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EVIDENCE AND CAUSES OF SPATIOTEMPORAL CHANGES IN RUNOFF AND SEDIMENT YIELD ON THE CHINESE LOESS PLATEAU

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ABSTRACT

Climate change and human activities are strongly influencing the eco-hydrological processes of the Chinese Loess Plateau. It is challenging to investigate the spatiotemporal changes of water and sediment yields and identify their potential causes. In this study, we used the annual runoff index (WI) and specific sediment yield (SSY) derived from 58 hydrological stations to quantify the changes and attempted to explain their potential causes. The WI exhibited significant ($P < 0.05$) decrease ranging from -0.1 to $-2.6\,\mathrm{mm\,yr^{-1}}$ during 1957–2012 in 44 sub-catchments. Similarly, the SSY in 52 sub-catchments reduced in a range between -2.86 and $-636\,\mathrm{Mg\,km^{-2}\,yr^{-1}}$. The region of Toudaoguai–Longmen has extremely high SSY ranging from 8000 to $41\,000\,\mathrm{Mg\,km^{-2}\,yr^{-1}}$ during 1957–1969. Budget analysis suggested that the area of Lanzhou–Toudaoguai contributed limited sediment but extracted large amount of water. The areas with negative SSY were increasing and mainly distributed along the mainstream of the Yellow River. The Loess plateau was becoming drier and warmer since the 1950s, whereas the intensive human activities including water withdrawal, soil and water conservation projects and the operation of dams and reservoirs are the dominant factors for the decline in WI and SSY on the Loess Plateau. Copyright © 2016 John Wiley & Sons, Ltd.

KEY WORDS: runoff index; specific sediment yield; loess plateau; spatiotemporal changes; driving forces

INTRODUCTION

Rivers are the main pathways delivering water and sediment from the land surface to the sea with abundant materials for sustaining aquatic ecosystems (Syvitski, 2003). Runoff and sediment transport play critical roles in global biological and geochemical cycles of the terrain ecosystem closely interlinked with the soil system (Berendse *et al.,* 2015; Brevik *et al.,* 2015; Decock *et al.,* 2015; Keesstra *et al.,* 2012; Smith *et al.,* 2015). At present, sustainable management of water resources and sediment load has become a challenge because the naturally balanced river system has been continuously disturbed over centuries (Borrelli *et al.,* 2015; Demissie *et al.,* 2015; Heaney *et al.,* 2001; Rodriguez-Blanco *et al.,* 2010). Intensive human activities (i.e. inappropriate irrigation, mining, dams and large reservoirs, land reclamation) have destabilized this equilibrium resulting in a number of environmental problems (Verstraeten & Poesen, 2002; Zhang *et al.,* 2015).

In the past several decades, considerable attention has been paid to assess the variation of runoff and sediment load in different scales and their potential driving factors (Milliman *et al.,* 1987; Syvitski, 2003; Walling, 2006). Runoff and sediment load reduction has been addressed in many large rivers throughout the world owning to climate change, land use/cover changes, soil and water conservation measures and reservoirs and dam construction (Buendia *et al.,* 2015; Cerdà, 1998; Cerdà & Lasanta, 2005; Keesstra *et al.,* 2005; Liu *et al.,* 2014; Milliman *et al.,* 2008; Nilsson *et al.,* 2005; Sanjuán *et al.,* 2016; Walling & Fang, 2003). Similar results have also been found in the Yellow River basin in China during the past several decades (Jiao *et al.,* 2014; Wang *et al.,* 2007; Xu, 2005; Xu, 2009; Yang *et al.,* 2004; Zhao *et al.,* 2014a). Peng *et al.* (2010) investigated sediment load and influence of human activities at three gauging stations in the upper, middle and lower reaches of the Yellow River basin. Their results indicated that sediment load decreased gradually over the past decades, and various human activities including large reservoirs construction, as well as soil and water conservation, were responsible for the reduction. Piao *et al.* (2010) addressed that climate change dominated the variation of runoff and increasing water withdrawals explained approximately 35% of the runoff reduction at the Huayuankou station in the downstream of the Yellow River. While the investigation from Zhao *et al.* (2014a) indicated that reservoirs and large amount of soil and water conservation measures were responsible for the sediment load reduction in the mainstream

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station of the Yellow River. Previous studies have conducted detail analysis on runoff and sediment load changes in the Yellow River basin, whereas the inconsistency requires further investigation on how the driving factors corresponded to the variation of runoff and sediment load. Furthermore, most of the studies focused on the main gauges along the Yellow River, and few studies have been undertaken for the whole Loess Plateau.

The Loess Plateau has been considered as one of the most severely eroded areas in the world (Tang *et al.,* 1991). More than 70% of the area is dominated by gully–hilly region because of massive soil erosion. The erosion-prone area was estimated to be approximate 472 000 km^2 on the Loess Plateau, and the area with average annual specific sediment yield (SSY) higher than 8000 Mg km^{-2} reached up to 91 200 km^2 (NDRC *et al.,* 2010). Since the 1950s, numerous soil and water conservation measures such as afforestation, grassing, check-dam construction, reservoirs and terraces have been implemented on the Loess Plateau (Hessel *et al.,* 2003; Yue *et al.,* 2014). However, soil erosion was still out of control until the late 1990s. In 1999, a large ecological restoration project named "Grain for Green" was launched by the Chinese government to control soil erosion and improve the vegetation cover through returning steep slope arable land to grass land and forests (McVicar *et al.,* 2007). After ten years effort on ecological restoration, the landscape changed greatly, resulting in remarkable impacts on changes of hydrological processes on the Loess Plateau. The government and decision makers need adaptive strategies and advices for further managing the limited water resources and maintaining the sustainability of ecosystem in this region.

Better understanding the changes in both runoff and sediment yield on the Loess Plateau is of great importance for river basin management and soil and water conservation (Wu & Chen, 2012; Zhao *et al.,* 2014b). Identifying the critical risk areas can also provide good references for decision makers to adapt distinct strategies for ecosystem restoration and riverine system sustainability in the future. Thus, the objectives of the study are (i) to conduct a comprehensive investigation on spatial pattern and temporal variation of runoff and sediment yield on the Loess Plateau and (ii) to assess potential driving factors of their variation.

