

Comparison of channel geometry changes in Inner Mongolian reach of the Yellow River before and after joint operation of large upstream reservoirs

SU Teng^{1,2}, *WANG Suiji¹, MEI Yanguo^{1,2}, SHAO Wenwei^{1,2}

1. Key Laboratory of Water Cycle and Related Land Surface Processes, Institute of Geographic Sciences and Natural Resources Research, CAS, Beijing 100101, China;

2. University of Chinese Academy of Sciences, Beijing 100049, China

Abstract: The impact of reservoirs on downstream river channel change has been a scientific issue in fluvial geomorphology during the last few decades. However, it is still a difficult issue as to how to express quantitatively the channel adjustment in the Inner Mongolian reach of the Yellow River induced by the joint operation of upstream reservoirs. Based on the shape parameters of channel cross-sections at four gauging stations in this river reach over a flooding season in two periods, 1978–1982 and 2008–2012, the present work investigated the channel changes in terms of shape parameter change rate under the same controlling water level in each flooding season at the channel cross-sections. Results showed that most of the change rates of the parameters evidently increased over a flooding season in both periods. However, the change rate of each parameter at the cross-sections decreased evidently in the latter period, compared with the former period. At the same time, the distribution pattern of the change rate of the shape parameters along the cross-sections thus changed from a convex curve in the former period to an S-shaped curve in the latter period. The obvious decrease of the change rates is related to the joint operation of the Liujiaxia and Longyangxia reservoirs. The reservoirs stored a large volume of water and decreased the peak discharge and maximum velocity in the flooding season; as a result, the erosion ability of the flood decreased accordingly. With the joint operation of the large reservoirs, the Inner Mongolian channel shrunk markedly. Therefore, the channel will present the possibility of an extreme flood in the future. Consequently, it is reasonable to adjust the function of the reservoirs in future. The total water and sediment discharges and the peak discharge in flooding seasons should be effectively controlled. Continuous shrinkage of the channel can thus be avoided and it can be ready for a potential extreme flood.

Keywords: channel cross-section; shape parameters; change rate; reservoir; joint operation; Yellow River

Received: 2015-01-15 **Accepted:** 2015-03-05

Foundation: National Natural Science Foundation of China, Grant No.41271027; National Basic Research Program of China (973 Program), No.2011CB403305; fund from the Ministry of Science and Technology of China, No.2013DFA91700

Author: Su Teng, Master Candidate, specialized in fluvial geomorphology. E-mail: sut.12s@igsnr.ac.cn

***Corresponding author:** Wang Suiji, PhD and Associate Professor, specialized in fluvial sedimentology, geomorphology and land surface process. E-mail: wangsj@igsnr.ac.cn

1 Introduction

Changes in channel morphology along rivers and their responses to different affecting factors in alluvial rivers are key research areas of fluvial processes. The Ningxia-Inner Mongolian reach is a main reach in the upper Yellow River whose scouring and silting processes are quite complex (Wang *et al.*, 2014a; Du *et al.*, 2014). Recently, the water regime of this reach has changed greatly under the effect of climate change, reservoir operation and water consumption as an irrigation region (Shen *et al.*, 2007; Shi *et al.*, 2012; Wang *et al.*, 2012a, 2012b; Zhou *et al.*, 2012; Zhang *et al.*, 2013). This obvious change has caused an increase of sedimentation rate as well as severe shrinkage of the active channel (Qin *et al.*, 2011; Fan *et al.*, 2012). The coastal area thus has to withstand more pressure from daily life related to production activities as the frequency of flood in low water level has increased. Therefore, a lot of works have studied the fluvial process in this river reach. Utilizing channel cross-section surveys, Shi *et al.* (2013) found that the Inner Mongolian reach experienced a scouring process from 1963 to 1982 and a silting process after 1982. Wang and Fan (2010) investigated the flood processes and channel responses of different channel patterns in the Inner Mongolian reach, the results showing that the channel bed erosion is mainly in the braided channel reach, the channel bed aggradation is in the meandering channel reach, and the slight aggradation or the balanced erosion–deposition is in the straight channel reach. Qin *et al.* (2011) constructed a time series of cross-section area and identified three different evolution tendencies for channel change in the Inner Mongolian reach. Hou *et al.* (2007) estimated the volumes of sediment erosion and storage in the Inner Mongolian section. Wang *et al.* (2014b) calculated the lateral migration rate of river banks in the Yinchuan Plain reach of the Yellow River using remote sensing images. Besides, other works have studied the causes of channel deposition (e.g., Petts, 1979; Zhao *et al.*, 1999; Yang *et al.*, 2003; Shen *et al.*, 2007; Wang *et al.*, 2012b; Ta *et al.*, 2008), change of hydraulic geometry along the river (Ran *et al.*, 2012), and characteristics of spring flood (Feng *et al.*, 2009). So far, few works have quantitatively studied the change rate of channel shape parameters over a flooding period. A quantitative study of channel morphology change rate over a flooding season is necessary for assessing channel stability and formulating reasonable river management measures.

The objective of the paper is to investigate the change rate of channel morphology over flooding periods under the effect of the joint operation of the Liujiaxia and Longyangxia reservoirs. The article selects the early 1990s as a time boundary when the Longyangxia and Liujiaxia reservoirs operated jointly. We also utilize every 5-year data before and after the time boundary to characterize temporal variation. Four parameters, namely cross-section area, channel width, mean water depth, and the width-to-depth rate, are used to describe the channel shape changes based on the cross-sectional data derived from four hydrological stations. This article is expected to provide evidence for the management of the Yellow River, such as flood control and disaster reduction.

2 Study area

The Inner Mongolian alluvial reach is located between Shizuishan and Toudaoguai gauging stations with a total channel length of 673 km and a mean annual runoff of 25.2 billion m³. The catchment of this river reach is 106°41'59"–110°06'30"E and 39°19'06"–41°18'15"N.

