Responses of streamflow and sediment load to climate change and human activity in the Upper Yellow River, China: a case of the Ten Great Gullies Basin

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ABSTRACT

Soil erosion and land desertification are the most serious environmental problems globally. This study investigated the changes in streamflow and sediment load from 1964 to 2012 in the Ten Great Gullies area of the Upper Yellow River. Tests for gradual trends (Mann–Kendall test) and abrupt changes (Pettitt test) identify that significant declines in streamflow and sediment load occurred in 1997–1998 in two typical gullies. A comparison of climatic variability before and after the change points shows no statistically significant trends in annual precipitation and potential evapotranspiration. Human activities have been very active in the region and during 1990–2010, 146.01 and 197.62 km^2 of land were converted, respectively, to forests and grassland, with corresponding increases of 87.56 and 77.05%. In addition, a large number of check dams have been built up in the upper reaches of the ten gullies. These measures were likely responsible for the significant decline in the annual streamflow and sediment load over the last 49 years.

Key words | climate change, human activities, streamflow and sediment decrease, the Yellow River

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INTRODUCTION

Climate change has become a major environmental challenge across the world in the twenty-first century. Environmental and social issues caused by climate change have induced widespread concerns, such as sea level rise, extreme weather, diseases, and energy crises. The global hydrological cycle has already been affected by climate change, including altered precipitation patterns and higher temperatures, which together affect streamflow discharge (Karl *et al.* 1996; Vorosmarty *et al.* 2000). Human activity has also significantly disturbed the temporal and spatial distribution of water resources, with more than half of the world's river systems significantly affected by human activities such as land-use change (Cho *et al.* 2009; Arrigoni *et al.* 2010; Schilling *et al.* 2010), practices of soil and water conservation, reservoir construction, irrigation, and water abstraction (Weiskel *et al.* 2007; Ma *et al.* 2012).

The Yellow River Basin is the second largest in China. The river has a total length of 5,464 km and a drainage area of 752.44×10^3 km^2. The basin contains 12.9 million ha of cultivated land, about 13% of the total cultivated area in China, but only 3% of the country's water resources and so faces a serious shortage of water (He *et al.* 2013). The average annual streamflow in the Yellow River decreased to 242.66×10^8 m^3 during 2001–2010, only 53% of the discharge in the 1950s. Sediment load concurrently decreased. The mean annual sediment load from 2001 to 2010 at Huayuankou station located at the upper reaches of the Lower Yellow River was 1.43×10^8 t, only 9.7% of the load in the 1950s.

The upper and middle areas of the Yellow River Basin occupy 97% of the total drainage area. A series of water and soil conservation measures, including planting trees, improving grasslands and constructing check dams, have been implemented since the 1970s to control soil erosion and maintain agricultural productivity. The potential impacts of the altered hydrology on streamflow and sediment load, however, have received little attention but require detailed studies, because they can have major implications for the ecology of the Yellow River and its tributaries. Such studies would help us to understand the measures needed for future efforts on soil conservation. Yang *et al.* (2004) suggested that the flow discharge of the Yellow River has decreased continuously during the last 50 years because precipitation has decreased

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(by 38.2 mm/decade) and evaporation has increased (by 52 mm/decade for pan evaporation). Zhao & Xu (2009) argued that the continued decrease of streamflow in the headwater area of the Yellow River Basin is inevitable and predicted decreases of 88.61 (24.15%), 116.64 (31.79%) and 151.62 m^3/s (41.33%) by the 2020s, 2050s and 2080s, respectively. Wang *et al.* (2007) observed that due to the construction of Liujiaxia and Longyangxia Reservoirs in the upper reaches of the river, sediment load at Toudaoguai Gauging Station, which is located at the downstream end of the Upper Yellow River, has decreased by 40% over the past 56 years.

