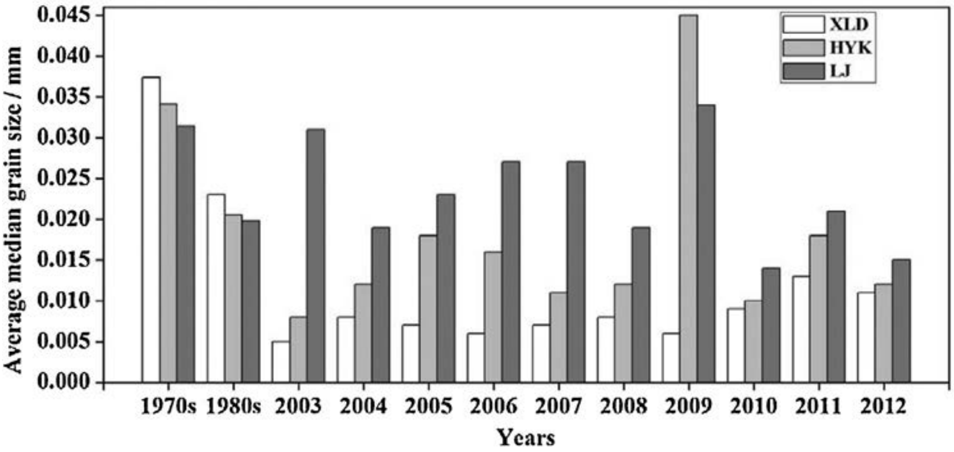

Fig. 8. Median sediment grain size at the Xiaolangdi, Huayuankou, and Lijin stations.

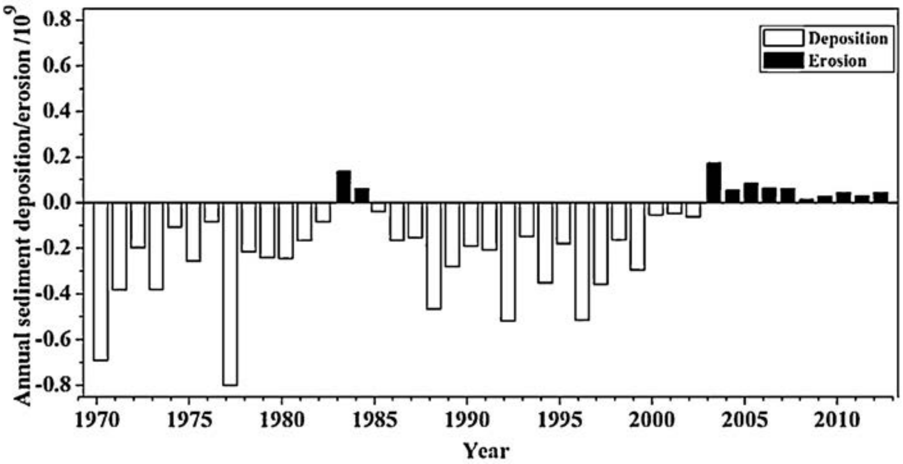

Fig. 9. Annual sediment deposition and erosion between the Huayuankou and Lijin stations from 1970 to 2012. Values were calculated as the annual sediment load at the Lijin station minus that at the Huayuankou station, with positive values indicating erosion and negative values indicating deposition.

Table 4
Segmented erosion and deposition in the lower Yellow River from October 2000 to October 2012.