MATERIAL AND METHODS

Geographic Setting

The Loess Plateau is located in the upper and middle reaches of the Yellow River basin, covering an area of 630 000 km^2 (Figure 1). Average annual precipitation ranges from 300 mm in the north to 800 mm in the southwest. More than 70% of annual rainfall occurs as heavy storms in the summer season, and leads to severe soil erosion in the region. There are more than 30 large tributaries (with catchment area larger than 1000 km^2), which contribute approximately 40% of the total runoff to the Yellow River, but nearly 90% of sediment (Tang *et al.,* 1991). The Loess Plateau can be divided into six zones because of their soil types, climate characteristics and geomorphology features, i.e. eastern rocky mountain region, hilly–gully plateau, Mu Su desert, Hetao alluvial plain, Fen-Wei River depression valley and high plain plateau (Zhao *et al.,* 2013). The hilly–gully plateau is covered by continuous loess on the surface with thickness ranging from 100 to 300 m, and contribute majority of sediment to the Yellow River.

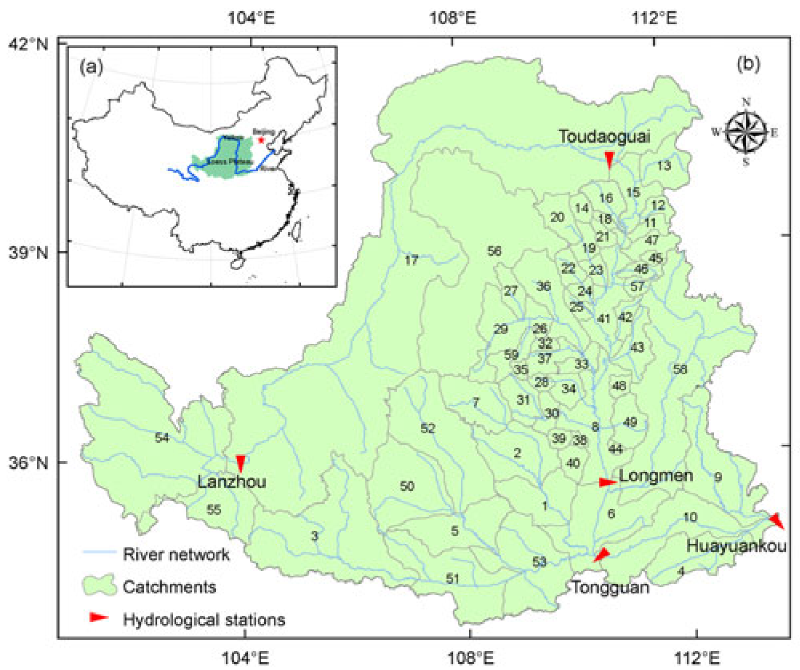

Figure 1. Location of the Loess Plateau in China (a, Inset map showing the location of the Loess Plateau; b, sub-catchments on the Loess Plateau).

Data Sources

We compiled annual runoff and sediment load data at 7 mainstream station and 51 tributary stations (runoff data at 10 stations were unavailable since 1995) from 1957 to 2012 in this study (Figure 1). Stations with data records less than 56 years in length were excluded from this analysis. Hydrological data were provided by Yellow River Conservancy Committee (YRCC). The consistency and reliability of the data were checked and firmly controlled by the YRCC before the data release. The YRCC provided the data about large-medium check dams through field survey in 2009. These data include the locations of the check dams, total storage capacities, construction date and sedimentation. The annual rainfall and temperature at 57 stations were obtained from the National Climate Centre of China Meteorological Administration (CMA). Two NDVI datasets at annual scales were employed in this study, which include GIMMS and MOD13A2. The GIMMS NDVI data issued by the Global Inventory Monitoring and Modeling Studies (GIMMS) group is derived from the NOAA/AVHRR land dataset at a spatial resolution of 8 km at 15-day interval for the period of 1981–1999 (Tucker *et al.,* 2005). Another NDVI data of MOD13A2 (1 km) product between 2000 and 2012 was obtained from the NASA EOS DATA Gateway (https://wist.echo.nasa.gov/api).

Methods

The non-parametric Mann–Kendall test method was applied to detect trends in runoff and sediment yield indices (Kendall, 1975; Mann, 1945) This method has been widely used to examine trends in hydro-meteorological time series such as runoff, sediment load, precipitation and temperature in numerous regions in the world (Yue *et al.,* 2003; Yue *et al.,* 2014; Zhao *et al.,* 2014b). For a given time series X $(x_1, x_2, \ldots, x_n)$, the statistic S is defined as:

$$S = \sum_{i=2}^{n} \sum_{j=1}^{i-1} sgn\left(x_i - x_j\right) \tag{1}$$

Where:

$$sgn\left(x_j - x_i\right) = \begin{cases} 1 & x_j > x_i \\ 0 & x_j = x_i \\ -1 & x_j < x_i \end{cases} \tag{2}$$

and it approximately normally distributed when $n \geq 8$, with the variance as:

$$var(S) = \frac{n(n-1)(2n+5)}{18} \tag{3}$$

The standardized statistic is:

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

A positive value of Z indicates an increasing trend and a negative value of Z indicates a decreasing trend. The null hypothesis of no trend is rejected if $|Z| > 1.96$ at 5% significance level. It should be noted that the presence of serial correlation would affect the detection of trends in a series. To eliminate the effects of the serial correlation on the MK test, the Trend-Free pre-whitening procedure was used to remove the effects of serial correlation (Yue & Wang, 2004). According to the autocorrelation coefficients at lag-1 for each annual time series, the hydrological series are time independent. In addition, the Kendall slope index was used for detect the slope of time series, which is calculated as:

$$\beta = Median\left(\frac{x_j - x_j}{j - i}\right) \tag{5}$$

Where: $1 < i < j < n$, the slope β is the median over all combination of record pairs for the whole data series.

To examine the abrupt changes of the hydro-climatic time series, we applied a regime shift index based approach, which was proposed by Rodionov (2006). A short introduction was given here, and more details of the method can be found in Rodionov (2006) and Wang *et al.* (2014). For a time series, the mean value of the first regime (R1) is estimated as:

$$\overline{x}_{R1} = \sum_{k=1}^{m} x_k \quad 1 \leq k \leq m \tag{6}$$

Where: m is the length of the regimes to be tested. The difference between two regimes (R1 and R2) is calculated through a Student's t-test:

$$\varphi = \overline{x}_{R2} - \overline{x}_{R1} = t\sqrt{2\delta_m^2/m} \tag{7}$$

Where: t is the value of t-distribution with $2m - 2$ degrees of freedom at a probability level p, and δ_m is the mean standard deviation for m-year intervals.