The river flows along the northwest margin of the Ordos Plateau with a gentle channel gradient (Hu *et al.*, 2012). As is shown in Figure 1, the reach lies at the end of the upper Yellow River and is the northernmost part of the whole basin. The reach is located in the peripheral area of the monsoon climate region and its mean annual precipitation is 150–400 mm. The intra-annual distribution of precipitation is extremely uneven with about 75% of the total occurring from July to September (Wang *et al.*, 2014a). The water surface is covered with ice from December to March and the spring flood is serious when the ice begins to melt in late March (Yao *et al.*, 2007).

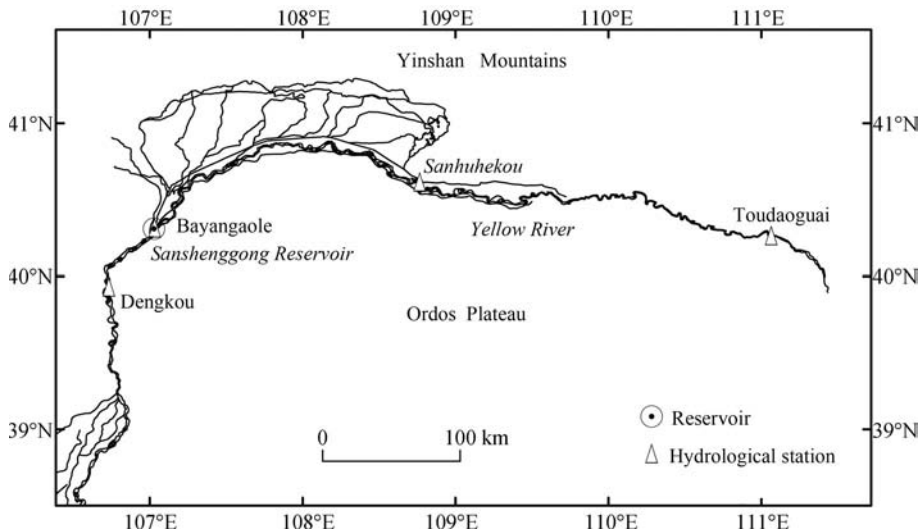


Figure 1 Sketch of the Inner Mongolian reach of the Yellow River

There are some tributaries in the river reach. Ten ephemeral tributaries drain into the Yellow River on the south side of the reach, and Dukunlun and Wudanggou tributaries drain into the Yellow River on the north side. These ten ephemeral tributaries can deliver large quantities of sediment into the main channel when a rainstorm occurs. As a result, the trunk channel at the junction is partly blocked and shifts northward, and the elevation of the main channel above the junction increases (Xu, 2014).

Several major reservoirs were constructed in the upper Yellow River during the period 1968–1986. The largest two are the Longyangxia and Liujiaxia reservoirs, constructed in 1986 and 1968 and with capacities of 24.7 billion m³ and 5.7 billion m³, respectively. Qingtongxia reservoir, with a relatively small capacity of 0.61 billion m³, has suffered severe sedimentation after impoundment. Sanshenggong reservoir with a capacity of 80 million m³ is the only reservoir located in the study river reach.

3 Data and method

To investigate the impact of the joint operation of reservoirs on the change rate of channel morphology in flooding seasons, the change rates of channel morphology both before and after the joint operation of Longyangxia and Liujiaxia reservoirs are separately estimated. Cross-sections, located at Dengkou, Bayangaole, Sanhuhekou, and Toudaoguai gauging stations, are used to calculate the channel morphological change along the Inner Mongolian reach (Figure 1). Those four stations are located in straight, braided, meandering, and

straight channel reaches along the Inner Mongolian reach, respectively. Two periods before and after the joint operation of the reservoirs are adopted. The former period is from 1978 to 1982 and the latter is from 2008 to 2012. The reasons are the following. (1) Longyangxia and Liujiaxia reservoirs began to operate jointly in 1986, which led directly to the unprecedented cut off in the lower reach. So the 1990s is a key period for investigating how the joint operation of the reservoirs affects the inflow conditions. The key scientific problem is how the joint operation of the reservoirs affects the variation of shape parameters over a flooding season. (2) There are no continuous sediment and water records in the period 1990–2007. (3) Generally, the bank-full discharge of the alluvial rivers in the world appears once in 2.33 years, thus 5 years of continuous data can well contain a bank-full discharge that may occur. Because Dengkou station only measured one time in 1979 and 1981, it is impossible to compare the change of shape parameters over a flooding season, so we choose the data in 1976, 1977, 1978, 1980, and 1982 instead.

All the above data are provided by the Yellow River Conservancy Commission (YRCC, 1976–1982, and 2008–2012) and are measured according to national standards. Cross-sections are surveyed at least twice each year to acquire the topographic change before and after a flooding season. Daily discharge and suspended sediment load (SSL) are measured by rating curve method. Those records measured in each gauge span more than 50 years. Variation of these sections can well reveal the change of channel morphology in the different channel patterns.

In the present work, four parameters, namely channel cross-section area, water width, mean water depth, and the width-to-depth rate, are used to describe the channel shape changes. All parameters are calculated before and after a flooding season in each year, and the difference between corresponding parameters is considered as the change rate. The measured water levels before and after a flooding season commonly are different, and thus we choose the lower one in each year as the controlling water level to calculate the related parameters and compare the channel change. Cross-section area is defined as the area below the selected water level; water width is defined as the channel width at the selected water level; and mean water depth is defined by dividing water width into cross-section area.

4 Results

4.1 Channel shape parameters before and after a flooding season

All the parameters of channel cross-section at the four measuring points before and after the flooding season in the years studied are calculated and listed in Tables 1 and 2. Those data include parameters of the channel cross-section for both actual water level and the controlling water level. The parameters of the channel cross-section under the controlling water level will be used to compare the change rates while those under the maximum water level will be used just for reference.

4.2 Temporal variation of change rates

The change rates of each parameter over a flooding season in the years studied for the Dengkou, Bayangaole, Sanhuhekou, and Toudaoguai cross-sections are shown in Figures 2–5, respectively.

