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Analysis of the contribution of multiple factors to the recent decrease in discharge and sediment yield in the Yellow River Basin, China

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Abstract: The Yellow River basin is well known for its high sediment yield. However, this sediment yield has clearly decreased since the 1980s, especially after the year 2000. The annual average sediment yield was 1.2 billion tons before 2000, but has significantly decreased to 0.3 billion tons over the last 10 years. Changes in discharge and sediment yield for the Yellow River have attracted the attention of both the Central Government and local communities. This study aimed to identify the individual contributions of changes in precipitation and human activities (e.g. water conservancy projects, terracing, silt dams, socio-economic and needs, and soil and water conservation measures) to the decrease in discharge and sediment yield of the Yellow River. The study used both improved the hydrological method and the soil and water conservation method. The study focused on discharge analysis for the upper reaches and the investigation of sediments for the middle reaches of the river. The results showed that discharge and sediment yield have both presented significant decreasing trends over the past 50 years. Precipitation showed an insignificant decreasing trend over the same period. The annual average discharge decreased by 5.68 billion m^3 above Lanzhou reach of the Yellow River from 2000 to 2012; human activities (e.g. socio-economic water use) contributed 43.4% of the total reduction, whereas natural factors (e.g. evaporation from lakes, wetlands and reservoirs) accounted for 56.6%. The decrease in annual discharge and sediment yield of the section between Hekouzhen station and Tongguan station were 12.4 billion m^3 and 1.24 billion tons, respectively. Human activities contributed 76.5% and 72.2% of the total reduction in discharge and sediment yield, respectively, and were therefore the dominant factors in the changes in discharge and sediment yield of the Yellow River.

Keywords: human activities; soil and water conservation; climate change; discharge and sediment yield; Yellow River, China

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1 Introduction

The Yellow River is known to carry a large amount of silt. The basin has an annual sediment yield of 1.6 billion tons with a sand content of 37.4 kg/m^3, which is 25% higher than that of the Grand Canyon of the Colorado River in the USA (WCHEE, 1981). The discharge and sediment yield of the Yellow River have decreased since the 1980s (Yao *et al*., 2013). The relationship between discharge and sediment yield also changed during this period, which has led to problems in water use and flood control. As a result, the research foundation of the Ministry of Water Resources implemented two research projects to examine the changes in discharge and sediment yield in the Yellow River (Wang and Fan, 2002a, 2002b). Many researchers have assessed the decrease in discharge and sediment yield caused by soil and water conservation, determined the relative impact of various causal factors, and predicted future changes in discharge and sediment yield (Xu and Niu, 2000; Zhang *et al*., 1998; Ran *et al*., 2000; Du *et al*., 2014). These studies provided baseline data for water use and control and the implementation of large water conservation projects. Based on observational data for water discharge and sediment load from 15 hydrological stations in the Yellow River Basin (YRB), Miao *et al*. (2010) applied the Mann–Kendall method to examine the causes of the changes in water and sediments from 1950 to 2000. They determined that the significant change in the water discharge from 1980 to 1990 can be attributed to human activities and that the significant change in the sediment yield was associated with reservoir construction. Wang *et al*. (2007) applied mathematical statistics to comparatively examine the cause of the gradual decrease in discharge and sediments in the Yellow River during the period 1950–2005 based on measurement data on water discharge, sediment load and rainfall data from four hydrological stations on the main branch of the Yellow River. Miao *et al.* (2011) investigated the contribution of climate change and human activity to the decrease in water in the upper Yellow River by reconstructing a time series for natural water and sediments from 1960 to 2008. Wang *et al*. (2013a) investigated contribution of human activities and climatic change to the change in discharge of the Kuyehe River using a hydrological simulation approach and showed that human activities (i.e. soil and water conservation measures) played a principal part in the reduction in discharge.

Water discharge and sediment yield in the Yellow River have recently decreased against the background of climate change and intensified human activities (Wang *et al*., 2013b). For example, the annual sediment yield from 2000 to 2010 was less than 18% of the annual total before 1986. These unexpected decreases in discharge and sediment yield in the Yellow River have attracted much attention (Fan *et al*., 2008; Gao *et al*., 2008; Yao *et al*., 2009). However, there have been few systematic evaluations of the variations in discharge and sediment yield in the Yellow River since 2000. In addition, the effect of rainfall intensity has not been fully taken into account. In the work reported here, surveying and modelling techniques were used to characterize the variations in discharge and sediment yield in the YRB during the period 2000–2012 and to identify the causal factors of these changes. In addition, the effects of soil and water conservation efforts and rainfall on the variation in discharge and sediment yield were also estimated. This study may be helpful in understanding the complex mechanisms driving variations in discharge and sediment yield in the Yellow River basin.

2 Study area

The upper reach above Lanzhou station and the Hekouzhen–Tongguan section in the middle reaches of the Yellow River were chosen as the study area. Discharge from the upper reaches above Lanzhou city (the river source area) contributes the largest proportion of discharge in the Yellow River, whereas most of the sediment load comes from Hekouzhen–Tongguan in the middle reaches. The upper reaches above Lanzhou have an area of 222,500 km^2 and occupy 28% of the YRB (Figure 1). The source area above Lanzhou is the main discharge area and occupies approximately 16% of the YRB, providing 40% (20.52 billion m^3) of the discharge in the Yellow River. The elevation in the river source area ranges from 4000 to 5000 m and the dominant landform types are wide valleys and fluvio-lacustrine basins. The dominant landforms from Maduo County to Gonghe County are characterized by high mountains and deep gorges; some wide valleys, lakes, marshy ground, steppe desert and alpine meadows are also found in this region. The total area of wetlands is 15,012 km^2 and includes the Xingxiu Lake, Zhaling Lake, Eling Lake, Maduo, Requ, Shouqu and Ruoergai regions. The annual precipitation in the basin is 485.9 mm and the evaporation rate ranges from 1200 to 1600 mm per year in the source area. The Huangshui and Taohe rivers are two tributaries that flow into the Yellow River above Lanzhou. The Huangshui river basin, with an area of 32,900 km^2, is high in the west and low in the east; it has a typical continental climate. The Taohe river basin, with an area of 25,500 km^2, is located in a transitional zone to the Qinghai–Tibet Plateau and its upper, middle and lower reaches have alpine moist, temperate semi-humid and temperate semi-arid climates, respectively.

