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ECOLOGICAL RESPONSE TO INTEGRATED WATER AND SEDIMENT REGULATION ON RIPARIAN CORRIDORS IN THE LOWER YELLOW RIVER

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ABSTRACT

Integrated water and sediment regulation (IWSR) is critical to protecting and safeguarding the flow of the lower Yellow River since 2002. At the same time, hydrological regimes are also highly altered, and lead to increases in aquatic ecosystem degradation risk. In this paper, we systematically analyze the relevant literatures to determine the ecological effectiveness of IWSR. We assess the ecological response to IWSR over the past 20 years, highlighting the benefits and effects on riparian corridors, based on the data analysis of hydrological regime alteration, reservoir sedimentation, remote sensing images and landscape patterns in the lower Yellow River. The results show the following: (1) IWSR can help increase the sediment flushing efficiency. The river bed elevation decreased due to sediment flushing, and the risk of sediment deposition decreased. The runoff has increased compared to the same water level conditions previously. (2) The riverine wetlands in riparian corridors have been severely impacted by continuous drought in the floodplain before the implementation of IWSR, and afterward hydrological connectivity has been restored. However, hydrological regime changes which departed significantly from the historical flow have adverse effects on the components of environmental flows (e-flows), including a decrease in the rate of water condition changes, loss of large flood pulses and frequency, and degradation of high flows and overbank flows. Therefore, the risk of connectivity between wetlands and mainstream has increased. (3) The area of the Yellow River delta wetland has increased by more than 60 km^2 since 2008, by implementing IWSR for estuaries. Therefore, this may be feasible for mitigating the “failing kidneys” of wetlands, and it is likely to promote dynamic vegetation successions and restore avifauna habitats. We suggest two initial ways by which to improve the quality of riparian corridors: (1) Establish the ecohydrology relationship between wetlands and e-flows releases. After this, the scientific basis for how flow releases affect riverine wetlands and how WSR affects the delta wetlands will be elucidated. (2) Determine a more systematic approach of e-flows on both natural and social requirements in the lower Yellow River, and launch an optimized operation of cascade reservoirs for multiple objectives.

Keywords: Integrated Water and Sediment Regulation, riparian ecosystems, environmental flows, Yellow River

1 INTRODUCTION

There are main three kinds of ecosystems on the Earth’s surface, namely upland ecosystems, aquatic ecosystems and riparian ecosystems. Riparian ecosystems refer to the area where the water and land interface is intermittently flooded by water (e.g. river banks, coasts, lakeshores and pond shores). As a staggered zone between terrestrial ecosystems and aquatic ecosystems, the riparian zone is characterized by ecological vulnerability, biological diversity, cyclicality of change, and frequency of human activity (Wantzen and Junk 2008). The riparian ecosystems act as buffer zones for water bodies, and have important filtering and buffering effects on nitrogen, phosphorus and other organic pollutants (González et al. 2017). The biodiversity of riparian ecosystems is very rich, thus providing habitats for animals. The special habitats of riparian ecosystems lead to the diversity of animals and plants there being greater than those of terrestrial and aquatic ecosystems.

The research of riparian ecosystems dates back to the 1950s. Based on the theory of energy flow in ecology, the flow of energy through a food chain and dynamic succession of riparian ecosystems have been discussed. Before the 1970s, the importance of riparian ecosystems was unclear, and the riparian zone was not treated as an ecosystem. In the mid-1970s, zoologists began performing avifauna surveys on the shores of the Arizona River. Research regarding riparian ecosystems entered a new era in 1977, when the concept of river continuum was proposed, and the term riparian ecosystem was defined. Riparian ecosystems were being degraded with river exploitation, population growth, industrial and agricultural production, urbanization, and other human activities. Due to river channelization intensity, many riparian ecosystems in urban areas almost disappeared. The degraded riparian ecosystems are often represented by serious destruction of vegetation, decrease of biodiversity, deterioration of microclimate, erosion of riparian zone, and loss of ecosystem function (Feld et al. 2018). According to statistics, more than 20% of the riparian vegetation in the world has disappeared, while the rest is rapidly disappearing or degrading. Among the factors of riparian ecosystems degradation, damming is a common problem throughout the world.

