Lateral erosion/accretion area and shrinkage rate of the Linhe reach braided channel of the Yellow River between 1977 and 2014

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Abstract: Quantitative studies on river channel lateral erosion/accretion area changes over time can reveal the characteristics of channel evolution. Taking the 213-km-long Linhe reach braided channel of the Yellow River as an example, area changes in channel bank erosion/accretion in four sub-reaches (S1, S2, S3 and S4) over 19 different periods were evaluated on the basis of remote sensing images captured since 1977. Mean channel shrinkage rate for the whole river reach was also obtained. Results show that the left and right banks of the Linhe reach were dominated by lateral net accretion between 1977 and 2014. The channel area of this section of the Yellow River was characterized by reduction between 1977 and 2001, while periods of alternate erosion and accretion occurred subsequent to 2001. Mean channel shrinkage rate in the Linhe reach braided channel was 6.15 km²/yr between 1977 and 2014, while the most remarkable changes in channel planform occurred in the 1990s. Compared to 1995, channel length and sinuosity increased by 5.8% and 6.6% by 2000, while channel area and mean width decreased by 39.4% and 42.8%, respectively. Significant changes in channel planform and shrinkage of the Linhe reach occurred in the 1990s, mainly as a result of the joint-operation of the Longyangxia and Liujiaxia reservoirs since 1986, which caused substantial reductions in runoff and sediment flux during the annual flooding season. In addition, bank erosion/accretion in the four sub-reaches was affected by the physical properties of local banks, engineering emplaced to protect channel banks, and hydrodynamic differences. However, since the implementation of integrated river management measures from 2000 onwards, these changes have been significantly mitigated and the health of the Linhe reach braided channel of the Yellow River has been restored.

Keywords: channel planform geometry; river bank; erosion-accretion variation; channel shrinkage; Linhe reach; braided channel; Yellow River

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1 Introduction

Channel evolution in the Ningxia and Inner Mongolian reaches of the Yellow River is complicated and varies in both time and space (Wang *et al.*, 2014). A number of different channel patterns coexist along the length of the river which have resulted from variations in their evolution. Over recent decades, the sedimentary rate in channels has increased alongside an obvious decrease of runoff as human activities have increased. This enhanced sedimentary rate has in turn led to notable channel shrinkage and a decrease in flood flowing capacity, resulting in an increased potential for disastrous flooding affecting riverside human production and life (Zhao *et al.*, 1999; Yang and Ren, 2004; Shen *et al.*, 2007; Liu *et al.*, 2009; Ran and Wang, 2010; Wang *et al.*, 2012a, b). Because of this increased flooding risk, numerous studies have focused on channel evolution, water and sedimentary processes in the channel reaches. For example, Li *et al.* (2003) analyzed spatio-temporal variation in the Houtao reach of the Yellow River over the last 2,000 years on the basis of historical documentary records, landforms, and remote sensing images, while Yang *et al.* (2003) studied the channel bed sediments of the Inner Mongolian reach to show that 80% of sediments with grain sizes greater than 0.1 mm are aeolian sands. On this basis, they concluded that the main sources of deposited sediment in the channel bed are the Ulan Buh and Kubuqi deserts. Wang *et al.* (1996) analyzed the responses of runoff and sediment change, channel scour-fill, and channel planform evolution in the Inner Mongolian reach of the Yellow River to upstream reservoir operations. Su *et al.* (2015) also studied the impact of jointly operating reservoirs on the change ratios of channel geometry in the Inner Mongolian reach of the Yellow River, concluding that the channel in this section of the river shrunk noticeably as a result of upstream reservoirs. Wang *et al.* (2014) calculated channel bank shift rates in the Yinchuan Plain reach of the upper Yellow River by comparing the lengths of channel cross-sections visible in remote sensing images from different years. Yao *et al.* (2011, 2012) also estimated erosion area change along the river banks in the Ningxia and Inner Mongolian reaches of the Yellow River based on satellite images from different years, concluding that annual mean erosion area decreased between 1958 and 2008. Additional research has been focused on thaw flood discharge (Yang, 1992), river course changes (Wu *et al.*, 2006), channel pattern changes (Wang, 2008), the responses of channel cross-sections to flood processes (Wang and Fan, 2010), spatio-temporal variations in sediment filling capacity and sedimentation rate (Wang *et al.*, 2012a), channel hydraulic geometric changes (Ran *et al.*, 2012), and the factors influencing channel evolution (e.g., Fan *et al.*, 2010; Qin *et al.*, 2011; Li *et al.*, 2012; Shi *et al.*, 2013; Wang *et al.*, 2014) in the Ningxia and Inner Mongolian reaches of the Yellow River.