4.2.1 Change rates at Dengkou cross-section

The cross-section area increased over the flooding season in the years studied for the Dengkou cross-section (Figure 2). The maximum and average change rates were 152.7% and 66.8% in the early period and 48.4% and 30.6% in the later period, respectively. Water width increased greatly in 1978 and 1980 while it decreased in the other years in the early period. In contrast, the water width increased in the later period, and the maximum and average change rates were 9.4% and 6.5%, respectively. The mean water depth increased over a

Table 1 Channel shape parameters under a given water level before and after a flooding season at Dengkou and Bayangaole cross-sections

Dengkou							Bayangaole						
Year	Date	S/m	A/m ²	B/m	H/m	B/H	Year	Date	S/m	A/m ²	B/m	H/m	B/H
1976	6–10	1060.12	648	260	2.5	104.3	1978	5–2	1050.41	622	449	1.4	324.1
	9–19	1060.69	1347	268	5.0	53.3		11–2	1050.16	1325	481	2.8	174.6
	9–19	1060.12*	1199	256	4.7	54.7		5–2	1050.16*	512	426	1.2	354.4
1977	4–21	1060.00	594	258	2.3	112.1	1979	4–25	1050.24	617	439	1.4	312.4
	10–20	1060.24	684	270	2.5	106.6		11–16	1049.66	598	468	1.3	366.3
	10–20	1060.00*	620	255	2.4	104.9		4–25	1049.66*	367	258	1.4	181.4
1978	3–17	1060.14	520	208	2.5	83.2	1980	5–10	1049.42	245	291	0.8	345.6
	9–19	1061.39	1655	288	5.7	50.1		11–20	1049.97	508	384	1.3	290.3
	9–19	1060.14*	1314	264	5.0	53.0		11–20	1049.42*	393	356	1.1	322.5
1980	5–2	1059.71	481	204	2.4	86.5	1981	4–13	1050.36	481	393	1.2	321.1
	10–26	1060.32	838	274	3.1	89.6		11–23	1049.47	1046	426	2.5	173.5
	10–26	1059.71*	682	247	2.8	89.5		4–13	1049.47*	225	250	0.9	277.8
1982	4–21	1059.84	646	278	2.3	119.6	1982	4–26	1049.63	621	373	1.7	224.0
	10–19	1060.48	1143	281	4.1	69.1		11–20	1049.71	603	400	1.5	265.3
	10–19	1059.84*	968	267	3.6	73.6		11–20	1049.63*	551	394	1.4	281.7
2008	4–30	1060.62	374	135	2.8	48.7	2008	4–7	1051.22	484	322	1.5	214.2
	11–1	1060.89	492	148	3.3	44.5		11–11	1050.6	416	361	1.2	313.3
	11–1	1060.62*	453	141	3.2	43.9		4–7	1050.6*	288	310	0.9	333.7
2009	5–16	1060.80	476	166	2.9	57.9	2009	4–1	1051.73	757	434	1.7	248.8
	10–18	1061.24	743	173	4.3	40.3		9–21	1051.2	1264	402	3.1	127.9
	10–18	1060.80*	668	176	3.8	46.4		4–1	1051.2*	533	407	1.3	310.8
2010	6–9	1061.30	620	181	3.4	52.8	2010	4–13	1051.54	739	418	1.8	236.4
	10–19	1060.96	565	197	2.9	68.7		8–11	1051.03	574	421	1.4	308.8
	6–9	1060.96*	558	180	3.1	58.0		4–13	1051.03*	527	413	1.3	323.7
2011	4–24	1060.77	465	172	2.7	63.6	2011	4–12	1050.93	482	321	1.5	213.8
	10–20	1061.19	767	199	3.9	51.6		9–21	1050.85	1036	348	3.0	116.9
	10–20	1060.77*	690	178	3.9	45.9		4–12	1050.85*	537	338	1.6	212.7
2012	4–22	1060.52	510	169	3.0	56.0	2012	3–24	1050.48	573	255	2.2	113.5
	10–24	1060.89	794	189	4.2	45.0		10–3	1051.12	1352	340	4.0	85.5
	10–24	1060.52*	725	184	3.9	46.7		10–3	1050.48*	1137	333	3.4	97.5

Note: *, controlling water level; S, water level; B, water width; H, mean water depth; B/H, width to depth rate.

Table 2 Channel shape parameters under a given water level before and after a flooding season at Sanhuhekou and Toudaoguai cross-sections