Damming activities do bring benefits, but such activities also affect downstream hydrological regimes, followed by the riparian ecosystem (Chen and Wu 2019, Wu and Chen 2017). Integrated Water and Sediment Regulation (IWSR) guarantees the environmental water and protects the ecosystem health of riparian zones (Chen et al. 2016). In China, the Yellow River is the second longest river, and has been highly regulated. Due to hydrological variation and increased water use by humans, the Yellow River has ceased flow 22 times since the 1970s, which has aroused great concerns about the health of the river. Authorized by the national government, the Yellow River Conservancy Commission (YRCC) implemented integrated water regulation (IWR) of the Yellow River in 1999. Since 2002, when the Xiaolangdi dam went into operation, integrated water and sediment regulation (IWSR) has been implemented on the basis of IWR and water and sediment regulation (WSR) of Xiaolangdi. Since this, the downstream has no longer ceased flow (Chen et al. 2016, Sui et al. 2015). IWSR guaranteed the structure and function of the river ecosystem in the lower Yellow River. However, the hydrological regimes and sediment load have changed. In addition, the riparian ecosystems of the downstream river have been affected, due to the degradation of riverine wetlands and delta wetlands, and the shrinkage of habitats.

This paper summarizes the scheduling operation effects of the cascade reservoirs in the Yellow River, based on the comprehensive analysis of the observed hydrological data, remote sensing image and relevant research. The sedimentation status and trends of the Xiaolangdi reservoir, hydrological trend of the downstream sections, and remote sensing image and landuse change of the four wetlands in the downstream riparian ecosystems are analyzed. Finally, the ecological response to IWSR and its effects on riparian corridors in the lower Yellow River are discussed.

2 MATERIALS AND METHOD

2.1 Study area

The downstream of the Yellow River is 785.6 km in length, with a drop of 94 m and an average ratio of 0.12‰. The downstream is wide in the upper reaches, and narrow in the lower reaches. A large number of silt deposits are found in the downstream, which result in the river bed rising year by year. The river bed is approximately 4 m to 6 m higher than the ground, and it is famous as an “above ground river”. The area of riparian zone in the downstream is about 4,000 km^2, with 2,267 km^2 of cultivated land, and a population of about 1.895 million. The riparian zone is critical for maintaining the health of the Yellow River. There are four main wetlands in the lower Yellow River, which are distributed in the riparian zone. Three of them are riverine wetlands, while the other is a delta wetland (Figure. 1).

Due to its special geographical location, the downstream wetlands of the Yellow River have their own characteristics, and are quite different from general wetlands, including seasonal and regional distribution, as well as strong interference from human activities. The downstream riverine wetlands mainly have the following characteristics.

(a) Instability. The main channel of the Yellow River is changeable, and has not yet been effectively controlled. There is also the possibility of large floods. Therefore, the riverine wetlands are also subject to change. Some riverine wetlands may also be converted into cultivated land by farmers, due to the construction of the production dyke. As a result of artificial flood peaks, some new riverine wetlands may also be formed.

(b) Natural land. Overbank flood generated by IWSR will cause a great amount of sediment load to be deposited on both shoal land sides. Therefore, most of the riverine wetlands are in the initial stage of wetland development, with a low degree of soil gleization (Seena et al. 2017). This is significantly different from a typical wetland ecosystem.

(c) Vulnerability. The environment of the riverine wetlands in the lower Yellow River possesses distinct vulnerable characteristics. At the same time, the frequency and magnitude of the downstream floods have been greatly reduced over the past years. The use of beaches is increasing, and the productive dykes are being built higher and higher. Therefore, riverine wetlands protection is becoming much more difficult.

The IWSR of the Yellow River seeks to maintain environmental flows (e-flows) through the rational management approach. YRCC implemented the IWSR by cascade reservoir regulation on the main streams of the Yellow River, such as Longyangxia, Liujiaxia, Wanjiazhai, Sanmenxia, Xiaolangdi and other reservoirs, while YRCC focused on monthly and ten-day water regulation plans and real-time regulation instruction.