The Yellow River flows for 830 km through the Inner Mongolia of China where the valley, bordered by the Ulan Buh and Hobq Deserts on the south side, is commonly called the Inner Mongolian Reach of the Yellow River. Thunderstorms and windstorms are frequent in the area, and produce surface runoff that erodes the land so severely that the annual sediment yield can be as high as 12,000 t km^{-2} (Dalad Banner Water Conservancy Annals 1989, unpublished data). The high erodibility of the Ulan Buh and Hobq deserts, the loess area upstream of the deserts, and floods from the tributaries of the Yellow River provide large amounts of sediments. Ten of these tributaries, named the Ten Great Gullies, originate in the center of the Ordos Plateau (an area prone to rainstorms) and flow through the Ulan Buh and Hobq deserts before running into the Yellow River. Most studies on the hydrology of the Yellow River have focused on the middle and lower drainage areas, and few have examined the Inner Mongolian Reach. Furthermore, very few studies have addressed the relationships of streamflow and sediment load with the hydromorphological responses to the changes in water discharge and sediment load in the Ten Great Gullies area.

The main objectives of this study are: (1) to detect trends and abrupt changes in water discharge and sediment load of typical gullies in the Ten Great Gullies area by the sequential use of the Mann–Kendall and Pettitt tests; (2) to determine the potential factors driving the changes in hydrological regime and sediment dynamics; and (3) to evaluate the natural and anthropogenic impacts on variations in water discharge and sediment load.

MATERIALS AND METHODS

Study area

The study area is located on the south side of the Inner Mongolian Reach of the Yellow River and has an area of 11,000 km^2. This area is the main source of sediments delivered to the Inner Mongolian Reach and characterized with low gradients (0.267–0.525%), gullies and sand-dunes, loose riverbed materials, high sediment loads and sparse vegetation. The region has a typical temperate continental monsoon climate, with a mean annual rainfall of 300–400 mm and a potential evapotranspiration of 1,000–1,400 mm. The whole study area is mainly composed of loess and sandy soil, and loess hilly and gully landscape dominates the upper areas of the Ten Great Gullies area, while aeolian sand-dunes prevail in the middle of the area. Short-durational heavy rainstorms frequently occur in summer, and high infiltration excess results in violent variations in surface runoff. The study area has two hydrometric stations: Longtouguai and Xiangshawan located separately on Xiliugou and Hantaichuan gullies (Figure 1).

Data

The streamflow and sediment data were collected from the Hydrological Data of the Yellow River Basin, issued yearly by the Yellow River Conservancy Commission. The data for precipitation from eight rainfall gauges in the region were obtained from the Erdos Hydrological Bureau. Data for temperature, wind speed, vapor pressure, and hours of sunshine were downloaded from the China Meteorological Data Sharing Service System and used to calculate the potential evapotranspiration (ET_0) using the FAO Penman–Monteith method (Allen *et al.* 1998). The basin-wide average precipitation was estimated by the Thiessen polygon method based on the distribution of the gauges. Digital elevation data were obtained from the global topographical database (http://telascience.sdsc.edu/tela_data/SRTR/version2/SRTM3/) at a spatial resolution of 3 arc seconds spatial resolution. Land-use/cover data of the study area during 1990–2010 were interpreted from Landsat Thematic Mapper images (30×30 m resolution). All images were obtained in June of the corresponding years and used to represent the decadal land-use/cover change (LUCC). The data sets were provided by the Data Sharing Infrastructure of Earth System Science, Chinese Academy of Sciences (http://www.geodata.cn/Portal/dataCatalog/dataList.jsp). Images were processed by ERDAS Imagine 9.2 (ERDAS, Inc., Norcross, Georgia) to differentiate categories of land covers using supervised classification and visual interpretation. All classes of land use in 2010 were verified by 48 terrestrial control points captured by GPS. The overall accuracy of the land classification was 73.5%, and the kappa coefficient was 0.67, suggesting that the land-use/cover

