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Temporal and spatial variations in water discharge and sediment load on the Loess Plateau, China: A high-density study

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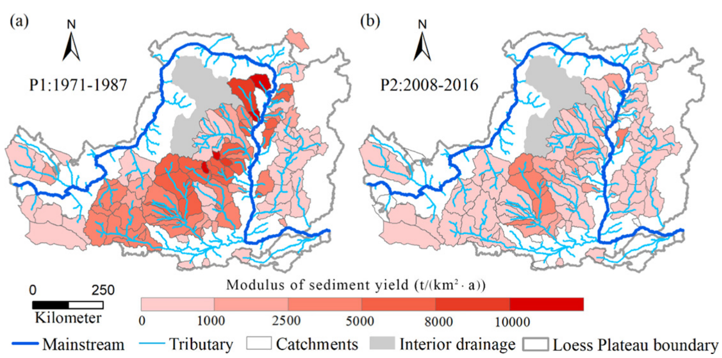
HIGHLIGHTS

- We present results from a high density observation of water discharge and sediment load on the Loess Plateau.
- Water discharge was reduced by 22% during the period 2008–2016, whereas the sediment load was reduced by 74%.
- Human activities contributed more than 72% of the changes in sediment load on Loess Plateau.

GRAPHICAL ABSTRACT



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ABSTRACT

Over the past 50 years, a series of soil and water conservation measures have been implemented on the Loess Plateau, including biological, engineering, and agricultural measures. As a result, water discharge and sediment load on the plateau have undergone significant changes. In this study, we compared the water discharge and sediment load at >100 hydrological stations across the Loess Plateau during the period 2008–2016 (P2) with the water discharge and sediment load during the period 1971–1987 (P1), and detected the main sources of sediment in each of the two periods. We then performed an attribution analysis to quantify the influence of different factors on the changes in sediment load. We found the following results: (1) Water discharge was reduced by 22% in P2 compared with P1, whereas the sediment load was reduced by 74%. (2) Sediment resources are mainly concentrated between Toudaoguai and Tongguan stations: this region contributed >88% of the total sediment load at the terminal station (Huayuankou station) in both P1 and P2. (3) When considering only the changes in sediment concentration on the Loess Plateau, we conclude that the contribution of human activities was >72%. This study provides a detailed description of the temporal and spatial variations in water and sediment across the Loess Plateau, providing a reliable reference for the future development of ecological soil and water conservation measures on the Loess Plateau.

1. Introduction

The Loess Plateau is the largest area of loess in the world, with deep and soft soil that is rich in nutrients (Chen et al., 2007; Yang et al.,

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2019a). It has a long agricultural history and is considered to be one of the birthplaces of ancient Chinese civilization. Today, the Loess Plateau is also known for its severe soil erosion (Fu et al., 2011) and is one of the world's most ecologically fragile regions (Chao et al., 2017). Previous studies found that the average soil erosion modulus for the Loess Plateau reached 7179.76 t/($km^2 \cdot a$) (Chen et al., 1988). As a result of the severe erosion, the Yellow River has become the most hyperconcentrated sediment-laden river in the world (Kong et al., 2017), and nearly 90% of the sediment in the Yellow River originates from the Loess Plateau (Chen et al., 2007). The high concentration of sediment in the river has in turn led to downstream siltation and a rise in the riverbed, with a consequent increase in the risk of loss of life from flooding. In order to control the severe soil erosion and to prevent the transported sediment from entering the river system, a series of soil conservation measures have been implemented on a large scale across the plateau since the 1970s, including engineering measures (dams, reservoirs and etc.), biological measures (afforestation), and tillage measures (no-till and rotating crops). A plan for the comprehensive management of small watersheds was initiated in China in the early 1980s. In 1999, the Chinese government implemented the "Grain for Green" project and achieved great success in intercepting sediment (Fu et al., 2017).