Sanhuhekou							Toudaoguai						
Year	Date	S/m	A/m ²	B/m	H/m	B/H	Year	Date	S/m	A/m ²	B/m	H/m	B/H
1978	5–14	1018.27	597	279	2.1	130.4	1978	6–11	985.06	300	185	1.6	114.1
	11–8	1017.61	883	328	2.7	121.8		10–9	988.03	1278	520	2.5	211.6
	5–14	1017.61*	401	255	1.6	162.2		10–9	985.06*	115	247	0.5	530.5
1979	5–19	1016.66	209	213	1.0	217.1	1979	7–17	984.78	224	185	1.2	152.8
	10–20	1017.63	800	203	3.9	51.5		11–26	987.13	738	362	2.0	177.6
	10–20	1016.66*	607	194	3.1	62.0		11–26	984.78*	198	146	1.4	107.7
1980	5–21	1016.57	275	211	1.3	161.9	1980	5–8	986.5	602	353	1.7	207.0
	10–27	1017.79	889	207	4.3	48.2		11–10	985.54	352	254	1.4	183.3
	10–27	1016.57*	655	172	3.8	45.2		5–8	985.54*	345	192	1.8	106.9
1981	5–14	1016.41	290	75	3.9	19.4	1981	5–9	986.03	467	314	1.5	211.1
	12–28	1018.34	1060	353	3.0	117.6		9–28	990.29	3064	727	4.2	172.5
	12–28	1016.41*	492	202	2.4	82.9		9–28	986.03*	1072	300	3.6	84.0
1982	5–7	1016.86	421	268	1.6	170.6	1982	5–19	985.56	370	243	1.5	159.6
	10–16	1018.42	1353	385	3.5	109.6		10–3	988.06	1091	537	2.0	264.3
	10–16	1016.86*	784	315	2.5	126.6		10–3	985.56*	119	245	0.5	504.4
2008	4–4	1019.33	615	224	2.7	81.6	2008	4–6	987.53	900	360	2.5	144.0
	11–10	1018.97	473	212	2.2	95.1		11–3	987.16	637	283	2.3	125.7
	4–4	1018.97*	527	211	2.5	84.5		4–6	987.16*	771	347	2.2	156.2
2009	4–4	1019.75	965	250	3.9	64.8	2009	4–7	987.62	744	335	2.2	150.8
	9–30	1019.04	585	211	2.8	76.1		11–1	986.89	572	306	1.9	163.7
	4–4	1019.04*	810	245	3.3	74.1		4–7	986.89*	515	309	1.7	185.4
2010	4–7	1019.57	796	269	3.0	90.9	2010	4–14	987.62	784	340	2.3	147.4
	10–15	1019.21	601	209	2.9	72.7		10–26	986.68	577	287	2.0	142.7
	4–7	1019.21*	718	264	2.7	97.1		4–14	986.68*	502	271	1.9	146.3
2011	4–8	1019.17	618	205	3.0	68.0	2011	4–5	987.37	635	297	2.1	138.9
	10–16	1019.02	528	210	2.5	83.5		10–23	987.14	737	290	2.5	114.1
	4–8	1019.02*	587	203	2.9	70.2		4–5	987.14*	562	295	1.9	154.8
2012	3–21	1020.46	888	320	2.8	115.3	2012	4–5	987.5	699	300	2.3	128.8
	10–17	1018.83	642	296	2.2	136.5		10–9	987.68	970	324	3.0	108.2
	3–21	1018.83*	442	187	2.4	79.1		10–9	987.5*	300	185	1.6	114.1

Note: *, controlling water level; S, water level; B, water width; H, mean water depth; B/H, width-to-depth rate.

flooding season in all years except 2010. The maximum and average change rates were 99.1% and 53.2% in the early period and 43.4% and 30.6% in the later period, respectively. The width-to-depth rate increased in 1980 and 2010, and decreased in the other years. The absolute maximum change rate and the average value were 47.6% and –25.06% in the early period and 27.8% and –11.2% in the later period.

4.2.2 Change rates at Bayangaole cross-section

Change rates of channel shape parameters at the Bayangaole cross-section over the flooding season in the years studied are shown in Figure 3. The cross-section area increased in all years except 1982, and the maximum and average change rates were 364.9% and 127.2% in the early period and 137.1% and 76.4% in the later period, respectively. The water width

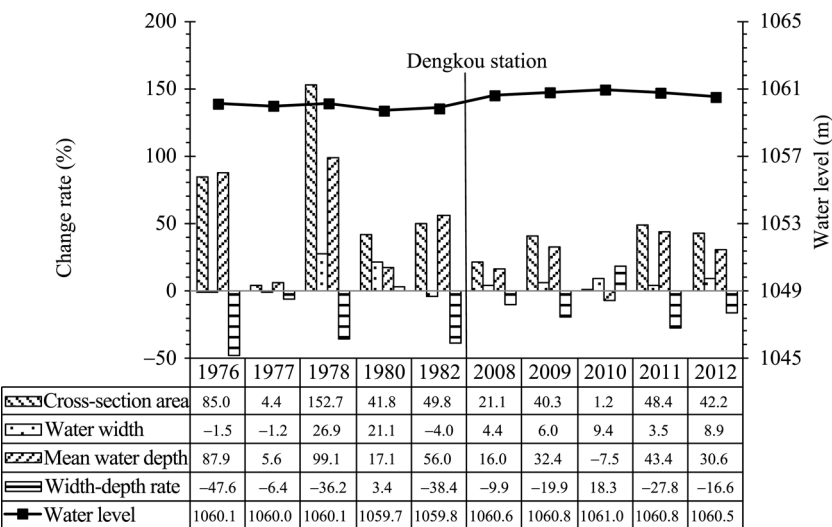


Figure 2 Change rates of channel shape parameters at Dengkou cross-section after a flooding season

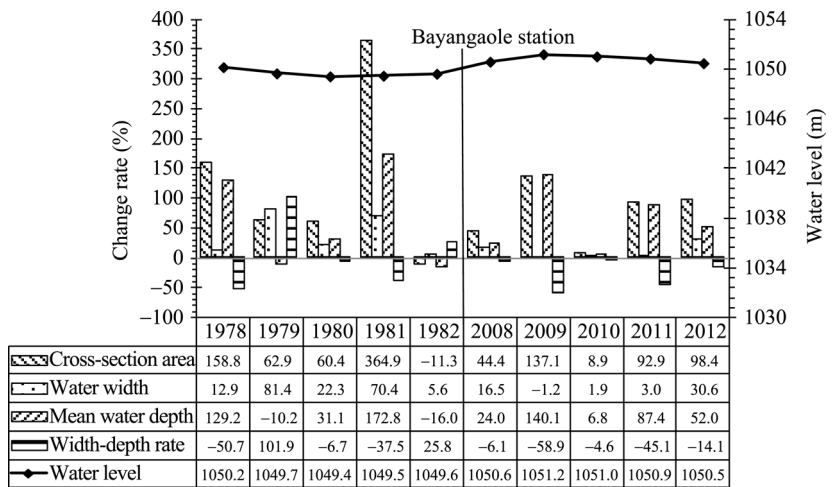


Figure 3 Change rates of channel shape parameters at Bayangaole cross-section after a flooding season

increased in all years except 2009, and the maximum and average change rates were 81.4% and 38.5% in the early period and 30.6% and 10.1% in the later period, respectively. The mean water depth decreased in 1979 and 1982 while it increased in other years. The maximum and average change rates were 172.8% and 61.4% in the early period and 140.1% and 62.1% in the later period, respectively. The width-to-depth rate increased in 1979 and 1982 and decreased in other years. The maximum and the average change rates were 101.9% and 6.5% in the early period and -4.6% and -25.7% in the later period. This shows that those four parameters increased mainly in the early period and decreased mainly in the later period over the flooding season.