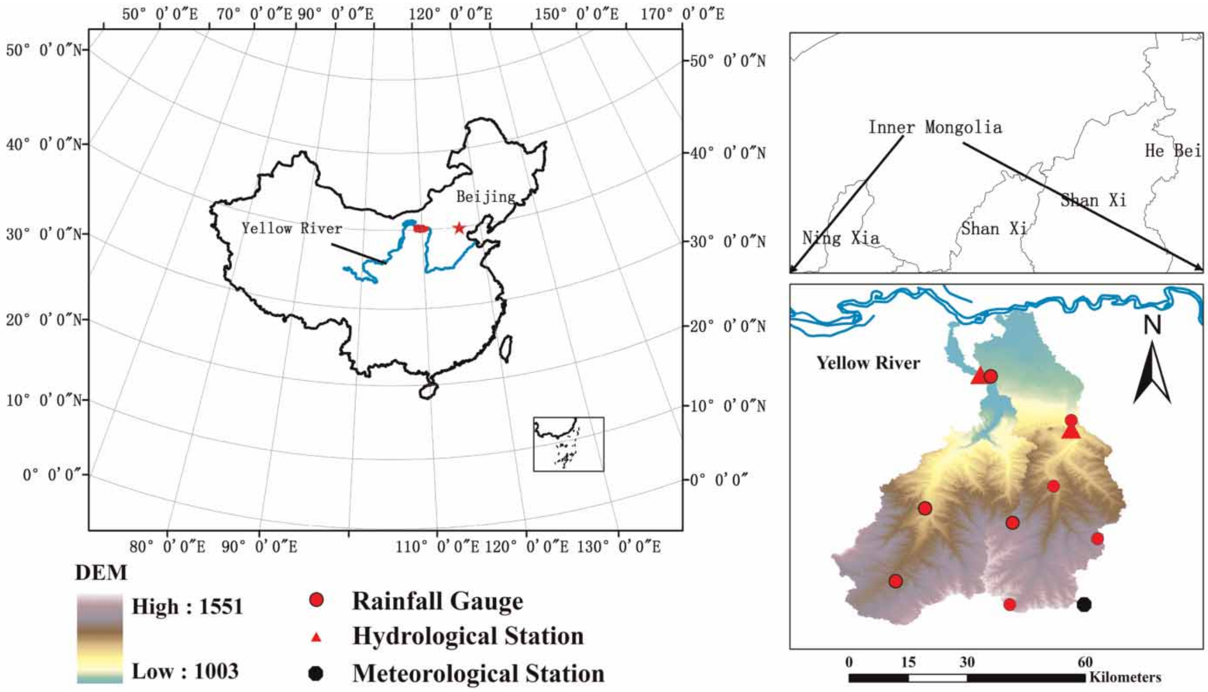

Figure 1 | Location of the study area.

data interpreted from the images were suitable for this study (Ma *et al*. 2009).

Methods

Trend test and change-point detection

The Mann–Kendall trend test (Mann 1945; Kendall 1975) is a non-parametric assessment of the significance of monotonic trends in hydro-climatic time series (Modarres & Sarhadi 2009). In the Mann–Kendall test, the null hypothesis, H_0, states that X_1, ..., X_n are samples of n independent and identically distributed random variables with no seasonal change. The test statistic S with zero mean and computed variance (as in Equation (3)), is asymptotically normal and according to Hirsch & Slack (1984) can be calculated from

$$S = \sum_{i=1}^{n-1}\left[\sum_{j=i+1}^{n}\operatorname{sign}(X_j - X_i)\right] \tag{1}$$

where

$$\begin{cases} \operatorname{sign}(X) = 1 \ \text{ for } \ X>0 \\ \operatorname{sign}(X) = 0 \ \text{ for } \ X = 0 \\ \operatorname{sign}(X) = -1 \ \text{ for } \ X<0 \end{cases} \tag{2}$$

If H_0 (no trend in the data) is true, then S can be assumed to be approximately normally distributed with

$$\begin{cases} E(S) = 0 \\ V(S) = n(n-1)(2n+5)/18 \end{cases} \tag{3}$$

where $E(S)$ is the mean, $V(S)$ is the variance of S, and the Z score of S is calculated from

$$Z = \begin{cases} (S-1)/\sqrt{V(S)} & S>0 \\ 0 & S=0 \\ (S+1)/\sqrt{V(S)} & S<0 \end{cases} \tag{4}$$

A positive value of Z indicates an increasing trend in the time series, and a negative value of Z indicates a decreasing trend.