Exhibiting a typical braided channel pattern, the Linhe reach (Figure 1) is the most complicated of the channels of the upper Yellow River in terms of its evolution. Despite the fact that the well-known ‘above ground’ section of the Yellow River (the ‘hanging river’ where the river level, surrounded by dykes, is meters above ground level) is located just within the river reach, there have been relatively few studies on the channel lateral erosion/accretion area and the rate of change of the braided channel. This study focuses on channel planform changes of the Linhe reach based on 20 remote sensing images captured between 1977 and 2014. The purpose of this study is to estimate lateral erosion/accretion area and the lateral change rate of the braided channel in the Linhe river reach. This work aims to determine the main period of channel shrinkage of the braided channel, and to analyze the influence of

natural and artificial processes on channel evolution. Results have significance to our understanding of channel evolution and river management in the braided river reach.

2 Study area

The Linhe reach of the Yellow River is located between Bayangaole and Sanhuhekou gauging stations (Figure 1) and has a total channel length of 213 km, a mean channel width of 1.3 km and a channel gradient of 0.00016 (Ran and Wang, 2010). This reach of the river flows across the Hetao Plain, located between Yinshan Mountains and the northern margin of the Ordos Plateau. Exhibiting a typical braided channel pattern, the Linhe reach has both broad and shallow channels and numerous mid-channel bars (Shi *et al.*, 2013). Channel banks are mainly silty sediment with dykes common on the left bank; the sediment on the channel bed is mainly fine sands (Wang *et al.*, 1996) and no tributaries join the river reach.

Figure 1 Schematic map of the study area

The Linhe river reach is located in the periphery of the monsoonal climate region where mean annual precipitation is about 150 mm. However, the intra-annual distribution of precipitation is extremely uneven with about 75% of the total occurring between July and September (Wang *et al.*, 2014). The river surface is covered with ice from December to March each year leading to a serious spring flood when the ice begins to melt in late March (Yao *et al.*, 2007).

3 Data and methods

Compared to traditional monitoring methods, the advantages of remote sensing include rapid data collection, the potential for macro-analyses, and research spanning time periods. This technology can be used for large-scale investigations and monitoring of channel evolution (e.g., Kang and Wang, 1999; Zhong *et al.*, 2006; Nicoll and Hickin, 2010; Wang *et al.*, 2014; Su *et al.*, 2015). In this study, remote sensing images collected over a 20-year period between 1977 and 2014 were used to measure the planform geometry of the channel reach each year (Table 1). All the images used in this study were downloaded from the website of the United States Geological Survey (<http://glovis.usgs.gov/>). Resolution of the multispectral scanner system (MSS) image obtained for 1977 and the enhanced thematic mapper (ETM) images obtained for the period 2010–2014 are 60 m and 15 m, respectively, while the

resolution of the thematic mapper (TM) images downloaded for all other years is 30 m.

Channel planform geometric measurements for each year as well as channel area and channel shrinkage rate calculations for each period along the river reach were completed via GIS analysis of historical images, a well-established technique (e.g., Nanson and Hickin, 1986; Petts, 1989; Gurnell, 1997; Wellmeyer *et al.*, 2005). To reduce errors in channel bank extraction, the remote sensing images used in this study were obtained in the flooding season (June–September), and taking both wide and shallow channels into account, the riverside vegetation boundary was used to mark the channel bank. To eliminate the influence of water level fluctuations on channel width, extraction of the channel bank using the riverside vegetation boundary is a generally adopted method (e.g., Gurnell, 1997; Winterbottom, 2000; Yao *et al.*, 2012; Wang *et al.*, 2014). The channel boundary for the individual channel sections, absent of riverside vegetation, can thus be regarded as the newly formed river bank for each year.

Using the WGS84 coordinate system and Envi 5 software, remote sensing images were processed in a three-step sequence. First, to highlight the river boundary and main current information, MSS data were processed using false color synthesis of bands 5, 4, and 3, while TM and ETM data were processed using false color synthesis of bands 4, 3, and 2. Second, implementing the image processing function in the Envi software, a 1:50,000 relief map was used to correct the same name points on the 2014 image using the quadratic polynomial method, before image pixels for other years were registered based on geometric precision correction of the 2014 remote sensing image (error is controlled within 0.5 pixels). Third, the software ArcGIS 9.3 was used to digitize the river boundary, trace the channel planform for each year, and then calculate channel bank length for each year and channel area change between each time period.