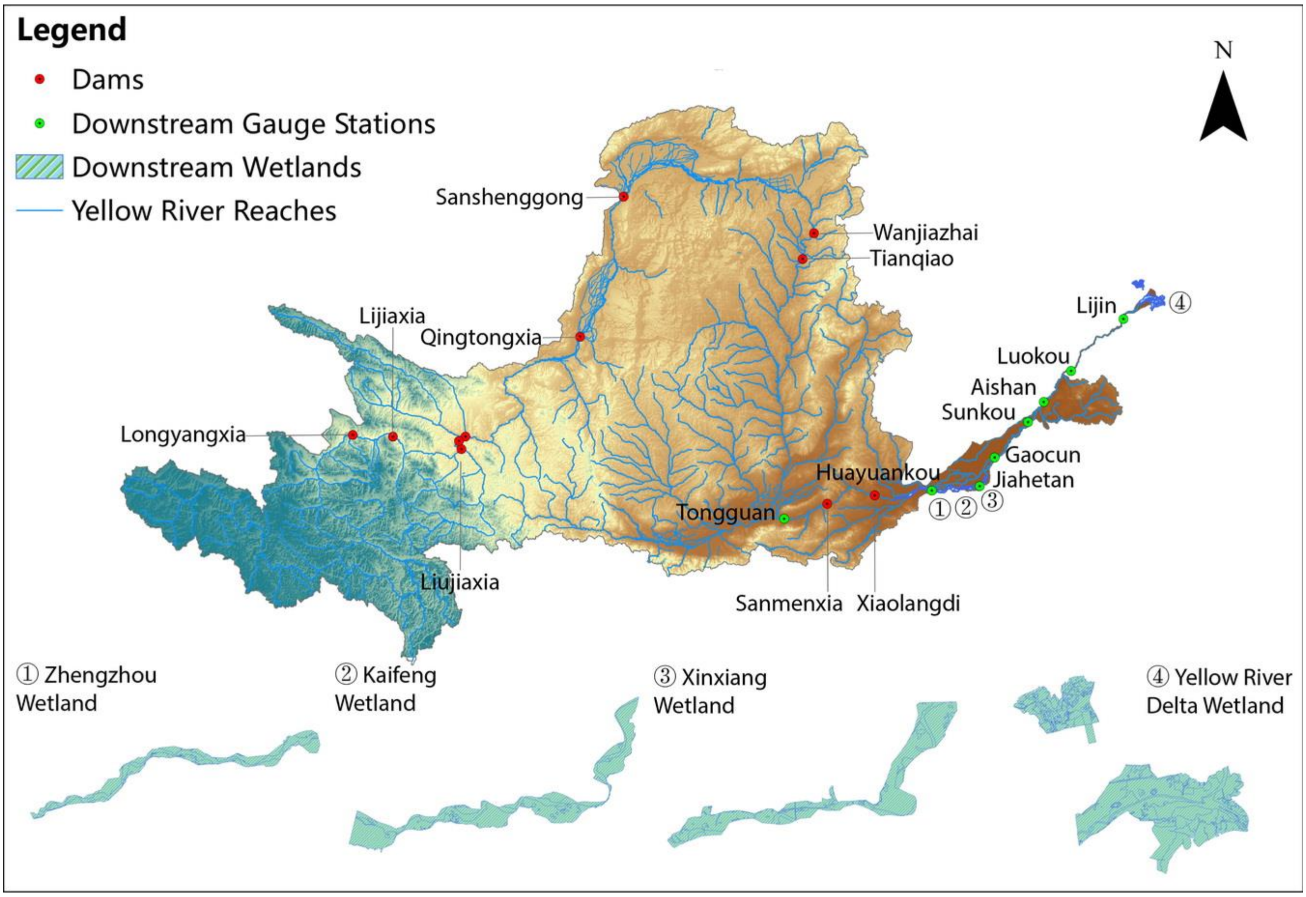

Figure. 1. Study area

2.2 Method

Through literature research review, this paper has collected and analyzed the literatures related to the riparian ecosystem of the lower Yellow River. The IHA (Indicators of Hydrological Alteration) method was used to compare the hydrological regimes during different periods. Based on GIS (Geographic Information System) and RS (Remote Sensing), the landuse changes of four wetlands were analyzed.

2.3 Data

Open and free materials such as peer review papers and dissertations were obtained through CNKI, Web of Science, and other databases. Other materials were mainly obtained by collecting relevant planning, design reports, research reports, evaluation reports, etc.

The flow regimes of Lijin gauge station from 1950 to 2010 were collected and divided into three periods, and 35 hydrological indicators (33 indicators of IHA and two indicators of overbank flow) in five groups were calculated.

- Period I: Natural flow (1950-1959);
- Period II: Before IWSR (1987-1998);
- Period III: After IWSR (2002-2010).

The Landsat TM data were selected as the data source for image interpretation. Images from 1990, 1995, 2000, 2005 and 2010 were used for extracting the landuse in different wetlands.

3 RESULTS

3.1 Hydrological alteration

The hydrological alteration of Lijin gauge station in different periods is shown in Table 1. Compared with period I, the flow pulses disappeared in periods II and III. The monthly average flow in period III is lower, except for that in late June, which is the period of WSR. Compared with period II, the annual average flow increased slightly in period III, and the distribution of the monthly average flow changed significantly throughout the year.