The Pettitt test (Pettitt 1979) was used to test one unknown change point by considering a sequence of random variables X_1, X_2, …, X_t, which have a change point at τ (X_t for $t = 1, 2, \ldots, \tau$ has a common distribution function $F_1(\chi)$, and X_t for $t = \tau + 1, \ldots, T$ has a common distribution function $F_2(\chi)$, and $F_1(\chi) \neq F_2(\chi)$) (Pettitt 1979). H_0 (i.e., no change) or $\tau = T$ is tested against H_1 (i.e. a change) or $1 \leq \tau < T$ using the non-parametric statistic

$$K_N = \mathrm{Max}_{1 \leq t \leq T}\left|U_{t,T}\right| \tag{5}$$

where the test used a version of the Mann–Whitney statistic $U_{t,T}$

$$U_{t,T} = U_{t-1,T} + \sum_{i=1}^{T} \mathrm{sgn}(X_t - X_i) \quad t = 2, 3, \ldots, T \tag{6}$$

and

$$\begin{aligned} &\text{if } (X_t - X_i) > 0 \quad \mathrm{sgn}(X_t - X_i) = 1 \\ &\text{if } (X_t - X_i) = 0 \quad \mathrm{sgn}(X_t - X_i) = 0 \\ &\text{if } (X_t - X_i) < 0 \quad \mathrm{sgn}(X_t - X_i) = -1 \end{aligned} \tag{7}$$

The associated probability, P, used in the test is given as

$$P = \exp\left(\frac{-6K_N^2}{N^3 + N^2}\right) \tag{8}$$

If $P < 0.05$, a significant change point exists, the time series is divided into two parts at the location of the change point.

RESULTS AND DISCUSSION

Trends in annual streamflow, sediment load and climatic factors

The annual average streamflow observed at Longtouguai station, located near the mouth of Xiliugou gully during the last 49 years, was 28.26 million m^3. The annual average streamflow at Xiangshawan station, located near the mouth of Hantaichuan gully from 1984 to 2012, was 10.82 million m^3, 38.3% of the annual average of Xiliugou gully. The average annual sediment loads at Xiliugou and Hantaichuan were nearly 3.72 and 1.09 million t, respectively. The streamflow and sediment load in Xiliugou gully were more variable than in Hantaichuan gully.

The average annual precipitation at the study area was 290.97 mm during 1964–2012, and the general trend was relatively stable. The average annual temperature was 6.35 °C in the same period. Temperatures rose linearly by 0.52 °C/decade, especially in autumn and winter. The annual potential evapotranspiration showed a decreasing trend in the study area, with an average of about 1,226.21 mm (Figure 2).

The annual trends of streamflow and sediment load in both Xiliugou and Haitaichuan gullies had statistically significant negative Z scores of −2.43, −2.68 and −3.09 except the streamflow of Hantaichuan gully (Table 1), indicating significant decreases in both annual runoff and sediment discharge. The Z scores were 6.11 for temperature, −1.90 for potential evapotranspiration, and −0.35 for precipitation, suggesting a significant trend of increasing temperature, and a non-significant decreasing trend in both precipitation and potential evapotranspiration.