To determine the change point, a test is detected between the average values of $x_1, x_2, \ldots, x_m$ and x_{m+1}. If the change point exists, the year is marked as an abrupt change point j, and subsequent values of the series are used to confirm or reject the hypothesis. The regime shift index is estimated as:

$$\mathrm{RSI}_{i,j} = \sum_{i=j}^{j+q} \frac{x_i - (\overline{x}_{R1} + \phi)}{m\delta_m} \quad q = 0, 1, \cdots, m-1 \tag{8}$$

Regime shift are searched continuously until all the available data were evaluated. The change points are determined through regime shift searching.

By using the gauge observed runoff and sediment load data, we proposed two indices to investigate the variation of runoff and sediment yield on the Loess Plateau. The runoff index WI is similar to the concept of runoff depth (mm), which is calculated as:

$$WI = \frac{V}{A} \tag{9}$$

for a catchment with a single hydrological station. For the area between two gauging stations, it is defined as:

$$WI = \frac{V_{lower} - V_{upper}}{A_{inter}} \tag{10}$$

Where: V is the annual total volume of runoff (m^3) and A is the controlled area between two stations (km^2). Runoff index WI can be defined as runoff depth for a single-gauged basin, whereas it denotes the differences of annual discharge for the region between two hydrological stations. Similarly, the SSY index ($Mg\,km^{-2}\,yr^{-1}$) is calculated according to the observed sediment load and controlled area for the investigation.

RESULTS

Temporal Trends in Annual Runoff and Sediment Load

We used the annual runoff and sediment load at Lanzhou and Huayuankou stations (Figure 1) to generally analyze the temporal variation of water resources and sediment yield on the Loess Plateau. Annual runoff indicates stepwise decline from 1957 to 2012 (Figure 2a) according to the estimated regime shift index. Average annual runoff reduction rate is estimated to be $-3.90 \times 10^8\,m^3\,yr^{-1}$. The mean annual runoff difference between Lanzhou and Huayuankou stations was $141.9 \times 10^8\,m^3\,yr^{-1}$ during 1957–1971, whereas it was negative within the period of 1991–2012, suggesting that water withdrawals in this region were much higher than the inflow from tributaries. Sediment load shows similar decreasing trends but different changing stages. Average annual sediment load decreased by $-0.25 \times 10^8\,Mg\,yr^{-1}$. A period with relatively low sediment load was detected from 1960 to 1962 because of Sanmenxia reservoir construction. Sediment load was estimated to be $13.5 \times 10^8\,Mg\,yr^{-1}$ between 1966 and 1978, and decreased to $0.83 \times 10^8\,Mg\,yr^{-1}$ within the 2000s.

According to the regime shift detection (Figure 2) and previous studies (He *et al.,* 2013; Wang *et al.,* 2014), three stages are divided to assess the temporal variation of runoff and sediment load. Although four stages for sediment load were detected, the differences between average annual values were relative gentle in the first two periods. Thus, we used three periods (1957–1979, 1980–1999 and 2000–2012) to investigate the changes in runoff and sediment load. Table I exhibits average annual runoff and sediment load in different periods at mainstream stations along the Yellow River. The average annual runoff at Lanzhou station is $281.1 \times 10^8\,m^3$ from 2000 to 2012, accounting for approximately 84.4% of that during 1957–1979 ($333.2 \times 10^8\,m^3\,yr^{-1}$). Average annual runoff between 2000 and 2012 at other stations shows approximately 50% reduction compared to that of the former period. By contrast, sediment load variation is inconsistent with runoff. Sediment load at all the stations demonstrate more significant decrease ($P < 0.01$) during the past decades, particularly for the downstream stations. Sediment load at Lanzhou station during 2000–2012 was $0.21 \times 10^8\,Mg\,yr^{-1}$, accounting for only 23.0% of that between 1957 and 1979. This is not the main reason led to sediment load reduction of the Yellow River. Whereas the reduction was mainly attributed to the changes between Toudaoguai and Huayuankou stations because this region contributes more than 90% of sediment to the Yellow River (Table I). Among these four stations, we can also clearly see that sediment load at Longmen and Huayuankou stations reduced by approximately 90% in the 2000s when comparing to the period between 1957 and 1979.

Spatiotemporal Variation of Annual Runoff and Sediment Yield

The runoff index WI is an indicator related to available water resources, which also represents the effects of human activities on surface runoff of the river in the specific section. The Mann–Kendall test was employed to the WI to identify the temporal trends of runoff at catchment scale (Figure 3a). Significant decreasing trends ($P < 0.05$) can be observed in most of the catchments except for the downstream of Wei river basin. The most significant reduction ($P < 0.01$) was found in the areas of Toudaoguai–Fugu and Tongguan–Huayuankou, with decreasing rates less than $-1.5\,mm\,yr^{-1}$ in WI, but the downstream of Wei river basin showed an insignificant increasing ($P < 0.05$) trend ($0.27\,mm\,yr^{-1}$). This may suggest that inflow water is not only from the upstream regions, but possibly delivered by additional irrigation system.

Figure 3b-d displays the spatial pattern of WI during different periods on the Loess Plateau. In general, we found negative values of WI from 1957 to 2012 in the sections of Lanzhou–Toudaoguai, Longmen–Tongguan and Tongguan–Huayuankou. This denotes that water consumption is always higher than the tributaries inflow in these regions. Spatial pattern of WI also exhibits rainfall distribution on the Loess

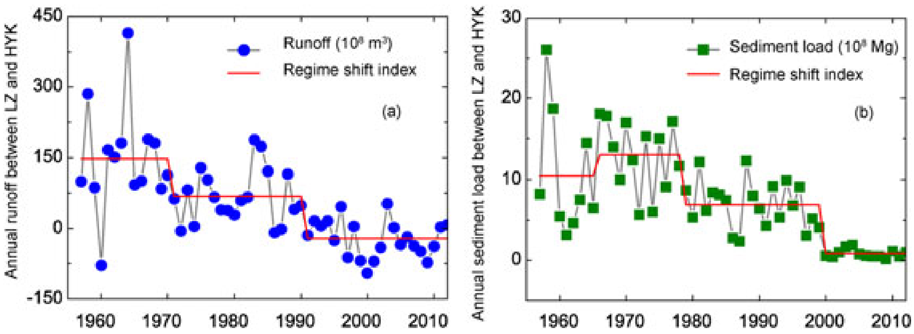

Figure 2. Temporal variation of annual runoff and sediment load between Lanzhou and Huayuankou station (LZ: Lanzhou; HYK: Huayuankou).