The monthly average flow changed significantly from May to October. During the flood season, the monthly average flow decreased from August to September, and increased from May to July and October. The largest increment was about 750 m^3/s in June, as a result of WSR. At the same time, as an important period of vegetation growth and fish reproduction, the monthly average flow largely increased in May. The largest reduction of monthly average flow was about 600 m^3/s in August. The change of monthly average flow in the non-flood season was relatively small.

The annual minima 1 d, 3 d, 7 d, 30 d and 90 d mean flow remained at 193-635 m^3/s in period Ⅰ, while in period Ⅲ its fluctuation range reduced significantly to 66-147 m^3/s. The maximum flow occurred 30 d earlier than previously. In period Ⅲ the frequency of low flow and high flow decreased, and the duration of low flow increased significantly. In period Ⅰ there were 12 floods in the delta, with an average duration of 5 days. In the later stage of period Ⅲ, the overbank process disappeared, and the rate of water flow change was significantly reduced. The rate and frequency of water condition changes decreased, which indicates that the downstream flow regimes have become apparently uniform since the 1960s with the operation of the cascade reservoirs of the Yellow River.

In general, the changes of the ecology and hydrology of the lower Yellow River are mainly reflected in the following aspects. The annual runoff from upstream of Lijin gauge station has changed significantly (Zhang et al. 2018). The monthly average flow of May and June largely increased before the flood season, while the monthly average flow of August decreased. The minimum flow and base flow index increased significantly in period Ⅱ, and the maximum flow appeared 15 d earlier than in period Ⅱ. The average duration of low flow pulses increased significantly, while the duration of high flow pulses decreased. Finally, the rate of water condition changes decreased, and the overbank floods disappeared.

Table 1. Indicators of hydrological alteration of Lijin gauge station in three periods

IHA Parameter Group	Hydrologic Parameters	Period Ⅰ	Period Ⅱ	Period Ⅲ
Magnitude of Monthly Water Conditions	Mean Value for Jan.	484	341	253
	Mean value for Feb.	639	222	164
	Mean value for Mar.	793	159	152
	Mean value for Apr.	1009	147	156
	Mean value for May.	832	126	284
	Mean value for Jun.	938	218	980
	Mean value for Jul.	2516	612	1026
	Mean value for Aug.	3690	1472	864
	Mean value for Sept.	2840	1007	744
	Mean value for Oct.	2195	398	847
	Mean value for Nov.	1547	434	549
	Mean value for Dec.	713	356	298
Magnitude and Duration of Annual Extreme Water Conditions	Annual minima, 1-day mean	193	0	66
	Annual minima, 3-day mean	210	0	73
	Annual minima, 7-day mean	249	0	80
	Annual minima, 30-day mean	440	14	104
	Annual minima, 90-day mean	635	72	147
	Annual maxima, 1-day mean	6794	3048	3338
	Annual maxima, 3-day mean	6547	2841	3230
	Annual maxima, 7-day mean	5956	2538	3118
	Annual maxima, 30-day mean	4414	1798	1886
	Annual maxima, 90-day mean	3302	1168	1251
	Number of zero-flow days	0	74	0
	Base flow index	0.1665	0.0004	0.1622
Timing of Annual Extreme Water Conditions	Julian date of each annual 1-day maximum	233	218	203
	Julian date of each annual 1-day minimum	138	97	116
Frequency and Duration of High and Low Pulses	Number of low pulses within each water year	10	8	8
	Mean duration of low pulses (days)	25	39	52
	Number of high pulses within each water year	10	8	7
	Mean duration of high pulses (days)	14	17	14
	Number of overbank flow within each water year	1.2	0.2	0
	Mean duration of overbank flow (days)	5	1	0
Rate and Frequency of Water Condition Changes	Rise rates	75	40	23
	Fall rates	-67	-34	-21
	Number of hydrologic reversals	137	104	164

3.2 Overbank full flow alteration

In the early years of IWSR, the annual runoff of Lijin gauge station was still very low. In 2004, the total annual runoff was 4.15 billion m^3. With the continuous adaptive management, the river runoff increased and gradually met the annual total runoff requirements. However, the runoff continued to decline from 2013, and in recent years it was slightly lower than the annual requirements (Figure. 2).