Change-point test of streamflow and sediment load

The results of the Pettitt tests for abrupt changes in streamflow and sediment load are shown in Figure 3 and Table 2. No significant abrupt changes occurred in the streamflow of Hantaichuan gully during 1982–2012. Change points were identified for streamflow and sediment load in 1997–1998 in the two gullies. The sediment load of Xiliugou gully decreased significantly ($P < 0.01$). The Pettitt test statistic K_N identified transitional decreases in streamflow, respectively, in 1981 and 1997 in Xiliugou gully, but only in 1997 was the decrease statistically significant ($P < 0.05$).

Possible causes for the changes in streamflow and sediment load

Climate change

The means and standard deviations of annual precipitation and potential evapotranspiration before and after the change points are evaluated to determine if climatic variables caused the changes (i.e., trends and change points) in annual streamflow and sediment load. No statistically significant trends in annual precipitation and potential evapotranspiration were identified (Table 3). This means that the decrease in streamflow and sediment load in the study area may be due to some potential anthropogenic impacts.

Land-use change

The influences of LUCC on hydrological processes have been identified in many circumstances (Li *et al.* 2007). Xiliugou gully is used as a representative example to describe the effect of LUCC due to its highly variable streamflow and sediment load. The land uses in the study area include cultivated land, forests, grassland, water bodies, resident land, sandy areas and unused land (Table 4).

Grassland and sandy areas are the dominant land-use types in the Xiliugou basin, together accounting for 45.73 and 48.98% of the entire area for 1990 and 2010,