Table I. Average annual runoff and sediment load in different periods along the Yellow River

Stations	1957–1979		1980–1999		2000–2012	
	Runoff (km^3)	Sediment (10^8 Mg)	Runoff (km^3)	Sediment (10^8 Mg)	Runoff (km^3)	Sediment (10^8 Mg)
Lanzhou	33.32	0.93	29.67	0.48	28.11	0.21
Toudaoguai	24.60	1.52	19.76	0.69	16.21	0.44
Longmen	31.04	10.64	23.72	4.9	18.28	1.60
Huayuankou	44.58	12.77	33.43	7.29	25.13	1.04

Plateau, which decreases from the south to the northwest. While a relatively wet region was detected in the Kuye river basin (Figure 3b) with high WI of 109 mm yr^{-1}, which can be attributed to the frequently occurred storms in the region. During the period from 1957 to 1979, the wettest regions with WI higher than 120 mm yr^{-1} are located in the Tao river, Wei river and Yiluo river in the southern Loess Plateau (Figure 1). A majority of catchments have WI between 40 and 80 mm yr^{-1}. However, the WI decreased to 0–40 mm yr^{-1} during the period 1980–1999 (Figure 3c), and this decreasing trend was more evident in 2000s, where all the sub-catchments between Toudaoguai and Longmen stations had WI between 0 and 40 mm yr^{-1}.

Figure 4a displays the spatial variation of annual SSY on the Loess Plateau from 1957 to 2012. The MK test suggests that annual SSY in most of the sub-catchments show significant reduction. These regions are primarily situated between Toudaoguai and Longmen station. The average annual reduction rate of SSY is higher than 50 Mg km^{-2} yr^{-1}. The most significant reduction can be found in the northern Loess Plateau, and the decreasing rates reached up to 600 Mg km^{-2} yr^{-1}. Three sub-catchments display insignificant increasing trend in annual SSY (downstream Wei river, mainstream sections of Longmen–Tongguan and Tongguan–Huayuankou). The increase in the SSY may result from historical sediment deposition in these river channels. In the earlier period (1957–1979), large amount of sediment deposited on the alluvial plain and elevated the river bed, whereas this amount reduced evidently because of limited sediment supply in the latter period.

During the period between 1957 and 1979, a large number of high erodible sub-catchments with average annual SSY bigger than 15 000 Mg km^{-2} yr^{-1} can be observed, and most of which lie between Toudaoguai and Longmen stations (Figure 4b). This region is also called 'the Coarse Sandy Hilly Catchments' (McVicar *et al.,* 2007), which contributed approximately 80% of the sediment to the Yellow River. Particularly high SSY was found in Gushanchuan

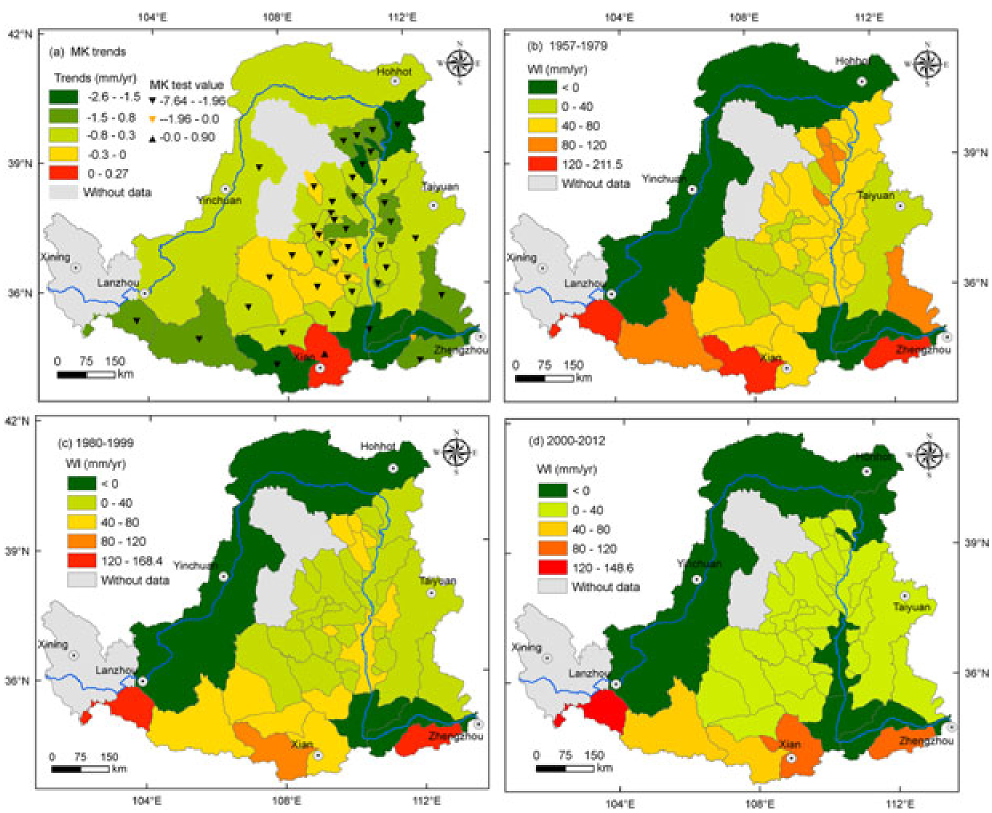

Figure 3. Spatial pattern and temporal trend analysis for runoff index on the Loess Plateau.