The Hekouzhen–Tongguan section in the middle Yellow River drains an area of 314,400 km^2, which contributes 90% of the sediment yield of the YRB (Figure 1). The section is also the main source of coarse sand (grain size>0.05 mm), accounting for 94.6% of the total

Figure 1 Map of the upper and middle reaches of the Yellow River Basin

amount of the coarse sand in the lower Yellow River. It contains both controlled and uncontrolled areas. The controlled areas are branches of the river above the hydrological station; the remaining basin area is uncontrolled (23.3% of the total drainage area of the Hekouzhen–Tongguan section). There is no observational data for the discharge and sediment yield in the uncontrolled areas, except for data from a few rainfall gauge stations.

3 Data collection and methods

3.1 Data

Soil erosion control practices have been implemented in the YRB since the 1950s. The current area of soil and water conservation measures above Tongguan station is about 147,400 km^2. Table 1 lists the various soil and water conservation measures taken between 2000 and 2012.

Table 1 Areas of soil and water conservation measures above Tongguan station

Year	Total area (hm^2)				
	Terraces	Afforestation	Planted grass	Silt dam land	Restoration of vegetation
2000	2989583	5439562	1129242	185125	703025
2001	3018006	5626139	1180396	186576	744286
2002	3127109	5942315	1251785	195022	901574
2003	3187173	6353727	1340012	199600	973949
2004	3249599	6688022	1400168	204215	938409
2005	3315377	6930351	1455666	209275	1040659
2006	3376576	7124452	1510179	211742	1004843
2007	3408842	7318927	1510064	214437	1011252
2008	3415145	7383969	1881860	214139	1014532
2009	3423730	7471440	2102674	206366	1014687
2010	3458880	7487907	2330178	195264	1014842
2011	3472442	7222939	2512108	186180	1009897
2012	3493737	7467613	2578059	184708	1018281

The sources of data for the soil and water conservation measures used in this study included statistics from all levels of government, including statistical yearbooks from provincial (local) governments in the upper and middle reaches of the Yellow River, the Yellow River Basin Commission and other concerned departments. This study used statistical data about soil and water conservation at the municipal and county level in Shaanxi, Shanxi, Gansu, Inner Mongolia, Ningxia and other provinces (regions), the *Basic Soil and Water Conservation Data of Yellow River* published by the Middle Yellow River Conservancy Bureau since 2000 and comprehensive management details and complete summaries from 459 watersheds in the middle reaches of Yellow River. Satellite images of the Huangfuchuan River at a resolution of 0.36 m from 2006 and the Gushanchuan River at a resolution of 1 m in 2002 were used to acquire information on soil and water conservation and land use. The first national water census data in 2011 was also used. The lack of statistical data for some of the years was overcome by the interpolation of annual trends based on the data from the first national water census. Based on these data, combined with field surveys, the interpretation of remote sensing images, verification of the sample areas, expert advice and other data collection methods in 25 typical small watersheds, such as the Huangfuchuan, Yanhe, Wudinghe and Beiluohe tributaries and 39 typical sample areas, we obtained data for the whole area of soil and water conservation from 2000 to 2012.

Temperature, evaporation, precipitation, and discharge data were collected in the source area (at Huangheyan, Jimai, Maduo, Maqu, and Tangnaihai stations) from 1950 to 2010. Daily precipitation, discharge, and sediment yield data were used in this study.

3.2 Methods

3.2.1 Estimation of sediment yield for controlled areas

The 'hydrological method' and the 'soil and water conservation (SWC) method' (Zhang *et al.*, 1994) were used to estimate the sediment yield from the controlled areas. The hydrological method was also used to establish the relationships among precipitation, discharge, and sediment yield before the implementation of control measures. The sediment yield after the implementation of control measures was estimated using the model based on data from the corresponding time period. The difference between the simulated and observed sediment yield represents sediment reduction resulting from the control measures. The amount of rainfall has typically been used as the main predictor variable in previous sediment yield models. Infiltration excess overflow is the main type of discharge in most parts of the Loess Plateau. Therefore the intensity of rainfall is important for the generation of discharge and sediment yield. In general, 80% of the total precipitation occurs during the flood season (from May to September) across most of the Loess Plateau. The intensity of rainfall during the flood season was therefore selected as a predictor in the simulation model for discharge and sediment yield.

The Hekouzhen–Tongguan section is composed of hilly–gully regions, tableland gully area and sandy areas of the Loess Plateau. The topography, soils, geological and hydrological conditions and soil erosion differ greatly, with different controls on the generation of discharge and sediment yield. Statistical analysis of the hydrology and the observed sediment data of 25 tributaries showed that the discharge and sediment generation models of the Hekouzhen–Longmen section and the Longmen–Tongguan section were different, so different discharge and sediment yield simulation models were established to examine these two sections. The model equations were as follows.

For the Hekouzhen–Longmen section:

$$Y = KP^{\alpha_1} I_i^{\alpha_2} (1 + F_i / F_0)^{\alpha_3} \tag{1}$$

where Y is the simulated object, such as the discharge yield (W) or the sediment yield (W_S); K is the discharge coefficient or the sediment yield coefficient; P is the average rainfall in the computation region (mm); I_i is the rainfall intensity (mm/min), corresponding to various degrees of concentration for the centre of heavy rainfall (40%, 50%, 60%, 70%, 80%, 90%, and 100%); F_i is the enclosed area (km^2) for various rainfall contours (i=10, 25, 50, and 75 mm); F_0 is the total area of the study cell (km^2); and α_1, α_2, and α_3 are indexes.