Time section	Erosion and deposition[a] ($10^6\,m^3$)							
	XLD–HYK[b]	HYK–JHT	JHT–GC	GC–SK	SK–AS	AS–LK	LK–LJ	Total
2000.10–2001.10	−55.18	−27.84	−8.04	6.16	−2.75	5.51	4.2	−77.92
2001.10–2002.10	−21.8	−29.74	−5.59	−39.05	−2.13	−4.63	−18.42	−121.4
2002.10–2003.11	−134.4	−47.4	−41.1	−25.9	−14.5	−39.8	−58.1	−361.1
2003.11–2004.10	−28	−42.6	−28.1	−5	−5.3	−11.2	−13.5	−133.7
2004.10–2005.10	−23.9	−26.6	−28.9	−19.7	−11.5	−19	−13.5	−142.8
2005.10–2006.10	−39.5	−63.4	−7.7	−21.4	−0.1	7.4	−3.8	−128.5
2006.10–2007.10	−43.8	−44.3	−15.9	−25.2	−6.5	−13.1	−16.1	−164.9
2007.10–2008.10	−27.8	−11	−9.8	−16.5	−3.9	1.2	−5.9	−73.7
2008.10–2009.10	−9.5	−27.1	−20.9	−21.9	−4.5	−3.8	−4.3	−92
2009.10–2010.10	−29	−29.3	−12.5	−13.3	−4	−10.1	−9.5	−107.7
2010.10–2011.10	−33.5	−43.3	−26.1	−12.6	−6.9	−6.7	−5.8	−134.6
2011.10–2012.10	2.3	−44.2	−17.7	−15.3	−5.8	−9.3	−9.4	−99.4

[a] Positive values represent deposition volume, whereas negative values represent erosion volume.
[b] From October 2006, the data represent the section from Xixiayuan to Huayuankou. Xixiayuan Reservoir is located 16 km downstream of Xiaolangdi Dam.

4.4. Evolution of the Yellow River Delta

The Yellow River Delta is an important region because of its location and unique ecological environment (Cui et al., 2009). Previous studies have demonstrated that the incoming sediment load at Lijin is the main factor controlling the evolution of the Yellow River Delta because the coastal dynamics at the Yellow River mouth have not evidently changed over the past 30 years (Cui and Li, 2011; Wang et al., 2006b). A threshold annual sediment load of 159×10^6 t has been needed to maintain the balance of the delta after the lower Yellow River channel changed in 1996 (Kong et al., 2015). As described in Section 4.1, the sediment load flowing into the lower Yellow River has been relatively stable since the implementation of the WSRS (Fig. 4). The average annual sediment load at Lijin was 158.6×10^6 t from 2002 to 2012 (Fig. 5), which is sufficient to maintain the dynamic balance of the Yellow River Delta.

5. The mechanism by which the WSRS influences the river channel

Through the above analysis, we can see that channel erosion and deposition in the lower Yellow River is not dominated by either incoming runoff or sediment load individually. The real dominant factor is the incoming sediment concentration. Fig. 12 shows the variation in average annual sediment concentration at Huayuankou, Gaocun, Aishan, and Lijin from 1950 to 2012. It can be seen that there were high levels of sediment concentration before 2000, with average values ranging from 24.66 to 26.57 $kg\,m^{-3}$. However, sediment concentrations plunged to low levels after 2000, with average values ranging from 4.18 to 8.29 $kg\,m^{-3}$. The change in sediment concentration is basically consistent with the changes in channel erosion and deposition. Thus, there must be a threshold value for suspended sediment concentration to influence sediment movement. Excessive sediment will be deposited on the riverbed when the suspended sediment concentration exceeds the threshold value. Correspondingly, when the suspended sediment concentration is below the threshold value, the sediment deposited on the riverbed will be rolled and washed away. Fig. 13 shows the relationship between the incoming sediment concentration at Huayuankou and the annual channel erosion between Huayuankou and Lijin. Despite the large degree of scatter in the data, there is a significant negative correlation between the incoming sediment concentration and the annual channel erosion during the period 1950–2012:

$$y = -0.01452x + 0.16999, R^2 = 0.592, P < 0.001 \quad (1)$$

where x and y are the incoming sediment concentration ($kg\,m^{-3}$) and the annual channel erosion (10^9 t), respectively. In Formula (1), the incoming sediment concentration (x) equals 11.7 $kg\,m^{-3}$ when the annual channel erosion (y) is 0. This indicates that the incoming