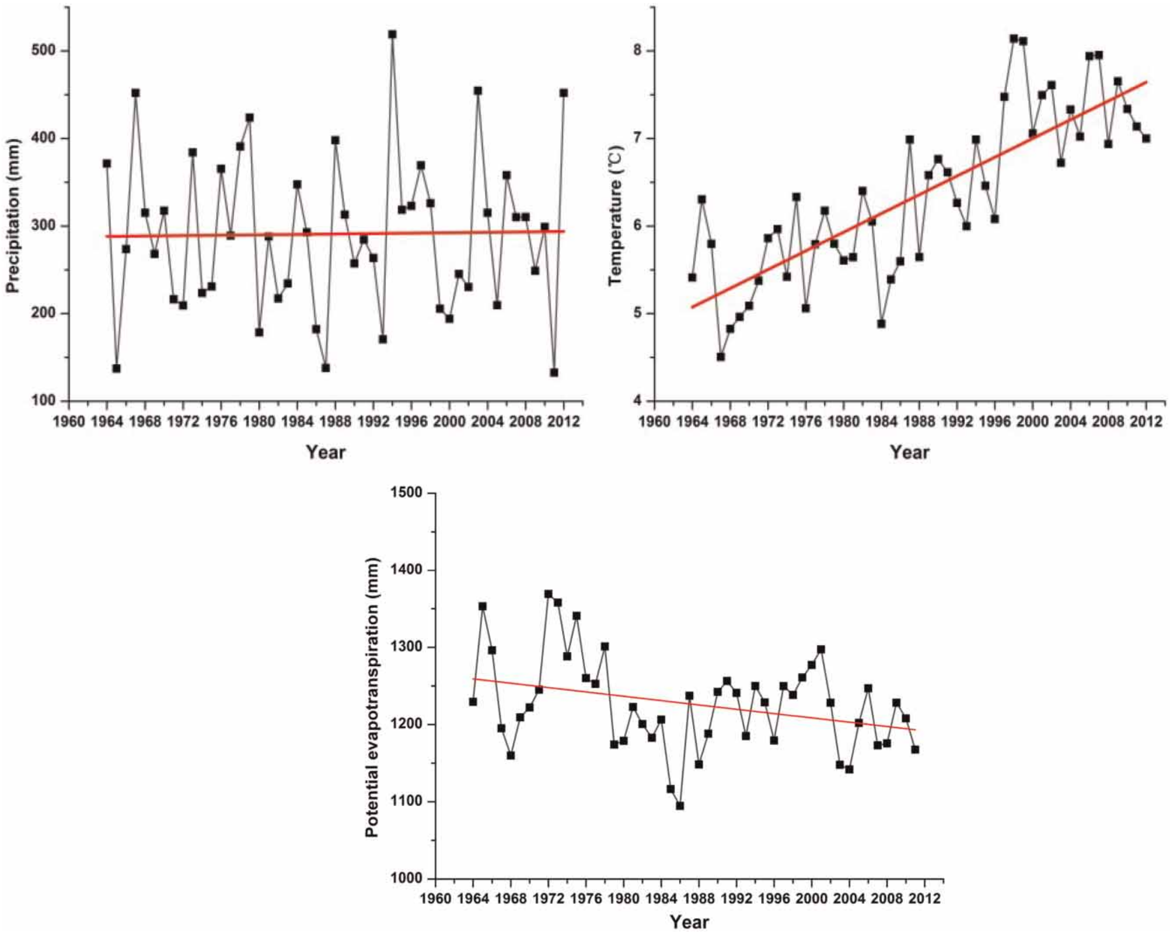

Figure 2 | Variations in annual precipitation, temperature, and potential evapotranspiration from 1964 to 2012 in the study area.

Table 1 | Trend analysis of climatic factors, streamflow and sediment load for Xiliugou and Hantaichuan gullies

Gully	Parameters	Z statistic	Sig. level	Trend
Xiliugou	Streamflow	−2.43	**	Decreasing
	Sediment discharge	−2.68	**	Decreasing
Hantaichuan	Streamflow	−0.82	ns	Decreasing
	Sediment discharge	−3.09	**	Decreasing
	Precipitation	−0.35	ns	Decreasing
Climate factor	Temperature	6.11	**	Increasing
	Potential evapotranspiration	−1.90	ns	Decreasing

Positive numbers indicate an increasing trend and negative numbers indicate a decreasing trend. ** Significant at $P = 0.05$; ns, not significant at $P < 0.05$.

respectively. The main trend of land-use change during 1990–2010 was an increase in forests and grassland and decreases in the other types. Comprehensive conservation of soil and water in the Xiliugou basin began in the 1960s, but the desired effects were not achieved due to the lack of investment for effective small-scale management. Various government-sponsored conservation projects implemented after 1990, however, improved the effectiveness of soil and water conservation practices. By the end of 1997, the area of grassland increased to 256.46 km^2, but 299.70 km^2 of sandy areas and 202.46 km^2 of unused land remained to be harnessed.

The national conservation programs of the Grain for Green Project and Protection of Natural Forests have been implemented since 1999, also in the Xiliugou basin. The areas of unused land and sandy areas decreased between 1990 and 2010 by 101.40 and 158.10 km^2, respectively, mostly due to conversion to forests and grassland. During the same period, the area of forests increased to 312.75 km^2, a net increase of 146.01 km^2, and the area of grassland increased to 454.08 km^2, a net increase of 197.62 km^2.