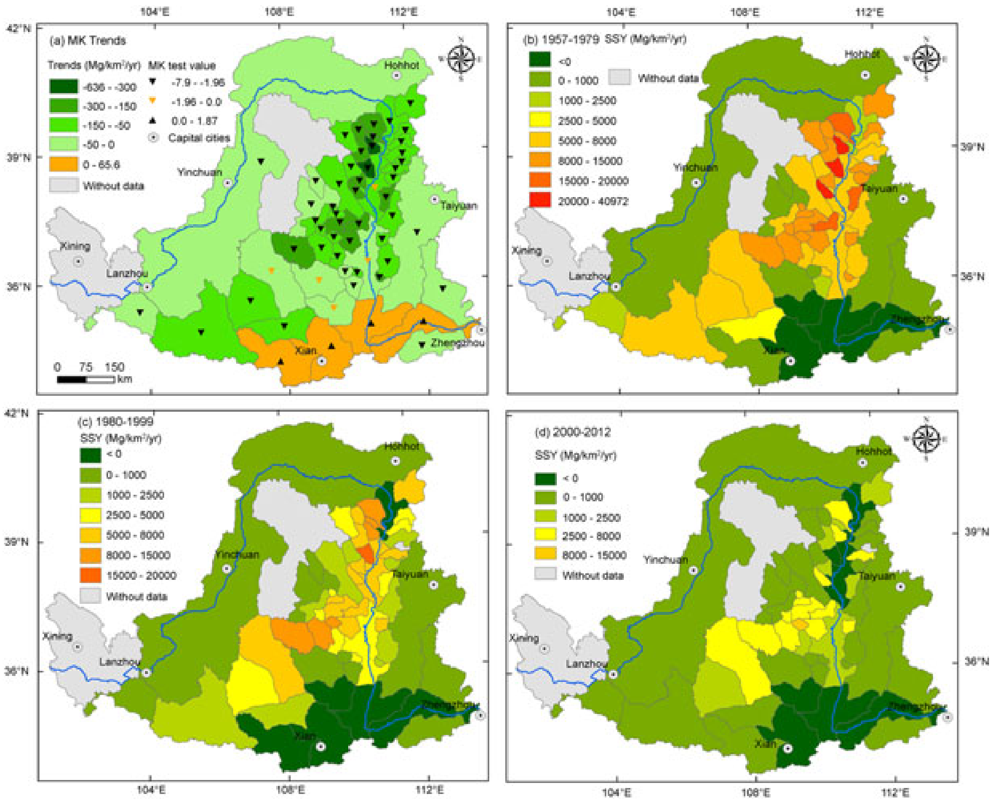

Figure 4. Spatial pattern and temporal trend of specific sediment yield on the Loess Plateau.

and Kuye river, and the average annual SSY ranges from 20 000 to 41 000 Mg km^{-2} yr^{-1}. This is also consistent with high values of WI because large amount of heavy storms occurred during the summer in these sub-basins.

In the latter two stages (1980–1999 and 2000–2012), the highest SSY decreased significantly ($P < 0.05$). The areas with negative SSY (sediment deposited in the channel) were increasing, as well as the areas with SSY <2500 Mg km^{-2} yr^{-1} (Figure 4c and d). In the 2000s (Figure 4d), areas with SSY >10 000 Mg km^{-2} yr^{-1} disappeared completely, and only a very small catchment covering an area of 923 km^2 in the upstream of Qingjian River has a SSY of 8395 Mg km^{-2} yr^{-1}, the area with SSY >5000 Mg km^{-2} yr^{-1} was 17.1×10^4 km^2 between 1957 and 1979, while in the later period all of them decreased and were lower than 5000 Mg km^{-2} yr^{-1} except the aforementioned small region.

Comparison of annual SSY among three periods presents remarkable spatial and temporal variation in different catchments. Annual SSY showed significant decline ($P < 0.01$) when comparing the SSY from 2000 to 2012 with that between 1957 and 1979 on the Loess Plateau. The catchments with significant downward trend ($P < 0.05$) were primarily distributed in the section between Toudaoguai and Huayuankou station. Particularly in the section from Toudaoguai and Tongguan stations, average annual SSY was 760.4 Mg km^{-2} yr^{-1} (2000–2012), which was much lower than that of the earlier period (4233 Mg km^{-2} yr^{-1}, 1957–1979) and represented more than 80% reduction.

Runoff and Sediment Load Budget Analysis

Figure 5 shows average annual runoff, inflow from tributaries and outflow in different sections. The differences among these variables indicate water resources availabilities and effects of human activities. The section between Lanzhou and Toudaoguai stations represents a water consumption region because the upstream inflow was always

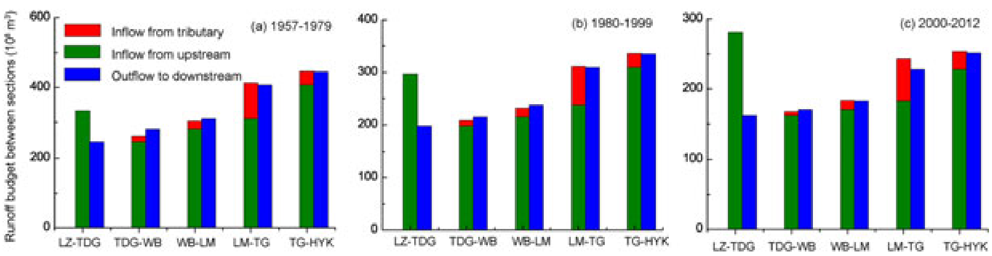

Figure 5. Runoff budget analysis among different sections (LZ: Lanzhou, TDG: Toudaoguai, WB: Wubao, LM: Longmen, TG: Tongguan, HYK: Huayuankou).

higher than the outflow at Toudaoguai station. This can be explained by the fact that only a few tributaries flow into the main river and contribute limited water flow to the section. Furthermore the water extraction was increasing in the latter two periods (Figure 5b and c). The difference between inflow of Lanzhou and outflow of Toudaoguai was $119 \times 10^8\,m^3\,yr^{-1}$ in the period of 2000–2012 (Figure 5c), which is much higher than that of 1957–1979 ($87.2 \times 10^8\,m^3$, Figure 5a). The inflow from the tributaries in the other five sections (between Toudaoguai and Huayuankou stations) is very limited compared to the runoff at Lanzhou station. The average annual inflow (from tributaries) between Toudaoguai and Huayuankou stations was $199.8 \times 10^8\,m^3\,yr^{-1}$ from 1957 to 1979, and decreased to $89.2 \times 10^8\,m^3\,yr^{-1}$ during 2000–2012.

Sediment budget displayed a different pattern compared to runoff variation. In general, sediment mainly came from the regions between Toudaoguai and Tongguan stations (Figure 6). The total amount of sediment income in Lanzhou–Toudaoguai section was very limited (0.59×10^8 Mg in 1957–1979), but still decreasing (0.23×10^8 Mg between 2000 and 2012). Between Toudaoguai and Huayuankou, three mainstream sections belonged to deposition regions, but only the Wubao–Longmen section was an erosive area. The differences between sediment inflow from upstream, tributaries and outflow to the downstream regions were relatively high in Toudaoguai–Wubao and Tongguan–Huayuankou sections. This may be attributed to trapping effects of several large reservoirs (Tianqiao, Wanjiazhai, Xiaolangdi and Sanmenxia Reservoirs). In 2003, the Chinese government launched a project to reduce sedimentation in the downstream by flushing the reservoirs. However, this project was not efficient to resolve the sedimentation of downstream channel. The difference between sediment inflow and outflow in the section between Tongguan and Huayuankou was 2.06×10^8 Mg during 1957–1979, and did not change remarkably during 2000–2012 (1.79×10^8 Mg). This suggests that the sedimentation was decreasing in this section, but not significant ($p < 0.05$).