Considering spatial differences in bank erosion/accretion rate that were reported by Yao *et al.* (2010) for the Inner Mongolian reach of the Yellow River, the Linhe river section studied here was divided into four sub-reaches: S1, S2, S3, and S4 along the length of the river (Figure 2), each with a channel length of 61.0 km, 42.5 km, 56.5 km and 54.0 km, respectively. Using the area differences in polygons comprising the right or left channel bank line and fixed boundaries, the lateral erosion/accretion area on both banks for the four sections in each time period was estimated. Thus, for the whole Linhe reach of the river, the lateral erosion/accretion area is the sum of the area changes of the four sub-reaches in a given period. For example, Figure 2 shows the polygons that comprise the right bank of the Linhe reach in 2014 as well as the fixed boundaries for the sub-reaches. For calculations in other years, polygons were simply changed on the right bank, while to estimate erosion/accretion area on the left bank, polygons similarly comprise sections of this bank for different years along with fixed boundaries. Thus, channel expansion/shrinkage area is the sum of the erosion/accretion area on the right and left banks along the river reach. There is a relatively low error inherent to this method for the calculation of channel expansion/shrinkage, as the polygon-bounded change in area consists of one variable, the right or left channel bank line, and a number of fixed boundaries (Figure 2), comparisons of the polygon-bounded area changes consist of just two (right and left) variable channel bank lines and given fixed boundaries.

Figure 2 Locations of sub-reaches and channel planforms in the Linhe reach of the Yellow River in 1977 and 2014

Table 1 Geometric parameters of channel planforms in the Linhe reach of the Yellow River between 1977 and 2014

Year	Channel length (km)	Channel area (km ²)	Mean channel width (km)	Channel sinuosity
1977	204.82	469.11	2.29	1.07
1988	205.63	401.44	1.95	1.07
1989	202.23	462.03	2.28	1.05
1991	206.84	391.67	1.89	1.08
1992	204.39	411.88	2.02	1.07
1993	205.75	374.60	1.82	1.07
1995	204.30	396.42	1.94	1.06
2000	216.07	240.18	1.11	1.13
2001	219.04	222.40	1.02	1.14
2002	214.35	245.71	1.15	1.12
2003	219.92	217.39	0.99	1.15
2004	213.87	241.69	1.13	1.11
2005	220.88	227.83	1.03	1.15
2006	211.65	229.91	1.09	1.10
2007	208.87	245.14	1.17	1.09
2009	210.74	278.79	1.32	1.10
2010	209.70	248.01	1.18	1.09
2011	211.10	230.92	1.09	1.10
2013	212.71	266.21	1.25	1.11
2014	213.82	241.22	1.13	1.11

To calculate channel mean width, channel area was divided by channel length. To calculate channel sinuosity, channel length was divided by valley length.

4 Results

4.1 Changes in channel planform parameters

Trends in variation in channel length and area in the Linhe reach of the Yellow River in the period between 1977 and 2014 are shown in Figure 3. Results show that channel area decreased during the period 1977–2000, fluctuated a little after 2000. Channel length fluctuated by about 205 km during the period 1977–1995, and increased markedly between 1995 and 2000. Channel length fluctuated by about 218 km during the period 2000–2005, decreased markedly in the period 2005–2007, and subsequently has increased gradually by a small amount.

Figure 3 Trends in variation of channel length and area in the Linhe reach of the Yellow River between 1977 and 2014

The channel length of the Linhe reach of the Yellow River increased by 11.77 km (from 204.3 km to 216.07 km) over the time period of this study, at a ratio of change of 5.8%. Over the same period, channel area decreased by 156.24 km² (from 396.42 km² to 240.18 km²), a ratio of change of 39.4%. Decrease in mean channel width over the study period, however, was more significant as this was reduced by 0.83 km (from 1.94 km to 1.11 km) at a ratio of change of 42.8%. Channel sinuosity for the whole Linhe reach showed a similar trend to variation in channel length; sinuosity for the whole Linhe reach increased by 0.07 (from 1.06 to 1.13) over the period between 1995 and 2000, a ratio of change of 6.6%.

Results show that a similar trend is evident in mean channel width (Figure 4a), but that there are differences between the four sub-reaches. Overall, mean channel width for the four sub-reaches decreased in the period before 2000, with the most marked reduction seen between 1995 and 2000, when the channel was the narrowest. A slight increase was seen subsequent to 2000. The greatest mean channel widths were seen in 1977 for the S3 sub-reach and in 1989 for the S1, S2, and S4 sub-reaches. The greatest mean channel width of the four sub-reaches was 2.8 km for the S2 sub-reach, while the difference in mean channel width between the four sub-reaches was greater before 2000 that it was afterwards. In addition, the extent of variation in mean channel width in the S1 and S4 sub-reaches was the smallest out of the four, especially before 1995.