4.2.3 Change rates at Sanhuhekou cross-section

The change rates of channel shape parameters at the Sanhuhekou cross-section over a flooding season in the years studied decreased greatly in the later period compared with the

early period (Figure 4). The cross-section area increased in all years except 2012, and the maximum and average change rates were 190.4% and 120.9% in the early period and 45.2% and –3.8% in the later period, respectively. The maximum value and average change rates of water width were 169.3% and 37.6% in the early period and 58.3% and 5.5% in the later period, respectively. The mean water depth increased mainly in the early period, the maximum and average change rates being 218.9% and 100.7%, respectively, while it decreased mainly in the later period, the maximum and average change rates being 5.7% and –8.5%, respectively. For the width-to-depth rate, the maximum and the average values were 327.6% and 26.7% in the early period and 72.5% and 16.3% in the later period.

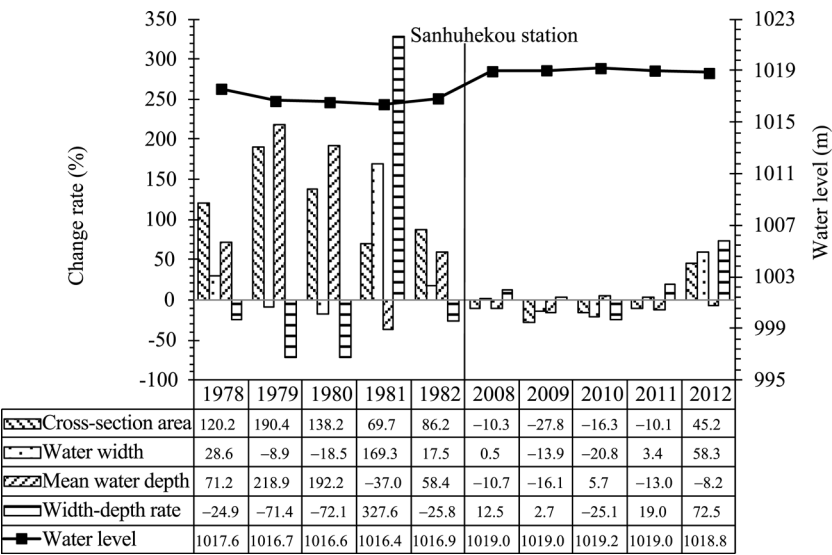


Figure 4 Change rates of channel shape parameters at Sanhuhekou cross-section after a flooding season

4.2.4 Change rates at Toudaoguai cross-section

The change rates of channel shape parameters at the Toudaoguai cross-section are shown in Figure 5. The maximum and average change rates of cross-section area were 129.6% and

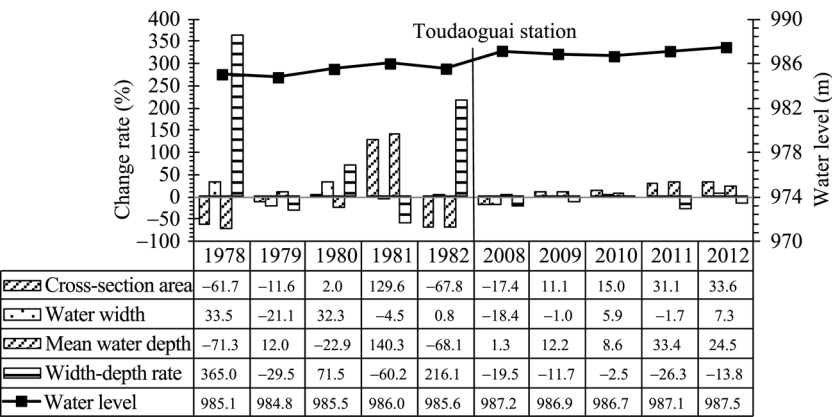


Figure 5 Change rates of channel shape parameters at Toudaoguai cross-section after a flooding season

54.5% in the early period, and 33.6% and 21.6% in the later period, respectively. For the change rates of water width, the maximum and average values were 33.5% and 18.4% in the early period and 18.4% and 6.9% in the later period, respectively. The maximum and average change rates of mean water depth were 140.3% and 62.9% in the early period and 33.4% and 16.0% in the later period, respectively. The change rates of width to depth decreased in each year of the later period. The maximum and the average change rates were 365.0% and 148.5% in the early period and -2.5% and -14.7% in the later period, respectively. The results also showed that change rates of the parameters decreased greatly in the later period compared with the early period.

4.3 Spatial variation of change rates

The average change rates of channel shape parameters at the Dengkou, Bayangaole, Sanhuhekou, and Toudaoguai cross-sections over a flooding season in the years studied are shown in Figure 6. Along the cross-sections, the change rates for both cross-section area and water width show a convex curve in the early period and an S-shaped curve in the later period (Figures 6a and 6b). For both the early and later periods, the maximum value was at the Bayangaole cross-section.