For the Fenhe River:

$$W = K_W (P_a + KP_{a-1})^{\beta_5} \tag{2}$$

$$W_s = K_s \left(\frac{\overline{W}_{s1}}{\overline{W}_{sa}} \frac{P_1}{\overline{P}_1} + \frac{\overline{W}_{s30} - \overline{W}_{s1}}{\overline{W}_{sa}} \frac{P_{30}}{\overline{P}_{30}} + \frac{\overline{W}_{sf} - \overline{W}_{s30}}{\overline{W}_{sa}} \frac{P_f}{\overline{P}_f} + \frac{\overline{W}_{sa} - \overline{W}_{sf}}{\overline{W}_{sa}} \frac{P_a}{\overline{P}_a} \right)^{\beta_6} \tag{3}$$

For the Beiluohe River:

$$W = K_W \left[P_f \left(\frac{P_1}{P_f} \right)^{\beta_7} + P_k^{\beta_8} \right] + b \tag{4}$$

$$W_s = K_s \left(\frac{\overline{W}_{s1}}{\overline{W}_{sa}} \frac{P_1}{\overline{P}_1} + \frac{\overline{W}_{s30} - \overline{W}_{s1}}{\overline{W}_{sa}} \frac{P_{30}}{\overline{P}_{30}} + \frac{\overline{W}_{sf} - \overline{W}_{s30}}{\overline{W}_{sa}} \frac{P_f}{\overline{P}_f} + \frac{\overline{W}_{sa} - \overline{W}_{sf}}{\overline{W}_{sa}} \frac{P_a}{\overline{P}_a} \right)^{\beta_9} \tag{5}$$

For the Weihe River and Jinghe River:

$$W = K_W P_a^{\beta_{10}} \tag{6}$$

$$W_s = K_s W_f^{\beta_{11}} \tag{7}$$

where K_W and K_s are the discharge coefficient and the sediment yield coefficient, respectively; $\beta_1 \ldots \beta_{11}$ are constants to be determined; P_a is the annual precipitation; P_f is the total precipitation from May to September; W is the discharge; W_s is the sediment yield; $\overline{W}_{s1}$ is the annual maximum daily sediment yield; $\overline{W}_{s30}$ is the annual maximum monthly sediment yield; $\overline{W}_{sf}$ is the sediment yield for the flood season; $\overline{W}_{sa}$ is the annual mean sediment yield; $\overline{P}_1$ is the annual maximum daily precipitation; $\overline{P}_{30}$ is the annual maximum monthly precipitation; $\overline{P}_f$ is the precipitation for the flood season; $\overline{P}_a$ is the annual mean precipitation; P_k is the precipitation for the non-flood season; b is the base flow; P_1 is the maximum daily precipitation for the current year; P_{30} is the maximum monthly precipitation for the current year; P_{a-1} is the precipitation for the previous year; and K is the coefficient of antecedent precipitation. These relationships were validated using observations from the earliest year for which records were available before 1970 (mostly during the 1950s). The results showed that the correlation coefficient (r) was >0.8 for all of the rivers except for the Beiluohe River ($r = 0.7$). The ‘hydrological method’ was mainly used to estimate the contributions of rainfall and human activities to changes in discharge and sediment for the different regions.

The SWC method is based on observations from field experiments. Reductions in discharge and sediment yield resulting from SWC measures are measured in the field and the total reductions in both are obtained by summing the reductions for each measure. The impacts on sediment yield of human activities and scour–deposition process in the channel are also considered. The effects of the SWC measurements on the reductions in discharge and sediment yield are then estimated. Based on the index selection procedures, the SWC measure consists of two methods: the index method and the ‘estimate sediment by flood’ method. The index method compares discharge and sediment yield observations from soil erosion experiments in a small plot, a standard plot (20 m × 5 m), and a reference plot. The reductions in discharge and sediment are determined for the unit area and are corrected for scale effects. The reductions in discharge and sediment yield are estimated for each SWC measure by multiplying the reductions by a given number for each measurement. The reductions for each SWC measure are then summed to estimate the total reductions in discharge and sediment yield for all SWC measures. The 'estimate sediment by flood' method establishes an index system for determining the reductions in discharge from SWC measures in areas of steep topography by comparing controlled and reference areas using a standard plot. The reduction in discharge from SWC measures on the sloping land is estimated by conducting flood frequency analysis and the flood–sediment yield relationship is established. Both methods were used for comparison in this study. The index method was used to investigate the individual contribution of different anthropic drivers to changes in discharge and sediment yield.

3.2.2 Estimation of sediment yield in uncontrolled areas

The sediment yield was estimated for the size of the uncontrolled area for each sub-catchment of the Yellow River. For each sub-catchment, the annual precipitation, discharge depth, annual sediment yield, and sediment yield for the flood period were estimated based on the corresponding isograms. The mean precipitation, discharge, and sediment yield for the uncontrolled areas for the different periods were estimated using the area-weighted average method. Using these values, the decreases in discharge and sediment yield were estimated using the relationships determined for the controlled areas.

4 Results and discussion

4.1 Decreases in discharge and sediment yield in the Yellow River basin

Annual discharge and sediment yield for the main hydrological stations showed a significant decreasing trend over the past 50 years. The discharge in the Yellow River has decreased significantly, especially since 1986, even though the precipitation has not decreased. The annual average sediment yield was 1.2 billion tons before 2000, but has sharply decreased to 0.3 billion tons over the last 10 years.