After long-term continuous afforestation, the vegetation in many areas on the plateau is almost a secondary forest. The water demands of some of these planted trees are greater than those of native trees or bare land (Gao et al., 2014). Because of the massive absorption of soil water by planted trees, the water content of the soil has decreased (Wang et al., 2011; Yang et al., 2019b). Simultaneously, the runoff depths of many tributaries on the plateau have declined, in some cases to zero (Chen et al., 2005; Zhao et al., 2017). There are several reasons for the decrease in surface runoff. Vegetation growth consumes some of the water from precipitation. In addition, precipitation falling onto slopes quickly infiltrates shallow ground (Xu, 2011). However, because of thick litter layers (Zhang et al., 2008), water present temporarily in shallow ground rarely becomes groundwater, and instead quickly evaporates (Xu, 2011). Research shows that evapotranspiration is greater in areas planted with trees (Sun et al., 2008). Furthermore, human water consumption has gradually increased on the plateau over the past few decades, contributing to declines in discharge (Yu et al., 2013). Improving soil protection on the plateau and reducing the amount of sediment transported by the Yellow River will not be achieved by reducing water discharge but by changing the relationship between water discharge and sediment load. This is the most feasible way to maintain the sustainable development of water resources on the Loess Plateau.

On the Loess Plateau, the process of soil erosion process is complicated by the influence of both human activities and climate change. Climate conditions across the Loess Plateau are sensitive to variations in the east Asian summer and winter monsoons (Porter and An, 1995). Sun et al. (2015b) showed that many catchments on the plateau have experienced climate change to different degrees, especially catchments in the southwest. Zhang and Liu (2005) predicted annual precipitation would increase by 23–37% and that maximum and minimum temperatures would rise by 2.3–4.3 °C and 3.6–5.3 °C, respectively, in the southern part of the plateau during the 21*st* century. Changes in human activity also play a key role in soil erosion, with both positive and negative effects on sediment load. Soil erosion has been aggravated by the large-scale conversion of forests into cultivated land, by reclamation of steeply sloping land, and by overgrazing. These are all regarded as negative behaviors since they act to increase the sediment in the river. Conversely, afforestation, dams, reservoirs, etc. all reduce the sediment load in the mainstream and are thus regarded as positive behaviors. In recent years, there have been interactions between these positive and negative effects, resulting in human activities playing a major role in the ecological and hydrological processes on the Loess Plateau (Gao et al., 2016; Wang et al., 2015; Gao et al., 2019).

Quantitatively distinguishing the relative impact of climate change and human activities on hydrological processes on the Loess Plateau has become a focus of intense research in recent years. To assess the effects on changes in runoff, Liang et al. (2014) analyzed the changes in water discharge at 14 hydrological stations over the period 1960–2009, using the elasticity method based on the Budyko hypothesis, and found that ecological restoration (regarded as a human activity) and climate change were respectively responsible for 62% and 38% of the total changes in runoff. Using the same method and the same research period but including 15 stations, Gao et al. (2016) showed that changes in land use/cover and precipitation contributed approximately 65% and 42% to reductions in water discharge. Wu et al. (2017), using ten commonly used quantitative methods, reported that climate change (54%) was the main factor influencing decreases in runoff in the Yan River basin, a secondary watershed on the Loess Plateau, with human activities contributing 46%. Zhao et al. (2017) investigated changes in sediment load in the Huangfuchuan catchment, a sub-basin on the Loess Plateau, using a combination of field work and modeling. They found that human activities (land use/cover and the construction of engineering measures) were responsible for 80% of the sediment load decrease in the catchment over the period 1990–2006. Gao et al. (2017) used time-trend analysis to calculate the relative contributions of climate change and human activities in 15 catchments on the Loess Plateau over the period 1960–2011, and reported values of 70% (land use/cover) and 30% (precipitation). The results from these studies are not universal but depend on the size of the catchment(s), the geological landforms, the climate conditions, and the degree of human interference, and may also be affected by the research periods and methods chosen.

Most of the prior analyses focused either only on a single catchment or only on the changes in water discharge and sediment load at a small number of hydrological stations across the Loess Plateau (usually <20). However, the plateau covers a vast territory and can be split into five sub-regions: moist and semi-moist forest, semi-moist and semi-arid forest grassland, semi-arid typical grassland, arid and semi-arid desert grassland, and arid desert (Zhang and Huang, 2001). The terrain is complex and diverse (Fu et al., 2011), and the intensity of human interference varies greatly (Tang et al., 1994). Moreover, the research periods in most previous studies are no longer current, yet, in recent years, the Loess Plateau has undergone very complex changes, in both climate (Sun et al., 2015a) and landforms (Fu et al., 2017). For this study, we collected water-discharge and sediment-load data from high-density hydrological observation stations across the plateau, covering almost all of the different regions. With these data, we performed an integrated analysis of the changes in water discharge and sediment load in different regions of the Loess Plateau over recent years, thus providing a comprehensive reference for the management of sediment in the Yellow River and studies of the ecological hydrology of the Loess Plateau.