DISCUSSION

Climate Change Effects

The significant decline of WI and SSY can be attributed to climate change and anthropogenic activities. However, quantitative assessment on the impacts of climate changes and human activities on runoff and sediment yields faced great challenges because of complex nonlinear processes and influencing factors. A synthesized analysis were undertaken to estimate the potential driving forces on changes of runoff and sediment yield based on previous publications and measurements data. We firstly analyzed the changing trends of annual average precipitation and air temperature on the Loess Plateau. As shown in Figure 7, the Loess plateau experienced a relatively dry and warm period during the past six decades. Average annual precipitation exhibited downward trend with an average decreasing rate of -1.23 mm per year. The average annual precipitation was about 470–480 mm yr^{-1} from 1950 to 1979 (Table II), while it decreased to approximately 440 mm yr^{-1} afterwards. Our previous studies suggested that the decreasing precipitation contributed approximately 20–30% of decrease in runoff and sediment load reduction (Li *et al.,* 2015; Zhao *et al.,* 2014a). Furthermore, average annual temperature increased by 0.3 °C per decade (Figure 7). A relatively warmer period was examined in recent years. Climate warming increases potential evapotranspiration and reduces runoff water to some degree (McVicar *et al.,* 2007; Zhang *et al.,* 2008).

Effects of Soil and Water Conservation

Numerous soil and water conservation practices, including both biological and engineering measures, have been implemented on the Loess Plateau since the late 1950s (Chen *et al.,* 2007; Jiao *et al.,* 2007; Zhang *et al.,* 2008). The biological measures consist of afforestation and planting grass, which may have delayed effects on runoff and sediment load reduction because they need time for growing. Improved vegetation can largely increase rainfall interception, infiltration and accelerate evapotranspiration with their growth (Costa *et al.,* 2015; Moreno-Ramón *et al.,* 2014; Novara *et al.,* 2013; Sadeghi *et al.,* 2015; Zhang *et al.,* 2001). Furthermore, plants take up more water for their growing. Thus, natural species of vegetation with limited water demand may be optional for ecological restoration on the Loess Plateau. In addition, natural vegetation can improve the landscape diversity and increase land surface roughness compared to the artificial vegetation. This may reduce surface runoff energy and hydrological connectivity, resulting in lower sediment transport capacities compared to the uniform land use/cover.

The NDVI is a widely used indicator representing the spatial and temporal variation of biological measures. In this

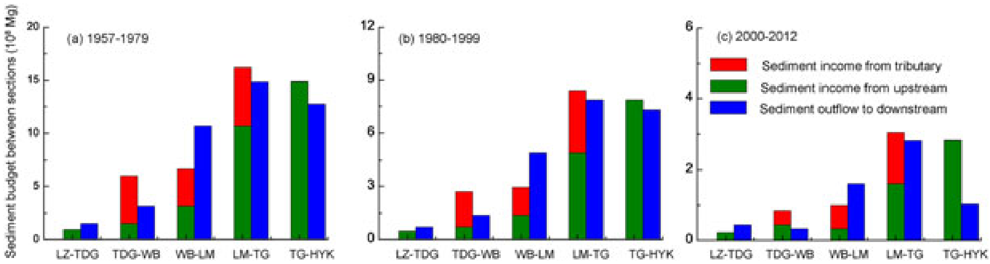

Figure 6. Sediment budget analysis among different sections.

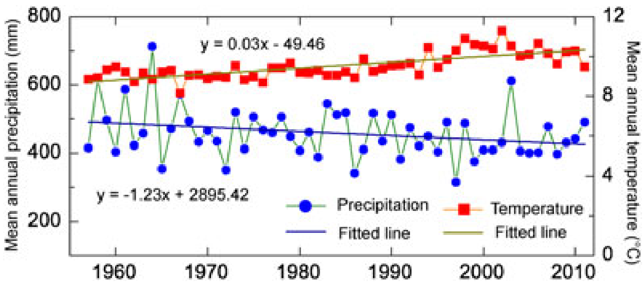

Figure 7. Changing trends of precipitation and temperature on the Loess Plateau from 1957 to 2012.

study, we employed a linear trend test for NDVI from 1981 to 2012 on the Loess Plateau. Figure 8 showed general increase of NDVI from the early 1981 to 2012, while the trends differ in regions within different periods. From 1981 to 1999, increasing NDVI mainly occurred in the downstream of the Wei river basin, northeastern Loess Plateau, but these trends are not significant ($P < 0.05$). Some small parts in the upstream of the Jing river, Beiluo river, downstream of the Qingjian river and middle reaches of the Fen river basin showed decreasing NDVI. This may be attributed to the implementation of the "Grain for Green" project. In the beginning of the project, large area of arable lands were planned to be converted to forests and grass land. However, the small new plants have limited canopy cover, and the uncovered land surface needs several years for restoration. The extreme large project contributed great effects to the evident increasing NDVI in the 2000s (Figure 8b) (Zhang *et al.,* 2008). The NDVI values in the area between Toudaoguai and Longmen stations displayed obvious increase between 2000 and 2012, particularly in the Wuding river basin. Gently upward trend can be also found in upper reaches of Wei river, Jing river and Beiluo river basin. The significant increasing NDVI ($P < 0.05$) shows homogeneous regions where runoff and sediment load decrease between 2000 and 2012.

The engineering structures mainly include terraces and dams, which affect runoff by reducing flood peaks and storing water within check-dams and reservoirs. These measures consequently decrease both the magnitude and the variability of runoff. A field survey in 2009 suggested that more than 5000 large- and medium-check dams have been built on the Loess Plateau (Figure 9). Most of them are located between Toudaoguai and Longmen stations, as well as the upstream of the Wei river, the Jing river and the Beiluo river basin. Check dam construction experienced a booming period since 1970s because of progress of techniques and various government-sponsored conservation projects. Taking the Huangfuchuan Watershed (northern Loess Plateau) as an example, among 507 check dams in the basin, nearly 90% of them were built after 1970, which controlled approximately 70% of the watershed (Tian *et al.,* 2013). Recent observation indicated that both magnitude and frequency of flood events became lower and less. Statistics suggested that about 110 000 check dams have been built on the Loess Plateau and approximately 21 billion m^3 of sediments have been captured by these dams over the past 60 years. Both biological and engineering measures resulted in dramatic decrease in streamflow and sediment load, and their impacts were becoming greater in recent years (Table II). As reported by Zhao *et al.* (2014a), the soil and water conservation measures became the dominant factor, and trapped $74.5 \times 10^8\,m^3\,yr^{-1}$ water and $6.1 \times 10^8\,Mg\,yr^{-1}$ sediment on average during 2000–2012.