4.1.1 Variations in precipitation

There was a clear spatial variation in precipitation in the study area. For example, the precipitation for the period 2000–2012 increased by 2.2% compared with precipitation (475.5 mm) in the reference period 1954–1969 in the reach above Lanzhou and the precipitation increased by 4.8% compared with the reference period in the reach above Tangnaihai. However, there was no change in precipitation between Tangnaihai and Lanzhou. The northern part of Shaanxi province in the section between Hekouzhen and Tongguan (the Huangfuchuan, Gushanchuan, Kuyehe, Tuweihe and Jialuhe rivers) had an annual precipitation of 419.8 mm in the reference period; the precipitation was 325.8 and 223.5 mm in the periods June–September and July–August, respectively. The average annual precipitation was 393.8 mm in northern Shaanxi during 2000–2012, a decrease of 6.2% compared with the reference period, and it decreased by 10.6% and 17.7% compared with that in June–September and July–August.

Southern Shaanxi (the Wudinghe, Qingjianhe and Yanhe rivers) had an annual precipitation of 444.5 mm in the reference period; the precipitation was 316.7 and 200.6 mm in June–September and July–August. The average annual precipitation was 464.9 mm in the period 2000–2012, an increase of 4.6% compared with the reference period, and the precipitation increased by 7.8% and 0.7% compared with the reference period in June–September and July–August.

Western Shanxi (the Hunhe, Pianguanhe, Zhujiachuan, Weifenhe, Qiushuihe, Sanchuanhe, Quchanhe and Xinshuihe rivers) had an annual precipitation of 508 mm in the reference period, and the precipitation was 373.3 and 248.2 mm in June–September and July–August. The average annual precipitation was 478.1 mm during the period 2000–2012, a decrease of 6% compared with the reference period, and the precipitation decreased by 9.9% and 20.0% compared with the reference period in June–September and July–August, respectively.

The Longmen–Tongguan section (the Jinghe, Beiluohe, Weihe and Fenhe rivers) had an annual precipitation of 554.8 mm in the reference period; the precipitation was 362.0 and 212.5 mm in June–September and July–August. The average annual precipitation was 530.9 mm during the period 2000–2012, a decrease of 4.3% compared with the reference period, whereas the precipitation increased by 3.6% and 0.4% compared with that in June–September and July–August, respectively. The precipitation in June–September, especially in July–August, will affect the discharge and sediment yield because it mainly occurs during the flood season.

The relationship between rainfall and discharge varied among the tributaries. It changed sharply in most tributaries above Tongguan station (Figure 2). However, the changes were different in different tributaries – for example, the discharge decreased after 1970 under the same conditions of precipitation in the Wudinghe, Sanchuanhe and Fenhe rivers, particularly after 2000, whereas the discharge only decreased under the same precipitation condition after 2000 in the upper reaches, such as in the Tangnaihai, Kuyehe, Weihe and Jinghe rivers, especially in the earlier years. There was no change in the relationship in some tributaries such as Beiluohe River, however.

4.1.2 Variations in discharge

The discharge in the Yellow River has decreased significantly (Table 2), especially since 1986, even though the precipitation has not decreased. The annual mean discharge was 28.24, 16.35, 18.41, and 23.12 billion m^3 for the Lanzhou, Hekouzhen, Longmen, and Tongguan stations, respectively, during 2000–2012, representing a decrease of 14%, 57%, 42%, and 44%, respectively, compared with the annual mean discharge from 1919 to 1986. The discharges at the Hekouzhen, Longmen, and Tongguan stations were 16.1, 16.9, and 26.1 billion m^3, respectively, for 2011, corresponding to decreases of 64%, 53%, and 64%, respectively, from the period prior to 1986. The magnitudes of the decreases in discharge clearly increased from the upper to the lower reaches of the Yellow River.

It should be noted that the proportion of the discharge occurring during the flood season in a given year changed dramatically. The ratio of the flood season discharge to the annual discharge, which was approximately 60% in the upper and middle reaches of the Yellow River prior to 1996, has decreased to 40% since 1997 in most areas, except in the reach above Tangnaihai. In addition, the flood discharge in the middle and lower reaches has changed dramatically since 1986, especially after 2000, with lower flood frequencies and smaller peak discharges. The numbers of flood events per year were 3.9, 3.9, and 5.0 at the Longmen, Tongguan, and Huayuankou stations, respectively, before 1986, decreasing to 2.2,