Figure 4 Trends in variation of mean channel width (a) and sinuosity (b) in the Linhe reach of the Yellow River

Variations in sinuosity were more complicated than those in mean channel width for all the four sub-reaches during the period 1977–2014 (Figure 4b). Channel sinuosity for sub-reach S1 was 1.16 before 1990 and approximately 1.20 after 1990. For sub-reach S2, it showed a decreasing trend (from 1.15 to 1.06) before 1995, increased remarkably during 1995–2003 and 2011–2014, and fluctuated slightly about 1.13 during 2004–2010. For sub-reach S3, sinuosity increased remarkably during 1977–2005 (from 1.08 to 1.32), decreased during 2005–2010, and then increased during 2010–2014. For sub-reach S4, channel sinuosity was approximately 1.16 between 1977 and 1995, increased slightly during 1995–2000, was approximately 1.20 in the period 2000–2004, and was 1.16 after 2005. Variations in channel sinuosity reflect channel migration for a river reach. Variations in channel sinuosity and mean channel width of the Linhe river reach indicate the highest channel migration occurred in sub-reaches S2 and S3 and the lowest in sub-reach S4.

4.2 Variation in erosion/accretion area on the left bank

If the area of a polygon is composed of given fixed boundaries (Figure 2) and if the left or right bank in a previous year is denoted A_1 , then the area of a polygon composed of these given fixed boundaries and the left or right bank in subsequent year will be A_2 . Thus, A_2 minus A_1 is the area of lateral erosion/accretion, shown for the years of the study period in Figures 5a and 5b, for both banks and for all sub-reaches (in Figure 5a, a positive value indicates lateral erosion, while a negative value denotes lateral accretion; in Figure 5b, a positive and negative value denotes lateral accretion and erosion, respectively). Calculated lateral erosion/accretion areas of the left bank for the four sub-reaches are shown in Figure 5a, variable among the four sub-reaches at different times. Overall, net lateral accretion was the dominant process affecting the left channel bank of all sub-reaches between 1977 and 2014. Net lateral accretion areas were 143.12 km², 33.16 km², 49.59 km², 29.52 km², and 30.85 km² for the whole Linhe reach and for the four sub-reaches, S1, S2, S3, and S4, during this period, respectively. In the five years from 1995 to 2000, areas of lateral net accretion were 99.92 km², 28.34 km², 25.37 km², 13.93 km², and 32.28 km², accounting for 69.8%, 85.5%, 51.2%, 47.2%, and 104.6% of the totals during 1977–2014 for the whole Linhe reach and for

the four sub-reaches, respectively. Data show that lateral net erosion mainly occurred in five periods and that the maximum net area of lateral erosion occurred between 1988 and 1989. Net lateral erosion was 11.07 km², 17.29 km², 5.36 km², and 3.7 km², respectively, for the four sub-reaches between 1988 and 1989, while the second most extensive period of lateral erosion was between 2001 and 2002.

Figure 5 Trends in the variation of erosion or accretion area on the left channel bank (a) and the right channel bank (b) of the sub-reaches in the Linhe reach of the Yellow River between 1977 and 2014

4.3 Variation of erosion/accretion area on the right bank

Calculated areas of lateral erosion/accretion for the right bank for the four sub-reaches are shown in Figure 5b. Results show that lateral erosion/accretion areas for the right channel bank were different among the four sub-reaches in different periods. Erosion/accretion were similar to that seen on the left bank, especially as lateral net accretion was also the dominant process controlling the development of the right bank in all sub-reaches in the period between 1977 and 2014. Over the 37 years of this study, areas of lateral net accretion on the right bank were 84.77 km², 30.83 km², 8.74 km², 26.44 km², and 18.76 km² for the whole Linhe reach and for the four sub-reaches (S1, S2, S3 and S4), respectively. In the period between 1995 and 2000, areas of lateral net accretion were 17.64 km², 9.78 km², 17.36 km², and 11.55 km² for the four sub-reaches, accounting for 57.2%, 111.9%, 65.7%, and 61.6%, respectively, of the total lateral accretion area for the period between 1977 and 2014. Lateral erosion was the dominant process controlling development of the right bank in the period between 1988 and 1989; areas of erosion were 12.73 km², 3.49 km², and 8.7 km² for sub-reaches S1, S2 and S4, respectively.

4.4 Variation in channel erosion/accretion area and shrinkage rate

4.4.1 Variation in channel area

The channel area in different years for the four sub-reaches of the Linhe reach of the Yellow River are shown in Figure 6. Overall, while channel area decreased over the study period, trends can be subdivided into two time-spans, between 1977 and 2001 and between 2001 and 2014. Channel area clearly decreased between 1977 and 2001, while it either fluctuated or increased slightly between 2001 and 2014.