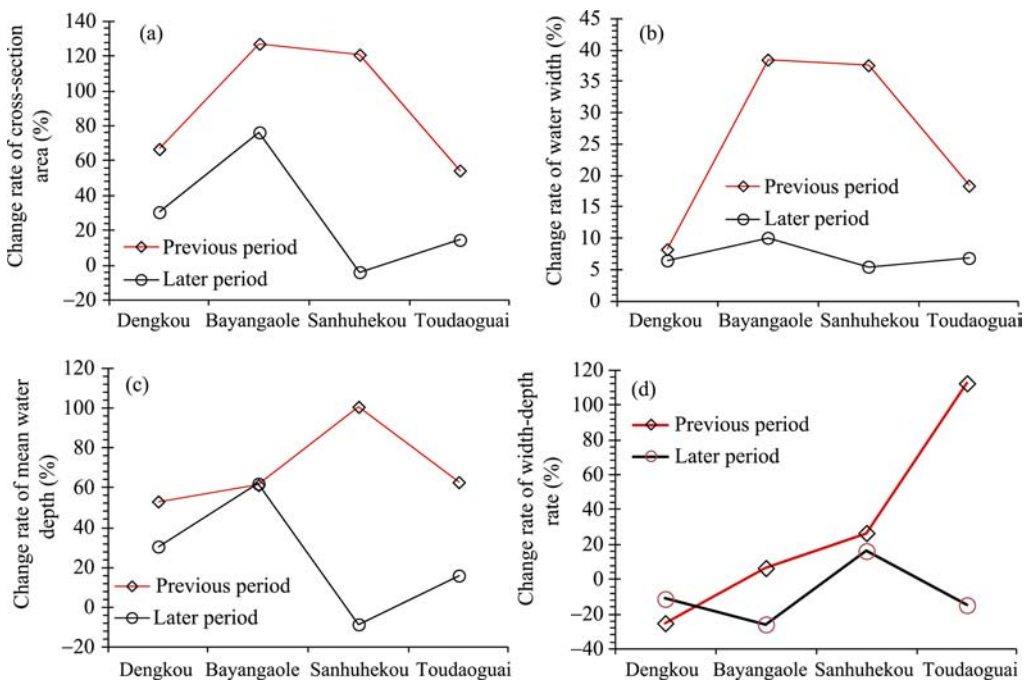


Figure 6 Spatial variation of the change rates of channel shape parameters during the periods 1978–1982 and 2008–2012

The average change rates of mean water depth and width-to-depth rate at the four cross-sections over a flooding season in the years studied are shown in Figures 6c and 6d, respectively. The change rate curves show an increasing tendency along the cross-sections except for the Toudaoguai station in the early period, whereas there is an S-shape in the later period. The maximum average change rate of mean water depth was at the Sanhuhekou

cross-section in the early period and at the Bayangaole cross-section in the later period. Meanwhile, almost all the mean average change rates of the parameters evidently decreased in the later period compared with the early period.

5 Discussion

5.1 Effect of decreased runoff and SSL in flooding seasons

Bank-full discharge is a primary control factor in channel adjustments and can appear in flood seasons for all rivers. Hu and Zhang (2011) studied the channel adjustment in the Yellow River Delta and pointed out that the bank-full cross-section area is sensitive to the variation of inflow conditions; furthermore, there is a positive correlation between bank-full cross-section area and water discharge in the flooding season. Yu *et al.* (2006) found that the variation of channel planform correlates with a decrease of bank-full discharge after impoundment of upstream reservoirs. The change rates of channel shape parameters in the Inner Mongolian reach changed greatly after reservoir joint operation, which is ascribed to the inevitable variation of inflow conditions in the flooding season. Therefore, annual variations in runoff and SSL in the flooding season are represented in Figure 7 to investigate the effect of reservoir joint operation and thus to investigate the responses of channel cross-section changes.

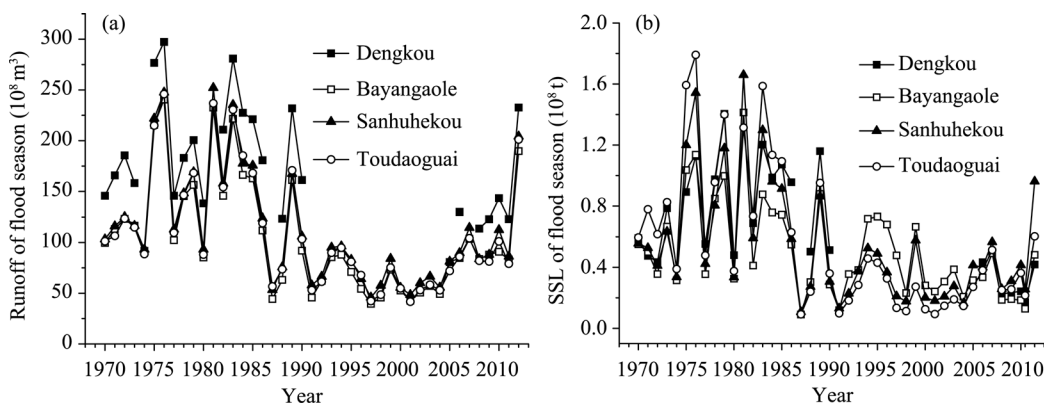


Figure 7 Variations of runoff (a) and SSL (b) in the flooding seasons in the period 1970–2012

The runoff and SSL in the flooding season at the Dengkou, Bayangaole, Sanhuhekou, and Toudaoguai gauging stations decreased greatly in the 1980s (Figure 7). The average runoff values at the stations were 19.50, 15.31, 16.41, and 15.88 billion m^3 in the early period and 14.71, 10.71, 11.49, and 10.89 billion m^3 in the later period, reductions of 24.58%, 30.05%, 29.96%, and 31.38%, respectively. The average SSLs at the stations were 75, 80, 91, and 96 million tons in the early period and 26, 23, 44, and 34 million tons in the later period, reductions of 66.20%, 70.67%, 51.84%, and 64.67%, respectively. However, the precipitation in the upper Yellow River did not change significantly during the same period. Consequently, the marked decrease in runoff and SSL could be induced by the joint operation of Liujiaxia and Longyangxia reservoirs. Apparently, the decrease of runoff and SSL in flooding seasons after reservoir joint operation leads to weak scouring in the channel, so the change rate of channel shape parameters decreases correspondingly.

5.2 Effects of decreased peak discharge and maximum flow velocity

The joint operation of large-scale reservoirs not only altered the annual runoff and SSL, but also influenced the flood characteristics. Compared with the floods in the early period without joint operation of the reservoirs, the floods are characterized by lower peak discharge and longer duration in the later period (Fan *et al.*, 2012). Furthermore, the flow velocity in the flooding season in the later period decreased obviously which reduced the scouring ability and correspondingly reduced the ability of the channel to change. Richard *et al.* (2005) pointed out that peak discharge is responsible for lateral migration. Hu *et al.* (2006) found that the bank-full cross-section area increases with an increase of peak discharge in the lower reach of the Yellow River. So it is essential to investigate the variation of peak discharge and maximum flow velocity and determine their impacts on change rates of channel shape parameters.