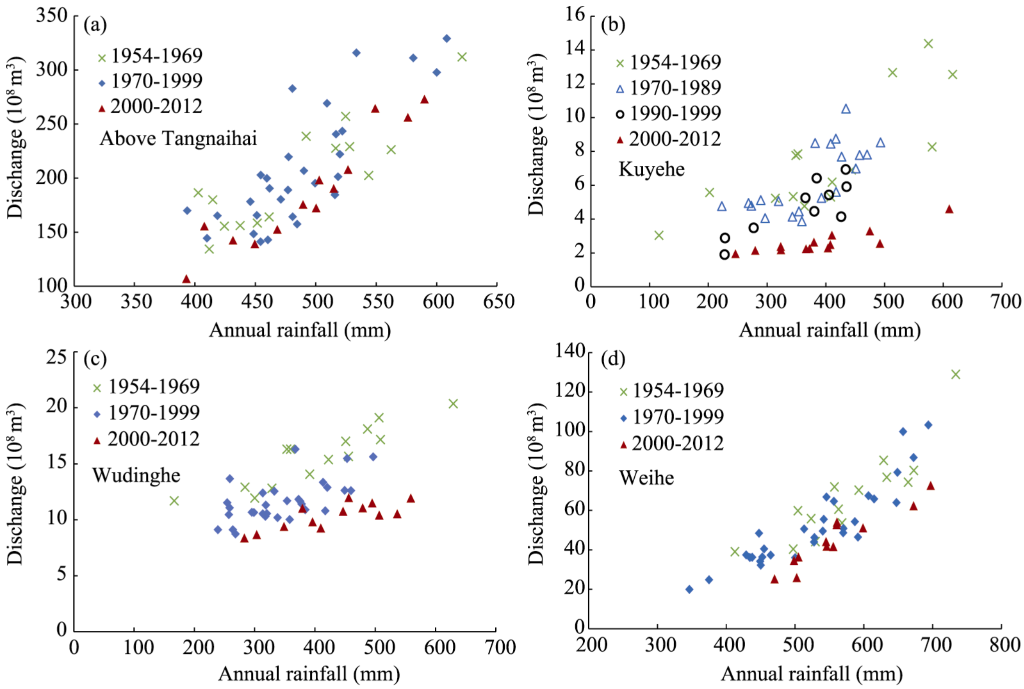

Figure 2 Relationship between annual rainfall and discharge in typical tributaries

Table 2 Discharge and sediment yield at the main hydrological stations in different periods

Station name	Period (year)	Discharge (10^9 m^3)			Sediment yield (10^9 t)		
		Flood season	Non-flood season	Annual	Flood season	Non-flood season	Annual
Tongguan	1919–1959	25.9	16.71	42.61	1.34	0.252	1.592
	1960–1986	23.03	17.24	40.28	1.013	0.195	1.208
	1987–1999	11.94	14.12	26.06	0.612	0.195	0.807
	2000–2012	10.64	12.48	23.12	0.209	0.068	0.276
	1987–2012	11.29	13.3	24.59	0.41	0.131	0.542
	1919–2012	21.04	15.92	36.96	0.989	0.203	1.191
Longmen	1919–1959	19.67	12.87	32.54	0.935	0.125	1.06
	1960–1986	17.31	13.42	30.73	0.75	0.099	0.848
	1987–1999	8.68	11.86	20.54	0.438	0.093	0.531
	2000–2012	7.59	10.82	18.41	0.125	0.032	0.157
	1987–2012	8.13	11.34	19.48	0.282	0.063	0.344
	1919–2012	15.8	12.61	28.41	0.701	0.1	0.801
Hekouzhen	1919–1959	15.59	9.48	25.07	0.117	0.025	0.142
	1960–1986	14.71	10.83	25.53	0.112	0.029	0.14
	1987–1999	6.46	9.98	16.44	0.028	0.017	0.045
	2000–2012	6.46	9.88	16.35	0.023	0.022	0.044
	1987–2012	6.46	9.93	16.4	0.025	0.019	0.045
	1919–2012	12.81	9.99	22.8	0.09	0.025	0.115
Lanzhou	1919–1959	18.74	12.31	31.04	0.091	0.02	0.11
	1960–1986	19.05	15.28	34.33	0.059	0.011	0.07
	1987–1999	11.14	15.64	26.77	0.04	0.011	0.051
	2000–2012	11.96	16.27	28.24	0.016	0.004	0.021
	1987–2012	11.55	15.95	27.51	0.028	0.008	0.036
	1919–2012	16.84	14.17	31.01	0.064	0.014	0.078

Note: Flood season refers to the period July–October.

3.0, and 2.6, respectively, for the period from 1986 to 1999 and 0.5, 0.5, and 1.2, respectively, for the period after 2000. The maximum peak discharge also significantly decreased by 21,000 and 15,400 m^3/s at the Longmen and Tongguan stations, respectively, before 1999 to 7340 and 4220 m^3/s, respectively, during the period 2000–2012.

4.1.3 Variations in sediment yield

Along with discharge, the sediment yield in the Yellow River also decreased after 1986 (Table 2). The sediment yields were 0.021, 0.044, 0.157 and 0.028 billion tons at Lanzhou, Hekouzhen, Longmen and Tongguan, respectively, for the period 2000–2012, a decrease of 43%, 69%, 84% and 80%, respectively, compared with the period 1919–1986. The decrease in sediment yield was more apparent in recent years. The sediment yields at Longmen were 0.078, 0.057, 0.078, and 0.048 billion tons for the years 2008, 2009, 2010, and 2011, respectively, and the sediment yields at Tongguan were 0.129, 0.111, 0.227, and 0.132 billion tons in 2008, 2009, 2010, and 2011, respectively. The spatial variation in sediment yield along the Yellow River was similar to the spatial variation in discharge, i.e. increasing from the upper to the lower reaches (Figure 3).

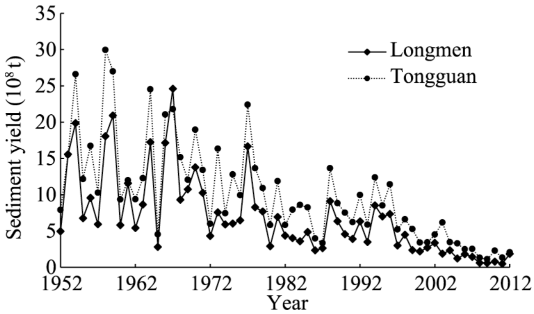

Figure 3 Variations in sediment yield at Longmen and Tongguan stations from 1952 to 2012

The sediment yield has decreased much more in some tributaries in recent years. For example, the average annual sediment yield was 105 million tons in the Kuyehe River, but was only 0.4, 0.03, and 0.13 million tons in 2008, 2009, and 2010, respectively. These values are 0.04%, 0.003%, and 0.01% of the average sediment yield over the years. It also decreased by 82%, 74%, 62%, 100%, and 94% in the Huangfuchuan, Wudinghe, Weihe, Fenhe, and Yiluohe rivers, respectively, during 2000–2012 compared with the period 1950–1999.