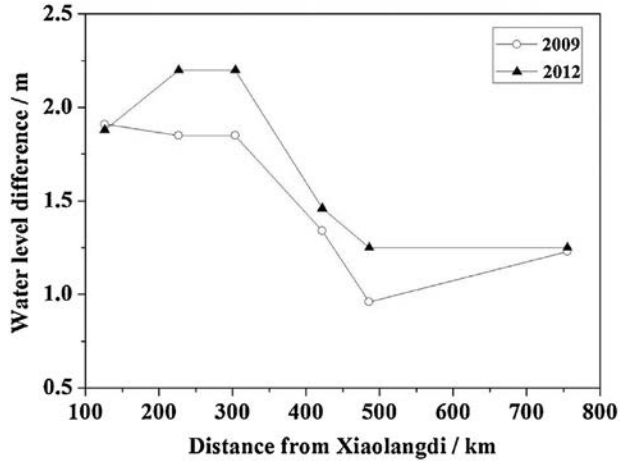

Fig. 10. Differences in water level along the lower Yellow River relative to measurements from 2000 when the water flow was 2000 $m^3\,s^{-1}$. Data derived from Qi et al. (2012) and Qi et al. (2013).

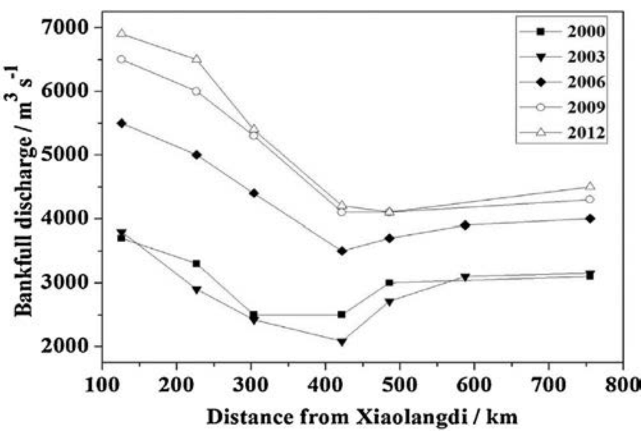

Fig. 11. Bankfull discharge of the lower Yellow River in different years. Data derived from Han (2008),Qi et al. (2012) and Qi et al. (2013).