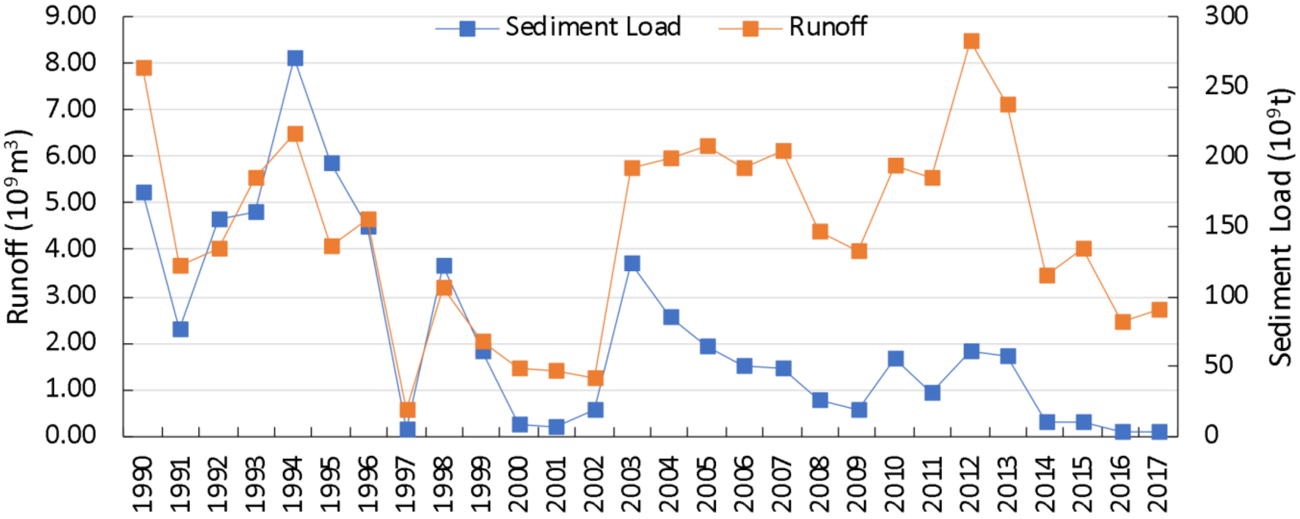

Figure. 2. Annual average runoff and sediment load of Lijin gauge station

According to bankful flow alteration of gauge stations in the lower Yellow River (Table 2), the riverbed is continuously flushing to a deeper depth, and the water level under the same flow conditions is being continuously reduced. The mainstream channel of the lower Yellow River has been undergoing erosion (Kong et al. 2015). The water level of current bankful flow saw a nearly 1 m reduction compared to the 1000-year return period designed bankful flow. The overbank flow in 2015 has increased by more than 1000 m^3/s compared to the flow in 1999. With the deep flushing of the river, the downstream flood peaks have not exceeded 5,000 m^3/s in recent years, which greatly reduces the probability of floodplain. Recently, the water of riverine wetland mainly depends on natural precipitation and groundwater infiltration for supplementation.

Table 2. Bankful flow alteration of gauge stations in the lower Yellow River

Gauge station	1000-year return period designed bankful flow (m^3/s)	Observed bankful flow (m^3/s)			Water level reduction in 3000 m^3/s flow (m)
		1999	2015	Increment	
Huayuankou	22000	3650	7200	3550	2.40
Jiahetan	21500	3400	6800	3400	2.66
Gaocun	20000	2700	6100	3400	2.35
Sunkou	17500	2800	4350	1550	1.60
Aishan	11000	3100	4250	1150	1.53
Luokou	11000	3200	4600	1400	1.76
Lijin	11000	3200	4650	1450	1.29

3.3 Reservoir sedimentation

The first WSR experiment of Xiaolangdi began in July 2002. The WSR experiment continued for three years, which conducted three different patterns of the Xiaolangdi reservoir, and this became normal operation in 2005. As of 2017, there had been 19 IWSR applications, of which 13 occurred before the flooding period, and 6 were in the flooding period. IWSR has not been very successful in recent years. Although WSR was planned in 2016 and 2017, it was fully implemented as there was not sufficient water. The inflow reduction of the Xiaolangdi reservoir was the main reason for this.

Through data collection, the changes of reservoir capacity of the Xiaolangdi reservoir from April 1997 to April 2016 are shown in Figure. 3. By the end of 2011, the capacity of reservoir sedimentation had reached nearly 2.7 billion m^3. At present, the Xiaolangdi reservoir has entered the later stage of the sedimentation period.