Figure 6 Trends in channel area variation for the different sub-reaches of the Linhe reach of the Yellow River

The area of channel erosion/accretion during a given time period can be calculated by subtracting the channel area in the first year in the period from the channel area in the last year (a positive value thus indicates channel lateral erosion, while a negative value indicates channel lateral accretion). Calculated areas of channel lateral erosion/accretion for the different time periods of this study are listed in Table 2 and illustrated in Figure 7a. In the period between 1977 and 2000, channel lateral accretion and erosion occurred alternately with just small variations in the four sub-reaches, especially in S1 and S2 (Figure 7a). Changes in channel area over the periods 1977–1988, 1988–1989, 1989–1991, and 1995–2000 for the whole Linhe reach were -67.67 km^2 , 60.59 km^2 , -70.35 km^2 , and -156.25 km^2 , respectively (Table 2), and lateral accretion was the dominant process between 1977 and 2014. Results show that cumulative areas of channel lateral accretion for sub-reaches S1, S2, S3, and S4, as well as the whole Linhe reach over the entire study period were 63.98 km^2 , 58.34 km^2 , 55.96 km^2 , 49.61 km^2 , and 227.89 km^2 , respectively. In the period between 1995 and 2000 areas of channel lateral accretion were 45.98 km^2 , 35.15 km^2 , 31.28 km^2 , and 43.83 km^2 for the four sub-reaches, and 156.25 km^2 for the whole Linhe reach, accounting for 71.87%, 60.25%, 55.91%, 88.35%, and 68.56%, of the totals for the entire period.

4.4.2 Rate of channel area change

The rate of change of channel area was obtained using channel net erosion/accretion area for a given period (unit year) divided by year. Thus, erosion/accretion rate data for the channel areas of the four sub-reaches and the whole Linhe reach are listed in Table 2, and variations in channel erosion/accretion rate for the four sub-reaches in the period between 1977 and

Table 2 Area and rates of channel lateral erosion (positive values) or accretion (negative values) for the sub-reaches of the Linhe reach of the Yellow River

Years	Erosion/accretion area (km ²)					Erosion/accretion rate (km ² /yr)				
	S1	S2	S3	S4	Linhe reach	S1	S2	S3	S4	Linhe reach
1977–1988	–16.97	–24.60	–20.16	–5.93	–67.67	–1.54	–2.24	–1.83	–0.54	–6.15
1988–1989	23.80	20.78	3.61	12.40	60.59	23.80	20.78	3.61	12.40	60.59
1989–1991	–33.22	–20.98	–11.46	–4.69	–70.35	–16.61	–10.49	–5.73	–2.35	–35.18
1991–1992	8.83	1.27	4.02	6.08	20.20	8.83	1.27	4.02	6.08	20.20
1992–1993	–8.10	–4.76	–8.22	–16.20	–37.28	–8.10	–4.76	–8.22	–16.20	–37.28
1993–1995	10.63	9.62	–0.05	1.62	21.83	5.32	4.81	–0.02	0.81	10.91
1995–2000	–45.98	–35.15	–31.28	–43.83	–156.25	–9.20	–7.03	–6.26	–8.77	–31.25
2000–2001	–4.82	–5.53	–0.49	–6.94	–17.78	–4.82	–5.53	–0.49	–6.94	–17.78
2001–2002	4.76	5.84	0.85	11.85	23.31	4.76	5.84	0.85	11.85	23.31
2002–2003	–4.96	–6.06	0.32	–17.63	–28.32	–4.96	–6.06	0.32	–17.63	–28.32
2003–2004	6.21	4.69	4.79	8.61	24.30	6.21	4.69	4.79	8.61	24.30
2004–2005	–9.07	–2.96	3.16	–4.98	–13.86	–9.07	–2.96	3.16	–4.98	–13.86
2005–2006	4.04	1.02	–3.91	0.94	2.08	4.04	1.02	–3.91	0.94	2.08
2006–2007	6.91	–0.57	7.34	1.56	15.23	6.91	–0.57	7.34	1.56	15.23
2007–2009	4.37	3.49	8.69	17.10	33.65	2.19	1.74	4.34	8.55	16.82
2009–2010	–4.97	–5.02	–2.12	–18.67	–30.78	–4.97	–5.02	–2.12	–18.67	–30.78
2010–2011	–9.37	–3.38	–11.71	7.37	–17.10	–9.37	–3.38	–11.71	7.37	–17.10
2011–2013	11.35	13.72	8.01	2.22	35.29	5.67	6.86	4.00	1.11	17.65
2013–2014	–7.42	–9.76	–7.33	–0.47	–24.99	–7.42	–9.76	–7.33	–0.47	–24.99
1977–2014	–63.98	–58.34	–55.96	–49.61	–227.89	–1.73	–1.58	–1.51	–1.34	–6.16