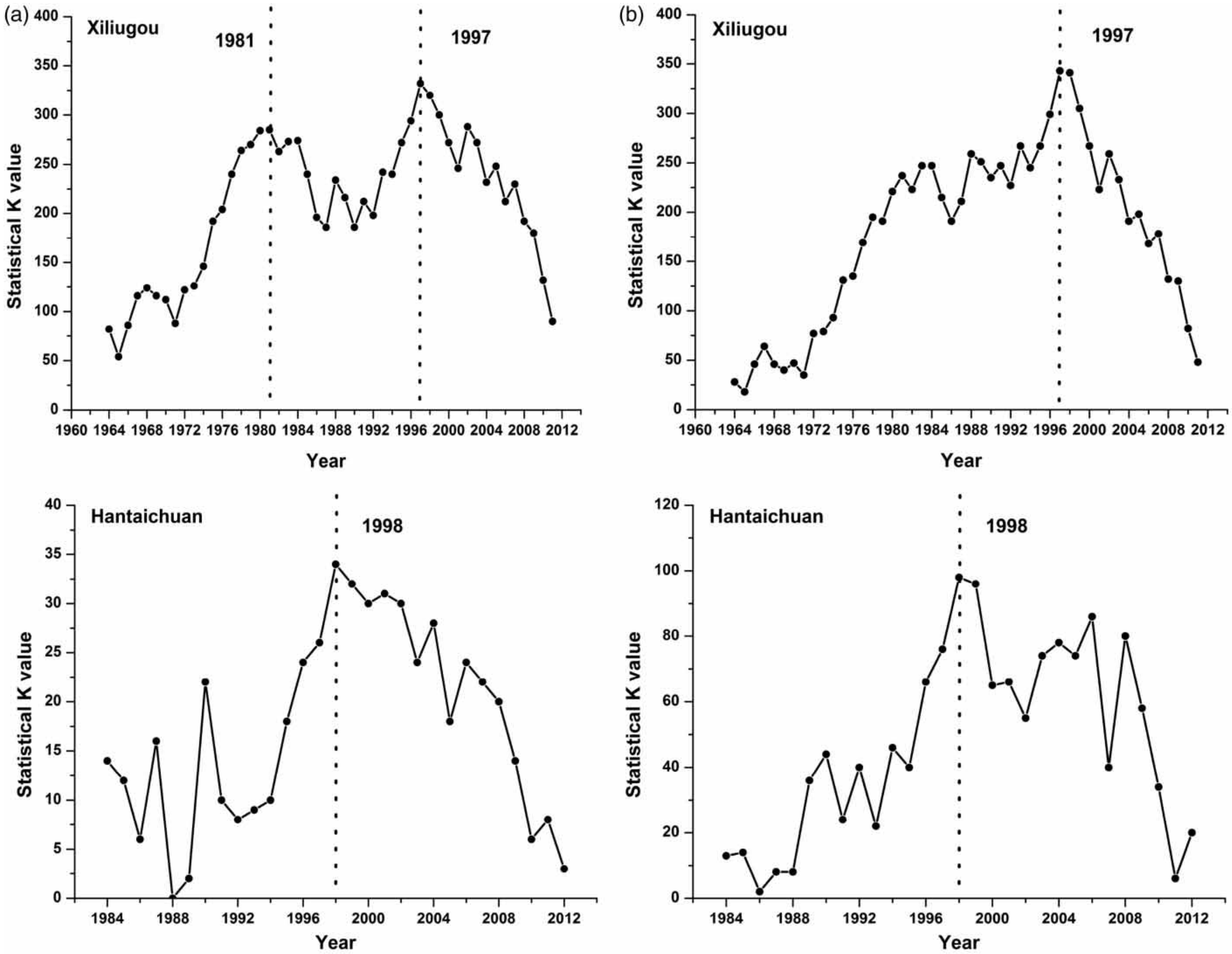

Figure 3 | Pettitt test for annual streamflow (a) and sediment load (b) in Xiliugou and Hantaichuan gullies.

Table 2 | Pettitt test for streamflow and sediment load series for Xiliugou and Hantaichuan gulies

Gully	Variable	*K* statistic	*P*	Sig level	Shift	*T*
Xiliugou	Streamflow	234	0.065	ns	–	1981
		282	0.014	[a]	Decrease	1997
	Sediment discharge	343	0.003	[b]	Decrease	1997
Hantaichuan	Streamflow	35	0.747	ns	–	1998
	Sediment discharge	98	0.036	[a]	Decrease	1998

[a]Significant at $P = 0.05$.
[b]Significant at $P = 0.01$.
ns, not significant.