Influences of Large Reservoirs Construction

More than 3150 reservoirs have been built in the whole Yellow River since the 1950s, and approximately 2500 of them were situated on the Loess Plateau (Ran & Lu, 2012). In the upstream of Lanzhou, a number of large- and medium-sized reservoirs have been built. For example, the Liujiaxia reservoir with total storage capacity of

Table II. Decrease of streamflow (Q, $10^8\,m^3$) and sediment load (Qs, 10^8 Mg) on the loess plateau and their response to potential influencing factors

Time period	1950–1956	1957–1979	1980–1999	2000–2012	1950–1956	1957–1979	1980–1999	2000–2012
Average P (mm)	470.6	479.0	442.8	443	470.6	479.0	442.8	443
Average Q and Qs[a]	172.9	112.6	37.6	−29.8	12.8	11.8	6.8	0.8
Decrease in Q and Qs[b]		60.3	135.3	202.7		1.0	6.0	12.0
		Contribution to Q reduction ($10^8\,m^3$/a)				Contribution to Qs reduction (10^8 Mg/a)		
Soil-water conservation[c]		—	45.8	74.5		1.8	3.1	6.1
Trapping by Reservoirs[d]		6.4	2.1	2.3		3.1	1.5	2.1
Changes from upper reaches[e]		−12.3	36.5	52.1		—	0.45	0.71
Increased water consumption[d]		22.7	47.9	46.9		—	—	—

[a]Average Q and Qs denote the differences of annual streamflow and sediment load between Lanzhou and Huayuankou stations, and the negative values means outflow at Huayuankou is lower than that of Lanzhou station, suggesting great abstraction in this section.
[b]Differences were estimated between relative period to the period of 1950–1956.
[c]Data were obtained from Wang et al. (2005) and Zhao *et al.* (2014a).
[d]Data were obtained from YRCC (2000–2012), http://www.yellowriver.gov.cn/zwzc/gzgb
[e]Changes from upper reaches denotes the variation of average annual inflow water and sediment flux at Lanzhou station.

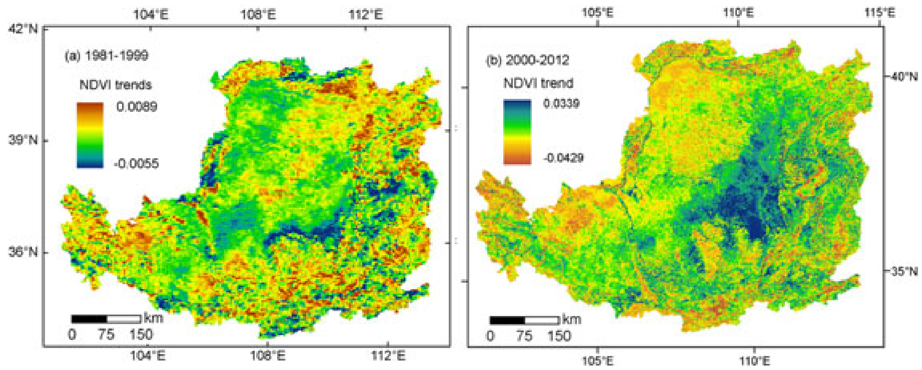

Figure 8. Variation of NDVI on the Loess Plateau from 1982 to 2012 (Trends of NDVI during each decades, a: 1982–1999; b: 2000–2012).

$57 \times 10^8\,m^3$, has the ability to store nearly 20% annual runoff at Lanzhou station. Similarly, several large reservoirs were built between Lanzhou and Huayuankou such as Qingtongxia, Wanjiazhai and Tianqiao reservoirs. Particularly in the section Tongguan–Huayuankou, four large reservoirs, including Sanmenxia, Xiaolangdi, Luhun and Guxian reservoir with total storage capacity of $248 \times 10^8\,m^3$, resulted in high trapping effects on both runoff and sediment load. The Sanmenxia reservoir trapped 7.9 billion Mg sediment during the first few years (1960–1973), and joint regulation with Xiaolangdi reservoir trapped about $2.1 \times 10^8\,Mg\,yr^{-1}$ sediment recently (YRCC, Yellow River Conservation Committee, 2000–2012). Yang *et al.* (2008) employed the 'range of variability' approach method to detect the spatial variability of hydrologic alterations because of dam construction in the section of Tongguan–Huayuankou, they found the impacts of the Sammenxia reservoir on the hydrologic alteration are relatively slight, while the Xiaolangdi reservoir has significant effect on the natural flow regime.

Long-Term Water Consumption

The Yellow River is regarded as the "Cradle of the Chinese civilization" sustaining 102 million people for surviving (An *et al.,* 2005). Rapid development of economy and the expansion of agriculture irrigation have led to over-exploitation of both surface runoff and groundwater. The average annual withdrawal between Lanzhou and Huayuankou was approximately $118.4 \times 10^8\,m^3\,yr^{-1}$ in the 1950s, and increased to $165.3 \times 10^8\,m^3\,yr^{-1}$ during 2000–2012 (YRCC, Yellow River Conservation Committee, 2000–2012; Zhang *et al.,* 2005a).

Statistics indicated that agriculture is by far the largest user of water, accounting for 80% of the total withdrawal; industrial, urban and rural domestic sectors share the remaining 20% (Zhang *et al.,* 2005a). Agricultural irrigation is the key factor for the reduction of runoff in the area between