4.2 Analysis of the contribution of multiple factors to the decrease in discharge and sediment yield

4.2.1 Causes of the decrease in discharge in the reach above Lanzhou

The annual discharge and sediment yield were 33.8 billion m^3 and 0.118 billion tons in the upper Lanzhou reach during the reference period, accounting for 75.6% and 7.1% of the total discharge and sediment yield at Tongguan station. The annual discharge was 20.3 billion m^3 in the reach above Tangnaihai, the source region of the Yellow River, during the reference period, accounting for 45.4% of the total discharge at Tongguan station (Table 3). The annual discharge and sediment yield in the reach above Tangnaihai decreased by 8% and 15%, respectively, in the period 2000–2012 compared with the reference period. The annual discharge decreased by 31% in period 2000–2012 compared with the reference period in the upper reaches from Tangnaihai to Lanzhou. The annual sediment yield decreased after 1986 when the Liujiaxia Reservoir was put into operation; in particular, after 2000 from Tangnaihai to Lanzhou, it decreased by 89% compared with the reference periods.

Table 3 Precipitation, discharge and sediment yield in the reach above Lanzhou station

Section	Area (km^2)	Parameter	1954–1969	1970–1986	1987–1999	2000–2012	1954–2012
Above Tangnaihai	121972	Rainfall (mm)	469.6	494.1	481.8	492.3	484.3
		Discharge (10^9 m^3)	20.3	22.25	18.69	18.75	20.16
		Sediment (10^6 t)	10.55	15.14	13.21	8.89	12.09
Tangnaihai–Lanzhou	100579	Rainfall (mm)	482.5	480	473.6	478.5	478.9
		Discharge (10^9 m^3)	13.49	10.91	7.88	9.36	10.6
		Sediment (10^6 t)	107.89	36.52	37.42	12.39	50.76
Above Lanzhou	222551	Rainfall (mm)	475.5	487.7	478.1	486.1	481.9
		Discharge (10^9 m^3)	33.79	33.16	26.57	28.11	30.76
		Sediment (10^6 t)	118.44	51.66	50.63	21.29	62.85

The relationship between precipitation and discharge showed a clear change in the reach above Tangnaihai after 2000 – the discharge decreased by 7.6% for the same precipitation – but there was no distinct change in the relationship between sediment yield and discharge during the flood season. There was a clear change in the relationship between precipitation and discharge between Tangnaihai and Lanzhou after 1970. The discharge decreased under the same precipitation conditions (Figure 4) and there were changes in the relationship between sediment yield and discharge after 2000 (Figure 5). A large change was observed in the discharge, whereas there was only a small change in the sediment yield (6 million tons).

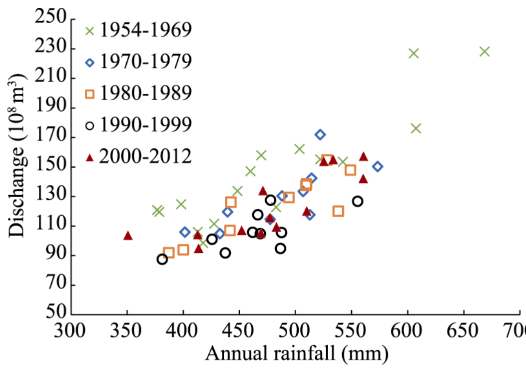

Figure 4 Relationship between annual rainfall and discharge in the Tangnaihai–Lanzhou reach

The continuous earlier dry period was one of the main factors affecting the decreased discharge in the section above Tangnaihai station. The precipitation effect had two stages of change. In the first stage (1990–2000), the precipitation decreased by 3.3% and the discharge decreased by 13.6% compared with the reference period; in the second stage (after 2000), the precipitation increased by 3.3% and the discharge decreased by 7.6% (1.55 billion tons). Further analysis showed that the decrease in discharge was the result of natural factors such as reduced precipitation, increased temperatures, increased evaporation and underlying surface factors such as the degradation of grassland, increasing rats' damage and receding glaciers. The average temperature in the 1990s was 0.47°C higher than the average and the area of degraded grassland in-

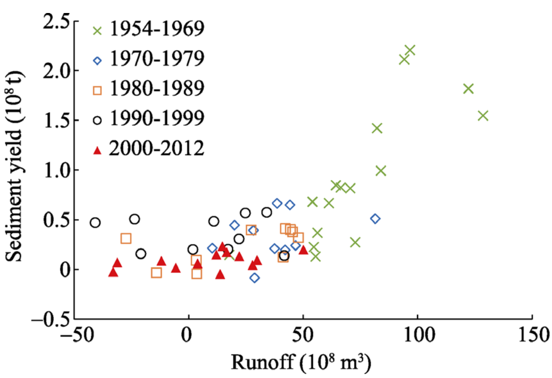

Figure 5 Relationship between sediment yield and runoff in the Tangnaihai–Lanzhou reach during flood periods

creased by 307% to 37000 hm^2 in the source region in 2001 compared with 1966, which contributed 90% of the reduction in discharge in the source region (Yao *et al.*, 2011). As a result of less rainfall from 2000 to 2003, the areas of lake wetland, lake area and water bodies in the source region shrank by >13%, nearly 40%, and 9%, respectively, which increased the water-carrying capacity of the underlying surface. Therefore the river discharge decreased by 7.6%, although the precipitation had increased since 2004. The period 1997–2004 tended to be dry based on the average precipitation in the source region from 1954 to 2012 (Figure 6), thus rainfall has filled the water bodies since 2004.