2014 are shown in Figure 7b. Results show that the channel erosion/accretion rate for sub-reaches S1 and S2 was faster before 2000 than afterwards, especially in the periods between 1988 and 1989 and 1989 and 1991. During these time periods, the erosion rate was 23.8 km²/yr and –16.61 km²/yr, and 20.78 km²/yr and –10.49 km²/yr, for sub-reaches S1 and S2, while in other time periods, channel erosion and accretion rates fluctuated around 5 km²/yr. In contrast, the channel erosion/accretion rate for sub-reaches S3 and S4 was lower before 2000 than afterwards when the whole time period is taken into account (Figure 7b). The average rate of change in channel area for sub-reach S3 was approximately 4.3 km²/yr and 4.2 km²/yr before, and after, 2000, while in sub-reach S4 these rates were 6.7 km²/yr and 7.4 km²/yr, respectively.

For sub-reaches S1, S2, S3, and S4, average channel erosion rates were 12.65 km²/yr, 8.95 km²/yr, 3.81 km²/yr, and 6.43 km²/yr during the period 1977–2000 and 4.96 km²/yr, 4.03 km²/yr, 3.54 km²/yr, and 5.71 km²/yr during the period 2000–2014, respectively. In contrast, average accretion rates for the channel were 8.86 km²/yr, 6.13 km²/yr, 4.41 km²/yr, and 6.96 km²/yr during the period 1977–2000, and 6.77 km²/yr, 4.76 km²/yr, 5.11 km²/yr, and 9.74 km²/yr during the period 2000–2014. The average accretion rate was greater in the period 1977–2000 than in the period 2000–2014, while overall this was the largest in sub-reach S4 and the lowest in sub-reaches S2 and S3.

The rate of change in channel area was commonly larger over relative short periods of time than over longer periods (Figure 7a). Indeed, for the whole of the Linhe reach, the

Figure 7 Trends in variation of channel lateral erosion/accretion area (a) and channel lateral erosion/accretion rate (b) for the sub-reaches of the Linhe reach in the period between 1977 and 2014

greatest rate of change in channel area occurred between 1988 and 1989 ($60.58 \text{ km}^2/\text{yr}$), while the least rate of change occurred between 1977 and 1988 ($-6.15 \text{ km}^2/\text{yr}$). Average channel accretion rates for the whole Linhe reach and the four sub-reaches were $6.16 \text{ km}^2/\text{yr}$, $1.73 \text{ km}^2/\text{yr}$, $1.58 \text{ km}^2/\text{yr}$, $1.51 \text{ km}^2/\text{yr}$, and $1.34 \text{ km}^2/\text{yr}$, respectively, while the average channel rate of change for the four sub-reaches was below $2 \text{ km}^2/\text{yr}$ between 1977 and 1988, and less than $5 \text{ km}^2/\text{yr}$, the average rate of change, between 2000 and 2014. In particular, between 1995 and 2000, average channel accretion rates for the four sub-reaches were $9.2 \text{ km}^2/\text{yr}$, $7.03 \text{ km}^2/\text{yr}$, $6.26 \text{ km}^2/\text{yr}$, and $8.77 \text{ km}^2/\text{yr}$, all slightly larger than the rate of change for these channels, respectively.

5 Discussion

Variations in water and sediment discharge are the main factors causing dynamic channel deformation in a river, although the discharge of entire banks in the flooding season can cause the greatest changes. Thus, the composition of materials in the channel bed and banks are subordinate factors controlling changes in channel morphology. The processes of interaction between silt-laden water flows and channel boundaries lead to channel deformation in a river, and human intervention has gradually increased alongside the social and economic development. For instance, construction of a river embankment will change the resistance to erosion of a river channel, while construction of dams and reservoirs, and water and soil conservation measures in a watershed change the water and sediment processes of a river, affecting channel change processes and deformation rates.

Clear changes in channel planform in the Linhe reach of the Yellow River occurred over the 37 years of this study, influenced by water and sediment changes, different channel erosion resistance, and variation in water power. For example, Figures 3 and 8 show that channel length in the Linhe reach has decreased as runoff has increased alongside the load of suspended sediment at Bayangaole gauging station. Channel area has also increased with runoff and decreased with increasing suspended sediment load at the station. These results are consistent with the relationship reported by Yao *et al.* (2012) between channel morphological changes in the Inner Mongolian reach of the Yellow River and water and sediment variations at the Qingtongxia gauging station.