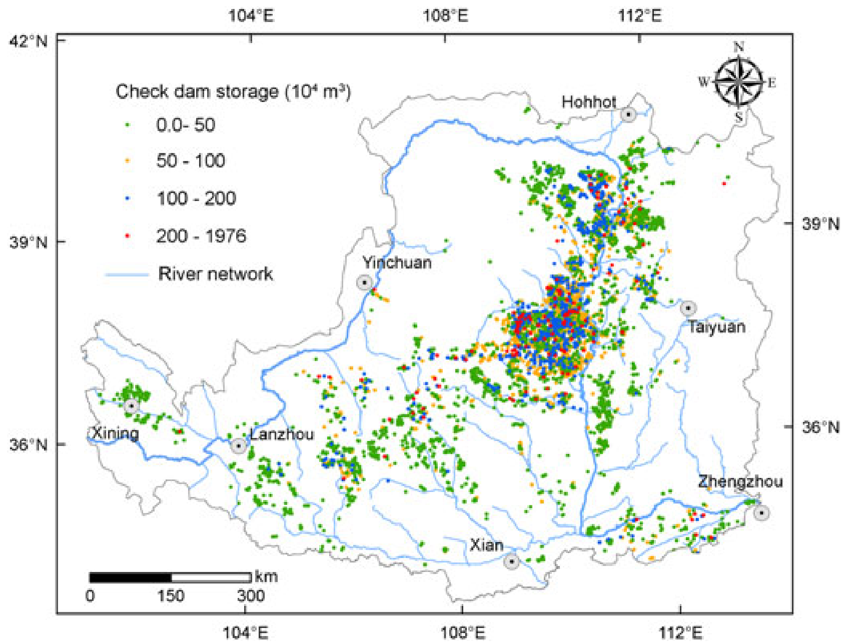

Figure 9. Spatial distribution of large-medium check dams on the Loess Plateau.

Lanzhou and Huayuankou station. There are three large irrigation areas on the Loess Plateau, two of which are located between Lanzhou and Toudaoguai (i.e. the Ningxia and Inner Mongolia irrigation districts). These irrigation districts withdrew 6.41 and $75.9 \times 10^8\, m^3\, yr^{-1}$ on average from 1997 to 2006, respectively. This inferred that agricultural irrigation was the main cause led to negative WI in this area. Another Guanzhong irrigation district is situated in the Wei River valley covering an area of $0.91 \times 10^4\, km^2$ irrigated lands, and consumed an average of $13.2 \times 10^8\, m^3\, yr^{-1}$ between 1997 and 2006 (Yao *et al.,* 2011).

Further Scopes of This Study

The present study selected 58 hydrological stations to investigate the spatial and temporal variation of runoff and sediment yield on the Loess Plateau. However, uncertainties related to the data measurements have not been addressed in our studies, neither in previous studies. In the study area, the daily runoff was estimated through measured water level using previously calibrated curve of runoff vs water level, where the water level was monitored by an automatic recorder. The water was sampled at different intervals to capture the flood processes and then used to analyze the samples in the lab to obtain the suspended sediment concentration (Tian *et al.,* 2016). All the annual runoff and sediment load data were obtained by summing up the daily observed values. In the Yellow River basin, hundreds of hydrological stations were continuously monitored for runoff and sediment load during the past decades. Of course, the measured tools would be updated, and sampling intervals are different. These may lead to different quality of the hydrological data, although the data has been checked out and validated before their releasing. Thus, it is necessary to study the uncertainties on data consistencies, measurement errors et al.

As aforementioned, a decreasing trend for annual precipitation and an increasing trend for temperature have been examined (Table II and Figure 7). However, this is not sufficient to explain the reduction in both runoff and sediment yield from Lanzhou to Huayuankou because of effects of intensive human activities. Previous studies emphasized the importance of variability in rainfall erosivity (Burt *et al.,* 2016; Capra *et al.,* 2015; Porto & Walling, 2012; Porto *et al.,* 2013), and found a general increase in the intensity, frequency and duration of major storms in several areas of the globe. These observations have important implications for soil erosion and sediment load. However, studies on the Loess Plateau presented a positive relationship between annual rainfall and annual erosivity, and a decreasing trend for rainfall erosivity over the period 1956–2008 (Xin *et al.,* 2011). Their results are consistent with our findings, which are both derived from daily rainfall. As most of the sediment loads were caused by several storms in the Loess Plateau, higher resolution rainfall data are required for further investigation, which are more adequate than daily, monthly or annual data to detect rainfall erosivity (Porto, 2015; Yin *et al.,* 2015).

We examined the effects of intensive human activities and climate change on runoff and sediment, while it is still not clear on how each driving force influences the runoff and sediment load changes. Thus, there is a need for more detailed studies on the mechanisms of different human activities (i.e. water abstraction, afforestation, terracing and dam construction) on hydrological processes in such a drastic changing area. In addition, the potential changes in runoff and sediment load in the future were an important issue because it strongly relates to the hydraulic projects planning and soil and water conservation measures implementation for the policy makers. Zhang *et al.* (2005b) found an increasing sediment load using projections for the next 80 years; however, this is contrasting to the present situation (significant reduction in both runoff and sediment load) because the human activities tend to reduce sediment transportation in the basin. Therefore, the future studies should consider the combining effects of climate variability and human activities on runoff and sediment load variation.

CONCLUSION

This study examined the spatiotemporal variation of runoff and sediment yield at catchment scale from 1957 to 2012 on the whole Loess Plateau. Annual runoff between Lanzhou and Huayuankou stations indicated stepwise decline with a reduction rate of $-3.90 \times 10^8\, m^3\, yr^{-1}$. Sediment load showed consistently decreasing trends. A period of extreme low sediment load was detected between 2000 and 2012, which accounted for approximately 10% of that during 1957 to 1979. A large number of sub-catchment displayed significant downward trends ($P < 0.05$) in runoff index WI with decreasing rates from -0.1 to $-3.1\, mm\, yr^{-1}$ between 1957 and 2012. The SSY in 52 sub-catchments showed decreasing trend with a range between -1.54 and $-677\, Mg\, km^{-2}\, yr^{-1}$. The spatial pattern suggested that the coarse sandy areas between Toudaoguai and Longmen stations had extremely high annual sediment yield ranging from 8000 to 41 000 $Mg\, km^2\, yr^{-1}$ from 1957 to 1979. The Kuye and Gushanchuan catchments showed relatively higher WI and SSY comparing to the nearby catchments because of frequently occurred heavy storms. Budget analysis in runoff and sediment load indicated that the area between Lanzhou and Toudaoguai stations contributed limited sediment load. Sediment deposition areas were increasing and mainly distributed along the mainstream of the Yellow River because of large reservoir construction. The Loess plateau experienced a relatively dry and warm period during the past half century, whereas the intensive human activities are the dominant factors for the significant decline in annual runoff and sediment load on the Loess Plateau. The adoption of large-scale soil and water conservation measures altered the runoff regime and led to gradual reduction in both runoff and sediment yield between Toudaoguai and Tongguan stations. Large reservoirs operation played a critical role between Tongguan and Huayuankou stations.

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ADDITIONAL INFORMATION

Competing financial interests: The authors declare no competing financial interests.

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