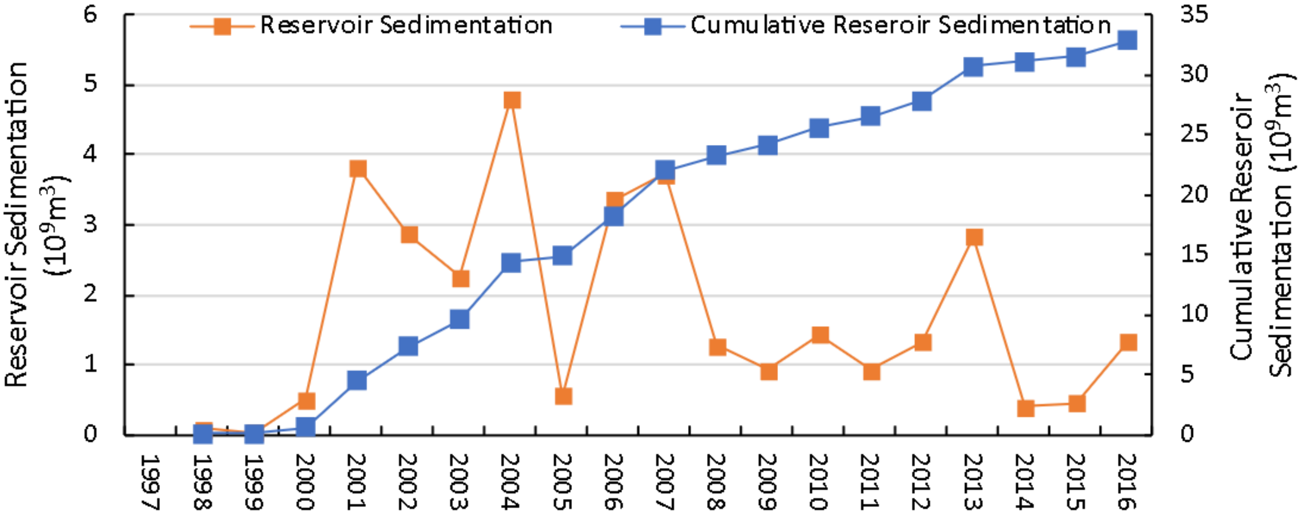

Figure. 3. Sedimentation in the Xiaolangdi Reservoir

3.4 Landuse changes

According to the landuse changes of the four wetlands (Figure. 4), the total area of the Zhengzhou wetland decreased slightly from 566.75 km^2 in 1990 to 543.11 km^2 in 2010. The landuse of the wetland is mainly composed of plain dry land, rivers and beaches, which account for about 90-95% of the total area. The area occupied by plain dry land increased about 20% from 1995 to 2000. From 2000 to 2010, the area showed a slow decreasing trend, while the beaches showed a decreasing trend, from 184.32 km^2 in 1990 to 41.80 km^2 in 2005, accounting for 32.5% in 1990 and 7.38% in 2005 of the total area. In 2010, this increased slightly to 49.70 km^2, which accounted for 9.15% of the total area. The river area was not linear. In 1990, the river area was 131.74 km^2, but this rapidly increased to 212.41 km^2 in 1995, then decreased to 120.91 km^2 in 2000. From 2000 to 2010, the area showed a relatively slow growth rate.

The total area of Xinxiang wetland decreased slightly from 248.88 km^2 in 1990 to 236.91 km^2 in 2010, among which rivers and plain dry land were the most important landuse types of the wetland, accounting for about 80-90% of the total area. In 1990, the areas of rivers and plain dry land were 105.11 km^2 and 119.26 km^2, respectively. In 2010, the river area decreased to 21.82 km^2 (accounting for 9.21% of the total area), and the plain dry land increased to 170.21 km^2 (accounting for 71.84% of the total area), which showed an overall increasing trend.

The landuse types of the Kaifeng wetland are mainly plain dry land, rivers and ponds, which account for 91-98% of the total area. Rivers and plain dry land have always been the most important landuse types, accounting for 80-93% of the total. The overall area of the rivers showed a wave-like downward trend.

According to landuse change in the Yellow River delta wetland, wetland contraction occurred from 1995 to 2005. The area reduced to 1111.30 km^2, of which the maximum reduction was 106 km^2 from 1995 to 2000. The area in 2005 increased compared with 2010. On one hand, it was affected by the runoff variation, while on the other hand it was also affected by human activities in the delta wetland. The total annual runoff of Lijin gauge station in 1995 was 13.7 billion m^3, and in 2000 it was only 4.9 billion m^3.

Above all, plain dry land, rivers and beaches were the main landuse types of the four wetlands. Plain dry land accounted for a large proportion, while rivers and beaches showed a downward trend. Before 2000, the wetland continued to shrink. After 2005, the wetland began to recover, and the area of rivers and beaches began to gradually increase.