In the Linhe river reach, channel banks are composed of silty sediment while a stone embankment has been intermittently constructed on the left bank, mid-channel bars are developed, and the main flow line often swings laterally. The channel reach in this section of the Yellow River exhibits a typical braided pattern (Ran and Wang, 2010). Results show that the total area of channel accretion in the Linhe reach between 1977 and 2014 was 227.89 km², and that the accretion areas of the left and right banks were 143.12 km² and 84.77 km², respectively. These data indicate that the channel of this river section has shrunk markedly over the last 37 years, and that in addition, the area of shrinkage of the left bank has been larger than that of the right bank, so as a whole the mid-river line has been displaced the right. This shrinkage trend has mainly been influenced by a decreasing discharge of water and sediment in the flooding season, controlled by the operation of upstream reservoirs and bank protection works. Of the four sub-reaches of the Linhe reach, the river channel is the broadest and swings strongly in sub-reaches S2 and S3 (Figure 4) as the channel banks in these sections have a relative lower resistance to erosion and high energy consumption because of shallow and dispersive flow. Because the entrance to sub-reach S1 is at the Bayangaole station, 422 m below the Sanshenggong reservoir, the channel swing in the S1 sub-reach is relatively small because water discharged from the reservoir cannot easily be diffused and river bank protection is strong. In contrast, channel swing for sub-reach S4 is the least because this section is located at the end of the Linhe reach, so it has the weakest flow power.

The rate of change of channel area in the periods 1977–1988 and 1977–2014 was 6.15 km²/yr and 6.16 km²/yr, respectively, far less than that which has occurred over short periods of one or two years (Table 2), because it is related to channel to-and-fro swing over long periods. The total channel accretion areas in these two periods were 67.67 km² and 227.89 km², respectively, clearly demonstrating that the channel in the Linhe reach of the Yellow River has shrunk overall.

Figure 8 Temporal variations in annual mean runoff and sediment load measured at Bayangaole gauging station

For the whole of the Linhe river reach, channel accretion area and rate of change were 156.25 km² and 31.25 km²/yr over the five years from 1995 to 2000, while channel accretion rates were 60.59 km²/yr and 35.18 km²/yr from 1988 to 1989 and from 1989 to 1991, re-

spectively. Clearly, while joint operation of upstream reservoirs resulted in substantial channel shrinkage in the 1990s (Wang *et al.*, 2014), the channel lateral erosion/accretion rate before 1990 was slightly greater than that after 1990 (Figures 5 and 6) and the channel net accretion area in the 1990s was far greater than that seen in the periods before 1990 and after 2000. Joint operation of the Longyangxia and Liujiaxia reservoirs since 1986 has decreased water volume and the load of suspended sediment in the flooding seasons, increased water volume in the non-flooding seasons for the river channel below the reservoirs, and decreased the peak flood flow (Wang *et al.*, 1996; Shen *et al.*, 2007). Operation of these reservoirs is the primary reason for substantial adjustments in channel planform and critical shrinkage in the Linhe river reach. Following improvements to the reservoir joint operation system implemented to reduce the influence of the dried up lower Yellow River since 2000, the intensity of channel lateral erosion/accretion in the Linhe river reach decreased.

6 Conclusions

The channel planform parameters of the Linhe reach of the Yellow River were different before, and after, 2000, as evidenced by the data presented here from the period 1977–2014. Dramatic changes were seen between 1995 and 2000; relative to 1995, channel length and sinuosity increased 5.8% and 6.6%, respectively, while channel area and mean width decreased 39.4% and 42.8% in 2000, respectively. For the four sub-reaches (S1, S2, S3, and S4) of the Linhe reach of the Yellow River discussed here, the clearest and most marked changes in channel planform were seen in the middle two sub-reaches (S2 and S3).

Lateral net accretion of both the left and the right banks of the Linhe reach of the Yellow River characterizes the period 1977–2014. Lateral net accretion of a channel can lead to shrinkage; the average shrinkage rate of channels in the river reach studied here was 6.15 km²/yr over the whole period. For the four sub-reaches of the Linhe reach in the period 1995–2000, lateral accretion areas of the left bank were 33.16 km², 49.59 km², 29.52 km², and 30.85 km², accounting for 85.5%, 51.2%, 47.2%, and 104.6% of the total accretion area of the whole period, respectively. Over the same period, the lateral accretion areas of the right bank were 30.83 km², 8.74 km², 26.44 km², and 18.76 km², accounting for 57.2%, 111.9%, 65.7%, and 61.6% of the total accretion area, respectively.

Between 1997 and 2014, the channel of the Linhe reach of the Yellow River shrunk overall. At the same time, lateral accretion has led to a remarkable decrease in channel area, as well as an increase in channel sinuosity and a slight increase in channel length. Over the 1990s, changes in channel planform parameters for this river reach exceeded 50% of all changes seen during the whole period 1977–2014. These changes have been caused by a decrease of water and suspended sediment load during the annual flooding season because of the joint operation of the upstream Liujiaxia and Longyangxia reservoirs since 1986. However, since 2000, as a result of the implementation of integrated river management measures, these changes have been significantly mitigated and the health of the Linhe reach braided channel of the Yellow River has been restored.