Check-dam construction

Another long-standing approach to reducing sediment yield has been the construction of sediment-trapping dams in the eroding areas of the Yellow River (Xu *et al.* 2004). The Ten Great Gullies of the Upper Yellow River pass through large deserts and no large dams can be built on the streams. By the end of 1997, there were only two medium-sized check dams built in the area. During 1997–2011, nevertheless, the number of check dams increased to 55: 17 large check dams, 29 medium-sized check dams and nine small check dams. These check dams can control gully erosion effectively, but only regulate streamflow to a small degree. Typically, they have been constructed on the head area of

Table 3 | Characteristic changes in streamflow and sediment load before and after the change point in Xiliugou and Hantaichuan gullies

Gully		First period			Second period			
		Mean	SD	CV	Mean	SD	CV	Ratio of means
Xiliugou	Streamflow	3,083.50	1,870.90	0.60	2,001.20	1,347.20	0.67	0.35
	Sediment load	477.10	866.20	1.81	195.90	414.60	2.10	0.58
Hantaichuan	Streamflow	1,136.80	1,393.86	1.23	671.20	819.05	1.22	0.41
	Sediment load	176.22	234.23	1.33	53.78	93.14	1.73	0.81
Climate factors	Precipitation	290.80	90.50	0.31	286.10	90.81	0.31	0.02
	Potential evapotranspiration	1,234.00	64.11	0.05	1,213.82	46.53	0.03	0.01
	Temperature	5.84	0.63	0.11	7.49	0.46	0.06	-0.28

The first and second periods were defined by the change points in annual streamflow and sediment load listed in Table 2. The units of streamflow and sediment load are, respectively, 10^4 m^3 and 10^4 t.

Table 4 | Land-use change during 1990–2010 in the Xiliugou basin

Land-use type	1990		2010	
	Area km^2	Percentage %	Area km^2	Percentage %
Cultivated land	207.87	17.09	137.82	11.33
Forest land	166.74	13.71	312.75	25.72
Grassland	256.46	21.09	454.08	37.34
Sand	299.7	24.64	141.6	11.64
Water	58.34	4.79	44.36	3.65
Resident land	24.71	2.03	24.33	2.00
Unused land	202.46	16.65	101.06	8.31

the gullies and so their effects on streamflow entering the Yellow River are very limited.

Soil-conservation measures, such as returning cultivated land to forests or to grassland, and check-dam construction were thus the dominant factors for decreasing streamflow and sediment load. During 1990–2010, 343.63 km^2 of land was converted to forests or grassland in the Xiliugou basin, accounting for 28.25% of the total area of the basin. This means that the decreases in stream flow and sediment load in Xiliugou gully is likely driven by the increase in area of grassland and forests and check-dam construction. This is because many previous studies have shown that when the area of woodland and grassland increases to 20% of the total land area, its effects on annual streamflow and sediment will reach a significant level (Brown *et al.* 2005). In addition, previous studies have shown that due to forest-grass re-vegetation and other engineering measures, the variations of streamflow and sediment in the tributaries of the Upper Yellow River decreased by more than 20 and 27% during 1997–2006, respectively (e.g., Gao *et al.* 2009).

CONCLUSIONS

Streamflow and sediment load show a declining tendency over the last 49 years in Xiliugou and Hantaichuan gullies, two typical gullies along the Inner Mongolian Reach of the Yellow River. This study identifies that this tendency is mainly due to human activities.

Statistically significant decreasing trends in streamflow and sediment load are justified with Z-scores of −2.43, −2.68 and −3.09, except for streamflow in Hantaichuan gully, and significant change points in annual streamflow and sediment load that occurred in 1997–1998. Annual precipitation and potential evapotranspiration, however, have not changed significantly during 1964–2012 in the region, indicating that they have played a limited role in affecting the decreases in the streamflow and sediment load.

Land use and land cover have changed considerably in the Xiliugou basin since the 1990s. The areas of unused land and sandy areas have decreased, while the areas of forests and grassland increased. This is mainly because of human activities. Over the last 49 years, many biological (e.g., re-vegetation) and engineering measures (e.g., building of check dams) for soil and water conservation have been implemented in the study area.

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