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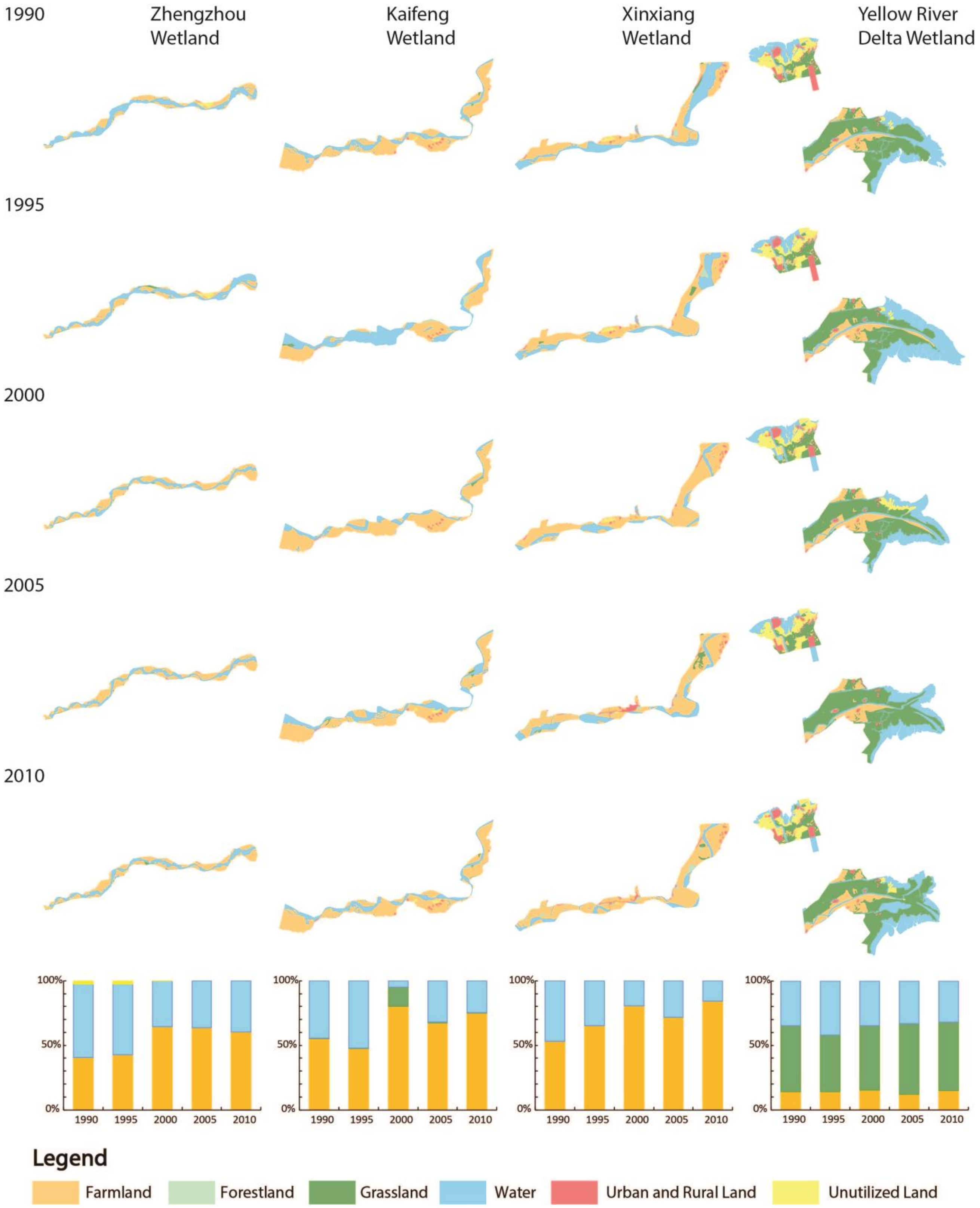

Figure. 4. Landuse changes of the four wetlands in the lower Yellow River

4 DISCUSSION

The hydrological regimes of the Yellow River were changing dramatically, which is mainly caused by climate change and human water diversion (YangYan and Liu 2012). The results showed that the annual runoff of the upper reaches and the middle reaches has decreased significantly since 1985. The Yellow River is in the period of dry years. After 1987, the frequency and duration of cutoff have increased. Human activity may be the main factor causing the Yellow River runoff reduction.