Peak discharge in the flooding season at the four gauging stations has decreased greatly since the end of the 1980s (Figure 8a). The average peak discharge at the stations was 2964, 3322, 3502, and 3298 m³/s in the early period and 1674, 1698, 1836, and 1836 m³/s in the later period, with reductions of 43.52%, 48.89%, 47.57%, and 47.33%, respectively. The average maximum velocity of water flow at the stations reduced from 3.27, 2.54, 2.87, and 3.05 m/s in the early period to 2.83, 2.61, 2.50, and 2.64 m/s in the later period, respectively (Figure 8b). It decreased by 14%, 13%, and 14% at the Dengkou, Sanhuhekou, and Toudaoguai gauging stations, respectively, and slightly increased by 2.8% at the Bayangaole gauging station. The maximum velocity corresponds to the peak discharge: the peak discharge indicates the maximum spatial extension of channel change is affected by a flood process, and the maximum flow velocity reflects the maximum ability of channel change in a flood process. So the joint operation of the large-scale reservoirs not only reduces the peak discharge but also the maximum flow velocity in the flooding season. The ability of channel deformation thus decreases.

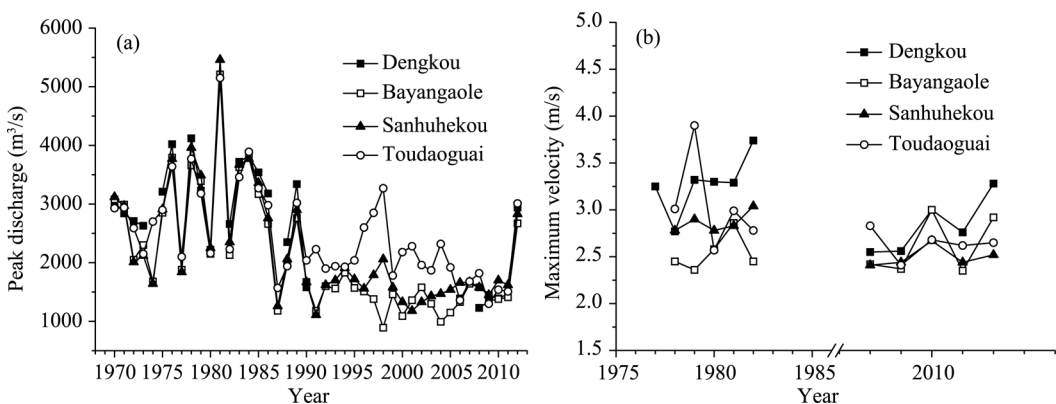


Figure 8 Variations of peak discharge (a) and maximum flow velocity (b) in flooding seasons

5.3 Spatial difference in change rates and its reason

There is little difference in annual runoff and peak discharge among the four stations in both the periods. However, there is an evident spatial difference in change rate of channel shape parameters among the stations especially in the later period. This evident difference is ascribed to the hydrodynamics and composition of bank material rather than to the water dis-

charge. Different channel patterns, straight, braided, meandering, and straight, appear along the Inner Mongolian reach of the Yellow River. The braided channel has a stronger hydrodynamic and erosion-prone bank materials; the unstable channel is the reason why the Bayangaole cross-section has a maximum change rate of cross-section area and water width in both the periods. However, the joint operation of the reservoirs causes the change rate of cross-section area and water width at the Sanhuhekou cross-section located in the meandering channel reach to vary from secondary-largest value in the early period to minimum value in the later period. This denotes the response to the decrease of runoff and maximum velocity owing to the joint operation of the reservoirs. The change rate of mean water depth at Sanhuhekou varies from the maximum value among the cross-sections in the early period to the minimum value in the later period. Apparently, due to reservoir joint operation, the decline of runoff and maximum flow velocity causes relatively little scouring at the channel cross-section. The change rate of mean water depth thus decreases accordingly. However, the meandering channel pattern as represented by the Sanhuhekou cross-section is most affected by the joint operation of the reservoirs, the braided channel pattern as represented by the Bayangaole cross-section is next, and the straight channel pattern as represented by the Dengkou and Toudaoguai cross-sections is the least affected.

6 Conclusions

The study estimated the change rates of channel shape parameters at the Dengkou, Bayangaole, Sanhuhekou, and Toudaoguai cross-sections over each flooding season in the 5-year periods before and after the joint operation of reservoirs. The main conclusions are as follows:

- (1) The cross-section area, water width, mean water depth, and width-to-depth rate evidently increased after a flooding season in both periods except for some individual parameters.
- (2) The change rate was greater in the early period and decreased greatly in the later period. Meanwhile, it was found that the average change rate of cross-section area, water width, and mean water depth decreased 3.4, 3.5, and 2.8 times after the joint operation of the reservoirs.
- (3) The joint operation of the large-scale reservoirs caused the change rate of channel shape parameters at the Sanhuhekou cross-section to vary from the second-largest value in the early period to a minimum in the later period. The distribution pattern of the change rate along the cross-sections changed from a convex curve in the early period to an S-shaped curve in the later period.
- (4) Joint operation of the reservoirs not only reduced the total runoff and SSL in the flooding season but also reduced the peak discharge and maximum flow velocity. Consequently, the ability of flood to scour the riverbed weakened and the change rate of channel shape parameters decreased accordingly. Apparently, the joint operation of the reservoirs caused channel shrinkage which will increase the potential for an extreme flood.
- (5) It will be reasonable to utilize the adjustment function of the reservoirs in future. The total water and sediment discharge and the peak discharge in flooding seasons must be effectively controlled. The channel thus can avoid continuous shrinkage and be ready for potential extreme flood.