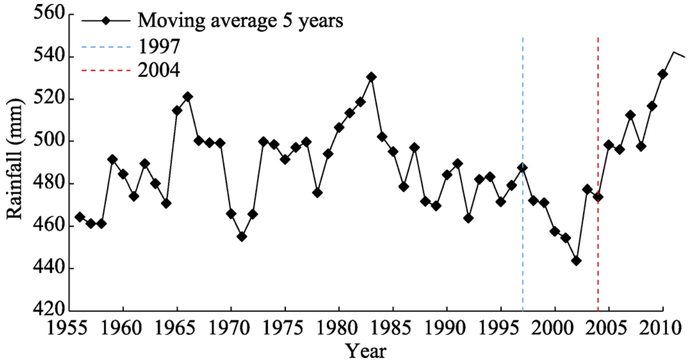

Figure 6 Transformation of the five-year moving average annual precipitation above Tangnaihai

The main factors resulting in the reduction of measured discharge in the Tangnaihai–Lanzhou section were the increased amount of water used for socio-economic needs and the evaporation of the reservoir. The water used for socio-economic needs has tended to increase in this region since 1970; the average amount of water used for socio-economic needs from 2000 to 2012 was 2.84 billion m^3, an increase of 1.59 billion m^3 compared with the reference period (1.25 billion m^3). At the same time, the exploitation of groundwater reduced the surface discharge by 0.17 billion m^3. In addition, the evaporation of 1.28 billion m^3 of water was observed at Liujiaxia, Longyangxia, Lijiaxia, Gongboxia and the other 44 reservoirs, which is also a major factor leading to the discharge reduction.

Retention in reservoirs was also a major factor in the reduction in sediment between Tangnaihai and Lanzhou. A total of 12 large- and medium-sized hydropower stations with a total capacity of 32.85 billion m^3 were built above Lanzhou, representing 97.2% of the measured discharge (33.79 billion m^3) in the reference period, and this played a major role in the reduction in sediment yield.

Based on this analysis, the continuous dry periods resulting in a reduction in precipitation, a shrinkage in the area of lake wetlands, an increase in the fill capacity of lakes and increases in the water used for socio-economic needs were the main factors resulting in the decrease in discharge; the contribution to the decrease in discharge of these factors was 42.1%. The retention of sediment in reservoirs and SWC measures were the root causes for the reduction in sediment yield; the contribution of these factors to the decrease in sediment yield was 66.5%, among which the SWC measures made up 13.6%.

4.2.2 Causes of the variation in discharge and sediment yield in the middle Yellow River

Prior to 1970, the discharge and sediment yield at Hekouzhen–Tongguan were 19.244 billion m^3 and 1.614 billion tons, respectively, and they decreased by 12.4 billion m^3 and 1.24 billion tons from 2000 to 2012, respectively. The decreases in both discharge and sediment yield were greatly affected by human activities, such as SWC measures, and natural factors such as precipitation. According to the hydrology method, the decrease in the annual discharge at Hekouzhen–Tongguan caused by SWC measures was 9.473 billion m^3 for the period 2000–2012. This decrease accounted for 76.5% of the decrease in the total discharge, with the other 5.6% (0.693 billion m^3) being attributed to changes in precipitation and evaporation. The decrease in annual sediment yield caused by SWC measures at Hekouzhen–Tongguan was 0.897 billion tons, accounting for 72.2% of the total change in sediment yield (1.24 billion tons). Thus the decrease in sediment yield caused by precipitation was 0.26 billion tons, or 20.9% of the total. The impacts of human activities are the main factors for the decrease in the total discharge and sediment yield (Table 4).

Table 4 Reduced discharge and sediment yield affected by various factors from Hekouzhen to Tongguan

Amount of decrease compared with the reference period		Natural factors		SWC measures					
		Rainfall	Evaporation	Terracing	Afforestation	Grass	Silt dam land	Vegetation restoration	Total
Discharge (10^9 m^3)	12.4	0.44	0.26	0.98	1.70	0.15	0.69	0.165	3.67
Sediment (10^9 t)	1.24	0.26	–	0.15	0.24	0.04	0.30	0.028	0.753

Amount of decrease compared with the reference period		Water conservancy factors				Other
		Socio-economic needs	Groundwater exploitation	Reservoir trapping	Irrigation	
Discharge (10^9 m^3)	12.4	4.16	1.64	0	0	2.22
Sediment (10^9 t)	1.24	0	0	0.131	0.013	0.086

The decreases in annual discharge and sediment yield attributed to land cover type (terracing–strip tread, afforestation, grassland, warp-land dams, and vegetation restoration) estimated by the SWC method during the period 2000–2012 were 3.67 billion m^3 (including flood and dry seasons) and 0.753 billion tons, respectively. These changes accounted for 29.6% and 60.6% of the change in total discharge and sediment yield, respectively. The decreases in annual discharge and sediment yield caused by water conservation projects were approximately 5.803 billion m^3 and 0.144 billion tons, respectively. The decrease in sediment yield caused by SWC measures was approximately five times the decrease resulting from water conservation projects. Therefore the SWC measures played an important role in reducing the sediment yield. The decrease in sediment yield caused by human activities using the SWC method at Hekouzhen–Longmen (including the uncontrolled areas) was 0.625 billion tons, accounting for 67.6% of the total decrease caused by human activities in the middle reach from 2000 to 2012.

This study gives a different result from previous studies. For example, Wang *et al.* (2007) found that rainfall and human activity contributed 30% and 70%, respectively, of the reduction in total sediment for the middle reaches of the Yellow River. However, Miao *et al*. (2011) argued that, from 1978 to 2008, the contributions of climate change and human activity to the decrease in discharge in the upper reach of the Yellow River were 71% and 29%, respectively, and the contributions of these factors to the decrease in sediment yield were 48% and 52%, respectively. Wang *et al*. (2012) analysed the causes of discharge variation of Huangfuchuan and indicated that the contributions of rainfall and human activity to the decrease in discharge were 16.81% and 83.19%, respectively. Previous studies have shown that the contribution rates of rainfall were larger than those found in this study.