According to statistics, there have been only 11 floods with the observed flow of larger than 10,000 m^3/s in Huayuankou gauge station since 1950, among which nine floods occurred in the 1950s. The largest flood occurred in 1958, and the observed maximum flood peak in Huayuankou gauge station was 22,300 m^3/s. At present, the construction of large dams plays an important role in bio-productivity. The cascade reservoirs operation and regulation have greatly reduced the risk of downstream floods, which have led to downstream runoff reduction since 2002. The operation of Xiaolangdi has controlled downstream flood peak to less than 5,000 m^3/s. In recent years, the maximum flow at Huayuankou gauge station occurred during the WSR period, and was about 4,000 m^3/s with a short duration. The mainstream corridor of the lower Yellow River was scoured and the opportunities of overbank flows decreased, which resulted in the shrinking of the riverine wetlands along the lower Yellow River.

Due to multiple factors such as soil and water conservancy, hydraulic engineering interception, IWSR and climate change, the sediment load from the lower reaches also showed a decreasing trend. According to the observed data from Tongguan gauge station, the annual average sediment load was only 264 million tons from 2000 to 2015, which was 83.6% less than the natural annual average sediment load of 1.592 billion tons. Although annual average runoff of the Yellow River during the same period was 46% lower than the natural annual average runoff, the sediment load also dropped by 71% to 10.8 kg/m^3. From 2000 to 2017, the average sediment transportation of Lijin gauge station was 110 million tons, approximately 10% of the annual average sediment load from 1960 to 1970.

YRCC has implemented IWSR by means of artificial water regulation into the downstream to increase the water in the wetland of the lower Yellow River since 1999 (Wang et al. 2017). Frequent disconnection of the lower Yellow River causes great damage to riverine wetlands. From 1990 to 1997, the annual average runoff into the downstream corridor (based on the data of Huayuankou gauge station) was 26.79 billion m^3/s, which was 46% lower than the annual average runoff from the 1950s to 1960s.The runoff entering the sea (based on the data of Lijin guage station) was 15.42 billion m^3/s, which was 68.6% less than that in the 1950s and 1960s. In the 1990s, the utilization rate of water resources in the Yellow River basin was as high as 66.3%. The excessively high utilization rate caused the lower reaches of the Yellow River to frequently dry up, which caused the riverine wetland to shrink and die out. The construction of production dikes in the downstream tidal area affected flood control, and also went against the development of wetlands. There are 1.8 million residents in the downstream floodplain area of the Yellow River, which resulted from the heavy historical evolution of the Yellow River. In order to protect agriculture production, production dykes were generally built. These were the major factors of blocking the water and sediment exchange between the mainstream of the Yellow River and wetlands. They were also the main factor of flooding risks.

The Yellow River delta wetland has been greatly affected by IWSR (Kong et al. 2015). The area of artificial wetlands increased by about 1,000 times from 1976 to 2014.The specific growth process can be roughly divided into three stages: (1) The period from 1976 to 1984 was a period of slow growth, with an average annual growth rate of 33 hm^2/a. (2) From 1984 to 1999, the annual growth rate was 6,659 hm^2/a. (3) From 1999 to 2014, the annual growth rate was 2,123 hm^2/a. The rapid increment of artificial wetlands was the result of human activities in delta wetlands. From 1976 to 2014, the area of natural wetlands fluctuated and decreased, with a decrease of 419%. In 1993, the area of natural wetlands increased to a certain extent. From 2004 to 2006, the area of natural wetlands decreased, but the trend slowed down. Since 2002, the wetland restoration project and IWSR experiment have been implemented. During the period of WSR, the amount of sediment entering the delta wetland increased significantly, which indicated that WSR can effectively improve the change trend of the Yellow River delta wetland area.

5 CONCLUSION

Through comprehensive analysis, it is concluded that after implementing IWSR, the hydrological alteration will lead to the succession of the wetlands in the downstream riparian ecosystems. In general, IWSR is not conducive to the development of riverine wetlands and the improvement of delta wetlands.

The hydrological regimes of Lijin gauge station have been improved, and the minimum flow has increased significantly. The rate of water condition changes has decreased, and the overbank floods have disappeared.

The evolution of mainstream corridor siltation is the main driving force for the changes of riverine wetlands. The key to protecting the riverine wetlands is to provide sufficient water to maintain the area of the wetlands, and guarantee e-flows for ecosystem health. Bankful flow and floods are important for the existence of downstream riverine wetlands. Due to the fact that the mainstream corridor of the lower Yellow River has gradually been brought under control at present, flood pulses will also be further reduced with the readjustment of engineering projects. The annual average runoff will then decrease, as water intake increases in the Yellow River basin. In conclusion, it will be more and more difficult for riverine wetland recovery through IWSR, but it is effective to improve the environment of the Yellow River delta wetland through IWSR.

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