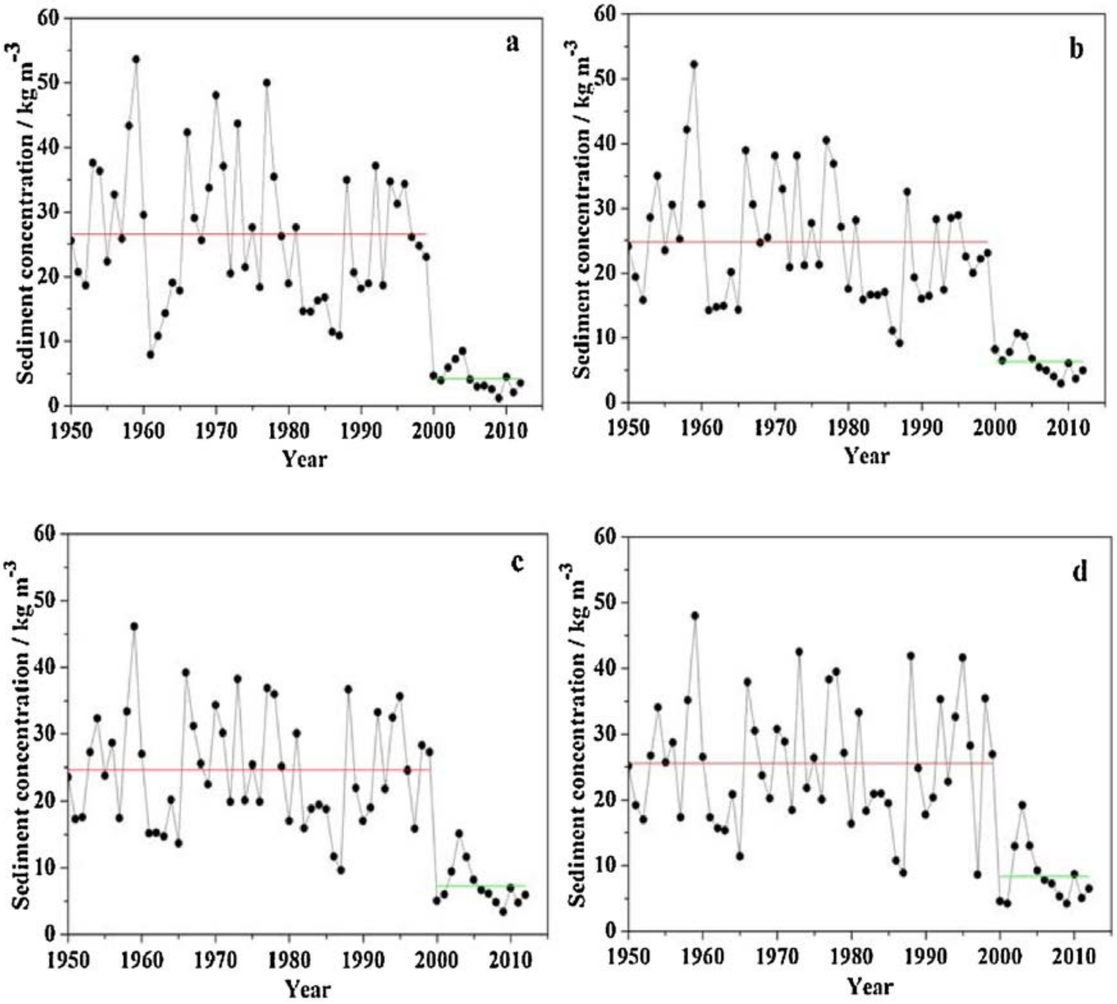

Fig. 12. Variations in the average annual sediment concentration at Huayuankou (a), Gaocun (b), Aishan (c), and Lijin (d) from 1950 to 2012. The red line represents the average annual sediment concentration between 1950 and 1999, and the green line represents the average annual sediment concentration between 2000 and 2012. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

sediment concentration at Huayuankou must be lower than approximately 11.7 kg m^{-3} to ensure channel erosion takes place between Huayuankou and Lijin. Data from most years are consistent with this value.

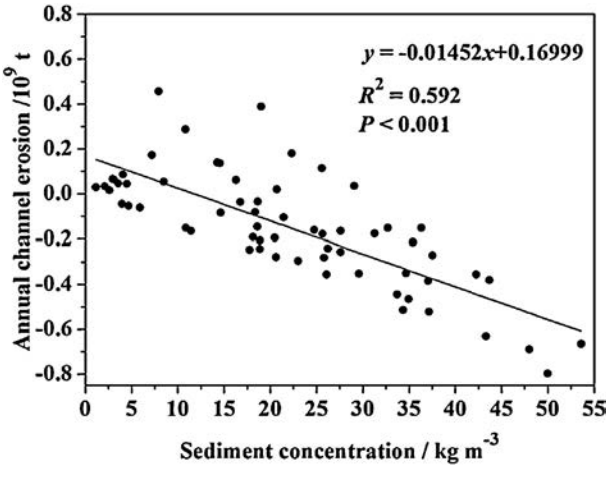

Fig. 13. Relationship between the incoming sediment concentration at Huayuankou and annual channel erosion between Huayuankou and Lijin.

6. Conclusions

Owing to the large sediment content derived from the middle reaches of the Yellow River, long-term deposition in the lower river has formed a world-famous “hanging river”, which brings huge risks to the local residents. Since 2002, the water–sediment regulation scheme (WSRS), has been carried out at the Xiaolangdi Reservoir, with assistance from other reservoirs on the mainstream and tributaries. Since the WSRS implementation, runoff and sediment load, sediment grain size, and the channel in the lower Yellow River have all altered dramatically. The variations in runoff and sediment load are no longer synchronized: runoff presents a rising trend, whereas sediment load remains relatively stable. The proportions of runoff and sediment load during the rainy season have decreased, whereas the proportions of runoff and sediment load during the dry season have increased. The month of maximal runoff and sediment load is now earlier than before. The problem of the lower Yellow River running dry during the dry season has been effectively solved. The median grain size displays a gradually increasing top–down trend along the lower Yellow River. The main river channels in the lower Yellow River have been fully scoured, leading to an increase in channel depth and bankfull discharge. In addition, the sediment load flowing into the estuary reach is relatively stable, with an average annual sediment load of 158.6×10^6 t, which is sufficient to maintain the dynamic balance of the Yellow River Delta. The incoming sediment concentration to the lower Yellow River dominates channel erosion and sediment deposition. Our exploration of the mechanisms by which the WSRS affects the lower Yellow River provide a reference case and theoretical basis for the management of other rivers.

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