References

- Fan X, Wang S, Ran L, 2010. Analysis of the channel evolution and influence factors in Ningxia reach of the Yellow River. *Journal of Water Resources & Water Engineering*, 21(1): 5–11. (in Chinese)

- Gurnell A M, 1997. Channel change on the River Dee meanders, 1946–1992, from the analysis of air photographs. *Regulated Rivers-Research & Management*, 12: 13–26.
- Kang Q, Wang X, 1999. Application of remote sensing technology in riverbed changes. *Acta Scientiarum Naturalium Universitatis Sunyatseni*, 38(5): 109–113. (in Chinese)
- Li B, Ge Q, Zheng J, 2003. Evolution of the Yellow River in the Houtao Plain of Inner Mongolia in the past 2000 years. *Acta Geographica Sinica*, 58(2): 239–246. (in Chinese)
- Li Q, Cai Q, Fang H, 2012. Channel evolvement and influence factors in the Ningxia-Inner Mongolia reach of the Yellow River. *Journal of Arid Land Resources and Environment*, 26(2): 68–73. (in Chinese)
- Liu X, Hou S, Chang W, 2009. Cause of main channel shrinkage occurred to the Inner-Mongolia reaches of Yellow River. *Journal of Hydraulic Engineering*, 40(9): 1048–1054. (in Chinese)
- Nanson G C, Hickin E J, 1986. Statistical analysis of bank erosion and channel migration in western Canada. *Geological Society of America Bulletin*, 97: 497–504.
- Nicoll T J, Hickin E J, 2010. Planform geometry and channel migration of confined meandering rivers on the Canadian prairies. *Geomorphology*, 116: 37–47.
- 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, 2010. Study on channel evolution and hydraulic geometry in the Inner Mongolia reach of the Yellow River. *Journal of Sediment Research*, 4: 61–67. (in Chinese)
- Ran L, Wang S, Fan X, 2010. Channel change at Toudaoguai Station and its responses to the operation of upstream reservoirs in the upper Yellow River. *Journal of Geographical Sciences*, 20(2): 231–247.
- Ran L, Wang S, Lu X, 2012. Hydraulic geometry change of a large river: A case study of the upper Yellow River. *Environmental Earth Sciences*, 66: 1247–1257.
- 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)
- Su T, Wang S, Mei Y et al., 2015. Comparison of channel geometry changes in Inner Mongolian reach of the Yellow River before and after joint operation of the upstream large reservoirs. *Journal of Geographical Sciences*, 25(8): 930–942.
- Wang S, 2008. Analysis of river pattern transformations in the Yellow River Basin. *Progress in Geography*, 27(2): 10–17. (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, 2014. 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 Y, Li Y, 2012a. 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.
- Wang S, Yan M, Yan Y et al., 2012b. 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 Y, Feng X, Wang L et al., 1996. Influence of reservoirs in the trunk channel of the upper Yellow River on the reach within Inner Mongolia Autonomous Region. *Yellow River*, 1: 5–10. (in Chinese)
- Winterbottom S, 2000. Medium and short-term channel planform changes of the Rivers Tay and Tummel, Scotland. *Geomorphology*, 34: 195–208.
- Wu J, Wang R, Yao J, 2006. Remote sensing monitoring and study on the change of the Yellow River course in Yinchuan Plain sector. *Remote Sensing for Land & Resources*, (4): 36–39. (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)
- Yang L, 1992. Analysis of the thaw flood discharge in the Ningxia-Neimenggu reach of the Yellow River. *Journal of Sediment Research*, (6): 62–68. (in Chinese)
- Yang Z, Ren H, 2004. Preliminary study on scour-silting and the water-sand relationship in the Ningxia-Inner Mongolia reach of Yellow River. *Northwest Hydropower*, 3: 50–55. (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)
- Yao Z, Ta W, Jia X et al., 2011. Bank erosion and accretion along the Ningxia-Inner Mongolia reaches of the Yellow River from 1958 to 2008. *Geomorphology*, 127: 99–106.
- Yao Z, Xiao J, Ta W et al., 2012. Planform channel dynamics along the Ningxia-Inner Mongolia reaches of the Yellow River from 1958 to 2008: Analysis using Landsat images and topographic maps. *Environ. Earth Sci.*, 70: 97–106.
- 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)
- Zhong K, Liu W, Huang J, 2006. A riverway evolution analysis based on remote sensing technique: A case study of the lower reaches of the Beijiing River. *Remote Sensing for Land & Resources*, (3): 69–73. (in Chinese)