The driving factors of the reduction in discharge and sediment yield at Hekouzhen–Tongguan changed over the last 10 years compared with 1997–2006. The relative contribution of human activities and precipitation to the decrease in discharge was 8:2 and their contribution to the decrease in sediment yield was 5:5. Human activities were the root cause for the reduction in discharge, whereas human activities and precipitation had almost the same effect in the reduction of sediment yield. However, from 2000 to 2010, human activities were the major factor affecting the reduction in discharge and sediment, whereas precipitation was a minor factor in the reduction in discharge and sediment yield, causing only 10% of the reduction in discharge and 21% of the reduction in sediment yield. The main reason for this result is that the analysis periods, regions, the changes in precipitation and the underlying surfaces of the watersheds (including SWC measures and land use) are different. For example, the reduction in rainfall from 1997 to 2006 was higher than that in the period 2000–2012, which will lead to different results. In the earlier period, the annual rainfall was generally reduced compared with the reference period. For example, in the source region of the Yellow River to Tongguan–namely, the source region and the Hekouzhen–Tongguan section – the annual rainfall decreased by 3% and 5%, respectively, although some sections witnessed a reduction of up to 11%. However, although a small reduction in the annual rainfall occurred, some sections have shown an increasing trend since 2000 – for example, the source region and southern Shaanxi increased by 4.8% and 4.6%, respectively, while other areas decreased by 4%–6%. The changes in total discharge and sediment yield were closely related to water conservancy construction and SWC measures. These results show that SWC measures have a greater impact on the sediment yield, whereas the water conservancy measures have a greater impact on the discharge.

It should be noted that the role of human activity, such as the impact of coal mining, has not been considered in this analysis. However, according to the survey, the impact of coal mining on discharge cannot be ignored. Coal mining may alter the hydrogeological conditions in a basin and cause changes in the discharge generation, flow, and drainage processes of water resources. These changes could cause decreases in discharge and affect groundwater storage. The base flow in the Kuyehe River has decreased dramatically since 1997, when coal mining greatly intensified (the base flow decreased by 26.9% compared with the period 2000–2012). The percolation of soil water caused by coal mining is responsible for 45.4% and 10.2% of the total drainage of groundwater in the Gushanchuan and Tuweihe rivers. Jiang *et al*. (2010) suggested that mining 1 ton of coal could cause a decrease of 5 m^3 in surface discharge.

5 Conclusions

The recent decreases in discharge and sediment yield for the section above Lanzhou (discharge source) and the Hekouzhen–Longmen section (sediment source) were determined using observational and survey data and the hydrological and SWC methods. The contributions of natural factors and human activities to the variation in discharge and sediment yield were assessed from 2000 to 2012. The following conclusions were drawn based on the results of the analyses in this study.

(1) The overall decreases in precipitation were small, but the precipitation showed spatial variations, with decreases in precipitation in some parts of the Yellow River basin, increases in precipitation in other parts of the basin and decreases in the intensity of precipitation in most parts of the basin. Compared with the reference period, the annual precipitation during the period 2000–2012 in the reach above Lanzhou increased by 2.2%, reduced by 6.2% in northern Shaanxi, increased by 4.6% in southern Shaanxi, reduced by 6% in the western Shanxi, and reduced by 4.3% in the Longmen–Tongguan section; however, it increased here by 3.6% in the flood season.

(2) The discharge and sediment yield decreased greatly, although the precipitation did not decrease. The magnitude of the decrease in discharge and sediment yield showed an increasing trend from the upper to the lower reaches of the river. There was only a low amount of discharge and sediment yield in the tributaries of the Yellow River. During the period 2000 to 2012, the discharge decreased by 10%, 31%, 39%, and 37% at the Lanzhou, Hekouzhen, Longmen and Tongguan stations, respectively, compared with the period 1950–1999. The ratio of the flood season discharge to the total annual discharge changed after 1997 in the upper and middle reaches, except in the upper reaches above Tangnaihai, where the proportion has remained at approximately 60%. The flood frequency was also greatly reduced. The annual sediment yield at the Hekouzhen–Huayuankou section decreased by 70%–90% from 2000 to 2010 compared with the period 1950–1999.

(3) The discharge of the Yellow River decreased by a total of 5.68 billion m^3 above Lanzhou during 2000–2012, even with an increase in precipitation. The main reasons for this included the shrinkage of wetlands, an increase in the storage capacity of lakes, and an increase in the amount of water used for socio-economic needs. The contribution rate of these factors to the decrease in discharge exceeded 40%.

(4) The discharge decreased by a total of 12.4 billion m^3 and the sediment yield decreased by 1.24 billion tons in the Hekouzhen–Longmen section, which was the main source of sediment from 2000 to 2012. Decreases of 9.473 billion m^3 for discharge and 0.897 billion tons for sediment yield, accounting for 76.5% and 72.2%, respectively, of the total changes, were caused by human activities such as SWC measures. Variations in precipitation and reservoir evaporation resulted in a decrease in discharge of 0.693 billion m^3 and a decrease in sediment yield of 0.26 billion tons, accounting for 5.6% and 20.9% of the total, respectively. Therefore human activities were a dominant factor in reducing both the discharge and the sediment yield.

The annual decreases in discharge and sediment yield caused by SWC measures in the Hekouzhen–Longmen section were 3.67 billion m^3 and 0.753 billion tons, respectively, accounting for 29.6% and 60.6% of the decrease in total discharge and sediment yield, respectively, and were caused by water conservancy construction and SWC measures. The decreases in discharge and sediment yield caused by water conservancy construction accounted for 46.9% and 11.6%, respectively, of the changes in total discharge and sediment yield from water conservancy construction and SWC measures. These results show that the SWC measures had a greater impact on the decrease in sediment yield, whereas water conservancy measures had a greater impact on the decrease in discharge.

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