References

- Du H Q, Xue X, Wang T, 2014. Estimation of the quantity of aeolian saltation sediments blown into the Yellow River from the Ulanbuh Desert, China. *Journal of Arid Land*, 6(2): 205–218. doi: 10.1007/s40333-013-0198-3.
- Fan X, Shi C, Zhou Y *et al.*, 2012. Characteristics of flood regime in Ningxia-Inner Mongolia reaches of the upper Yellow River. *Resources Science*, 34(1): 65–73. (in Chinese)
- Feng G, Chaolun B, Gao R *et al.*, 2009. Research on ice flood control strategy for Inner Mongolia reach of Yellow River. *Hydrology*, 29(1): 47–49. (in Chinese)
- Hou S, Wang P, Chang W *et al.*, 2007. Evaluation on the volume of scour and fill of Inner Mongolia section of the Yellow River. *Yellow River*, 29(4): 21–23. (in Chinese)
- Hu C, Chen J, Liu D *et al.*, 2006. Studies on the features of cross section's profile in lower Yellow River under the conditions of variable incoming water and sediment. *Journal of Hydraulic Engineering*, 37(11): 1283–1289. (in Chinese)
- Hu C, Zhang Z, 2011. Relationship between adjustment of section configuration and flow-sediment of tail channels in the Yellow River estuary. *Journal of Basic Science and Engineering*, 19(4): 543–553. (in Chinese)
- Hu X, Wang J, Lan Y *et al.*, 2012. Relationship between channel scouring/silting amount and water-sediment transport process in Inner Mongolia reach of Yellow River. *Journal of China Hydrology*, 32(2): 44–48. (in Chinese)
- Petts G, 1979. Complex response of river channel morphology subsequent to reservoir construction. *Progress in Physical Geography*, 3(3): 329–362.
- Qin Y, Zhang X, Wang F *et al.*, 2011. Scour and silting evolution and its influencing factors in Inner Mongolian Reach of the Yellow River. *Journal of Geographical Sciences*, 21(6): 1037–1046.
- Ran L, Wang S, Lu X X, 2012. Hydraulic geometry change of a large river: A case study of the upper Yellow River. *Environmental Earth Sciences*, 66: 1247–1257.
- Richard G, Julien P, Baird D, 2005. Statistical analysis of lateral migration of the Rio Grande, New Mexico. *Geomorphology*, 71(1): 139–155.
- Shen G, Zhang Y, Hou S *et al.*, 2007. Impact of water and sediment regulation by reservoirs in the upper Yellow River on Inner-Mongolia reaches. *Journal of Sediment Research*, (1): 67–75. (in Chinese)
- Shi C, Fan X, Shao W *et al.*, 2013. Channel change of the Inner Mongolian reach of the Yellow River and its causes. *Geographical Research*, 32(5): 787–796. (in Chinese)
- Shi C, Shao W, Fan X *et al.*, 2012. A study on characteristics and sediment rating curves of floods in the Inner Mongolian reach of the Yellow River. *Progress in Geography*, 31(9): 1124–1132. (in Chinese)
- Ta W, Xiao H, Dong Z, 2008. Long-term morphodynamic changes of a desert reach of the Yellow River following upstream large reservoirs' operation. *Geomorphology*, 97(3): 249–259.
- Wang H, Jia X, Wang H, 2014a. Effect of flood scouring channel deposits in Inner Mongolian reach of the Yellow River. *Journal of Desert Research*, 34(4): 1143–1149. (in Chinese)
- Wang S, Fan X, 2010. Flood processes and channel responses in typical years of the different channel patterns in Neimenggu Reaches of the upper Yellow River. *Progress in Geography*, 29(4): 501–506. (in Chinese)
- Wang S, Li L, Cheng W, 2014b. Variations of bank shift rates along the Yinchuan Plain Reach of the Yellow River and their influence factors. *Journal of Geographical Sciences*, 24(4): 703–716.
- Wang S, Yan M, Yan Y *et al.*, 2012a. Contributions of climate change and human activities to the changes in runoff increment in different sections of the Yellow River. *Quaternary International*, 282: 66–77.
- Wang S, Yan Y, Li Y, 2012b. Spatial and temporal variations of suspended sediment deposition in the alluvial reach of the upper Yellow River from 1952 to 2007. *Catena*, 92: 30–37.
- Xu J, 2014. Temporal and spatial variations in erosion and sediment yield and the cause in the ten small tributaries to the Inner Mongolia reach of the Yellow River. *Journal of Desert Research*, 34(6): 1–9. (in Chinese)
- Yang G, Ta W, Dai F *et al.*, 2003. Contribution of sand sources to the silting of riverbed in Inner Mongolia section of Huanghe River. *Journal of Desert Research*, 23(2): 152–159. (in Chinese)
- Yao H, Qin F, Shen G *et al.*, 2007. Ice regime characteristics in the Ningxia-Inner Mongolia reach of Yellow River. *Advance in Water Science*, 18(6): 893–899. (in Chinese)
- Yellow River Conservancy Commission (YRCC), 1976–1982, 2008–2012. The hydrological data in the Yellow River Basin. (in Chinese)
- Yu M, Dou S, Kong F *et al.*, 2006. Investigation on the variation of meandering channels downstream reservoirs. *Journal of Sediment Research*, (2): 77–81. (in Chinese)
- Zhang X, Su X, Zheng Y *et al.*, 2013. Features and trends of recent changes in runoff and sediment regimes in wide-valleyed desert reach of upper Yellow River. *Journal of Sediment Research*, (2): 44–51. (in Chinese)
- Zhao W, Cheng X, Hou S *et al.*, 1999. Analysis of scouring and sedimentation in the channel from Ningxia to Inner Mongolia in the upper Yellow River. *Yellow River*, 21(6): 11–14. (in Chinese)
- Zhou L, Cui Z, Luo Q, 2012. Water and sediment variation and characteristics of scouring and deposition of Ningxia-Inner Mongolian reach of the Yellow River. *Yellow River*, 34(1): 25–26. (in Chinese)