2. Methods

2.1. Study area

The Loess Plateau covers 640,000 km^2, accounting for about 7% of the total land area in China. It is a typical highland region with an average altitude of 1000 to 2000 m. The plateau is rich in loess, with a thickness of 50 to 80 m in most areas. In eastern and northern Shaanxi province, the thickness of the loess reaches 150 m, and the thickest parts can reach 200 m (Zhang, 1991). The Loess Plateau has a typical arid and semi-arid climate and belongs to the edge of the temperate monsoon climate zone; the instabilities associated with a continental and monsoon climate are prominent. Although the annual precipitation ranges from 400 to 600 mm in most regions (Tang et al., 2018), precipitation is highly concentrated in the summer months. >80% of heavy rains fall in June, July and August, and >70% of the total rainfall during these three months falls in the form of heavy rain (Zhang, 1983). Usually, single heavy rainfall events account for 30% or more of the total annual precipitation (Zhang et al., 2008). The maximum yearly sediment load used to reach 1.6 Gt at Tongguan station (Fig. 1), but, over the past 20 years, the sediment yield has dropped to <0.1 Gt per year owing to climate change and surface environment changes (Wang et al., 2015).

2.2. Data

Data on daily water discharge [m^3/s] and daily suspended sediment concentration [m^3/kg] were obtained from the Hydrological Yearbooks of the People's Republic of China, compiled by the Yellow River Conservancy Commission (YRCC) (http://www.yellowriver.gov.cn/). Precipitation and temperature data at 302 meteorological stations (Fig. 1) were obtained from the National Climate Centre of China Meteorological Administration (CMA) (http://data.cma.cn/). We used the kriging interpolation technique to estimate regional monthly mean precipitation and monthly mean temperature with input from a digital elevation map (DEM). A 90-m resolution DEM of the Loess Plateau provided by the International Scientific Data Service Platform (http://datamirror.csdb.cn/) was used to delineate the hydrological boundaries of all the sub-catchments.

2.3. Hydrological data quality control

In the process of hydrological monitoring, data loss is inevitable to some extent. On the Loess Plateau, the hydrological data loss is much more serious in the dry season (November–April) than in the wet season (May–October). Considering that runoff and sediment are mainly generated in the wet season, we set a wet-season missing-data limit of 5% in this study. If the missing-data rate for a hydrological station exceeded 5%, then that hydrological station was excluded from this study. Ultimately, data from 122 hydrological stations for P1 (1971–1987) and 104 stations for P2 (2008–2015) were included in this study.

For hydrological stations with <5% missing data, we used the average of the values from the same month in the two adjacent years to fill in missing wet-season data, and the mean value from same month in all P1 or P2 years to replace missing dry-season data. Using these hydrological data, we plotted the respective spatial characteristics of discharge and sediment yield for the two time periods. We also used the hydrological observations from 104 stations with data for both P1 and P2 to compare the changes in water discharge and sediment load in the two periods. More detailed information about these hydrological stations is presented in Supplementary Table 1.

2.4. Methodology

2.4.1. Calculating suspended sediment yield

We used the water-discharge data and the sediment-concentration data to obtain the sediment load per day. Therefore, the annual suspended sediment yield can be calculated by the following formula:

$$S = \sum_{i=1}^{365/366} Q_i \cdot SC_i \cdot 86400/1000 \quad (1)$$

$$\overline{S} = \frac{\sum_{j=1}^{n} S_j}{n} \quad (2)$$

$$Q = \sum_{i=1}^{365/366} Q_i \cdot 86400 \quad (3)$$

$$\overline{Q} = \frac{\sum_{j=1}^{n} Q_j}{n} \quad (4)$$

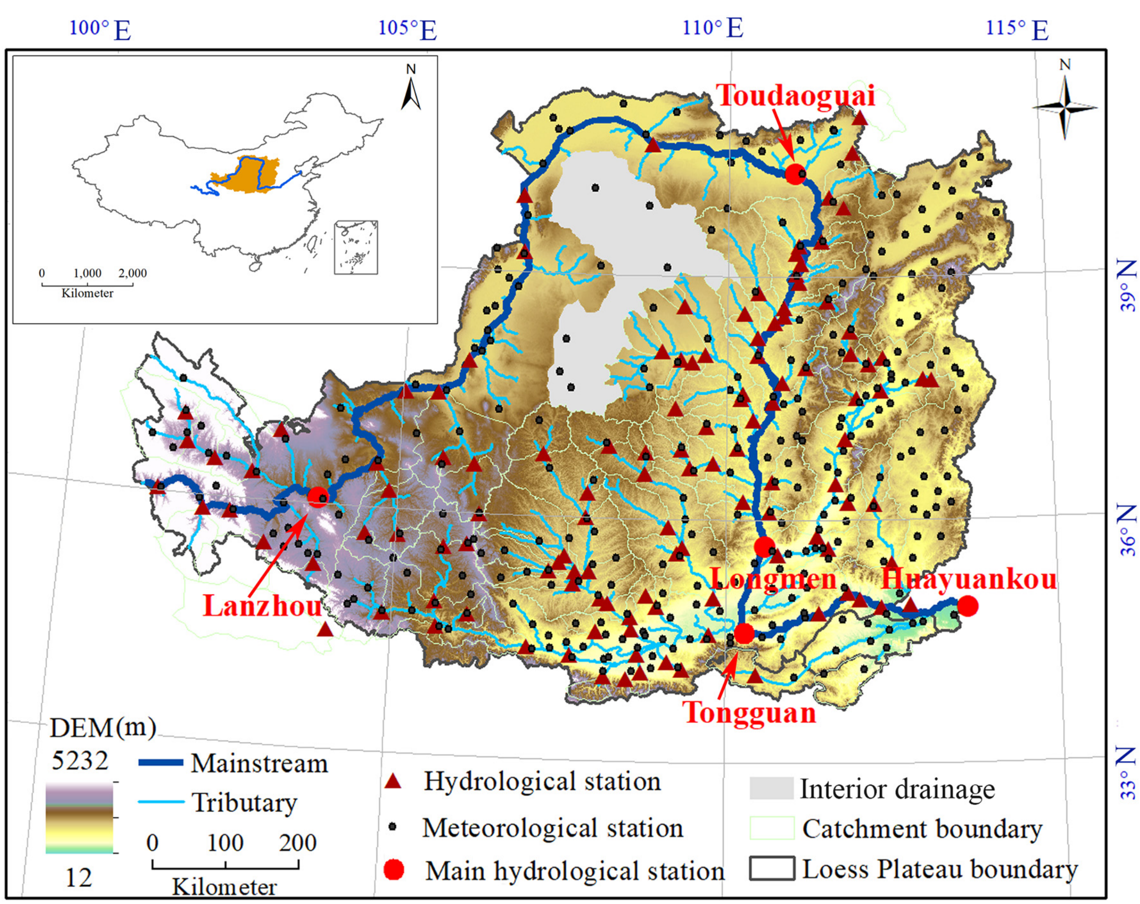

Fig. 1. The locations of hydrological and meteorological stations on the Loess Plateau.

$$SSY = \frac{\overline{S}_2 - \overline{S}_1}{A_2 - A_1} \tag{5}$$

where S [t/year] is the annual sediment load; Q_i [m^3/s] and SC_i [kg/m^3] are the water discharge and sediment concentration on the ith day, respectively; *365* and *366* represent the number of days in non-leap years and leap years. 86,400 is the conversion factor between seconds and years, and 1000 is the conversion factor between kilograms and tons. $\overline{S}$ [t/year] is the annual mean sediment load for n years where S_j is the sediment load in jth year. Q [m^3/year] is the annual water discharge. $\overline{Q}$ [m^3/year] is the annual mean discharge for n years where Q_j is the water discharge in jth year. SSY [t/(km^2·a)] is the suspended sediment yield, which equals the difference between the annual mean sediment load (i.e. $\overline{S}_2 - \overline{S}_1$) of two hydrological stations divided by the difference between the control areas (i.e. $A_2 - A_1$) of the two hydrological stations.

2.4.2. Tributary contribution rates to the sediment load at Tongguan station

The tributary contribution rates are the ratios of the annual (annual wet-season) mean sediment load at the controlled hydrological stations of tributaries to the annual (annual wet-season) mean sediment load at Tongguan station (Li and Liu, 2018; Zhang et al., 2018). The contribution rate roughly reflects the sediment-transport capacity of each tributary and the contribution to the total amount of soil erosion on the Loess Plateau. In this research, the contribution rates were calculated for both the P1 and P2 periods.

2.4.3. Runoff coefficient (Cr) and annual mean sediment concentration (AMSC)

The dimensionless runoff coefficient [Cr] relates the amount of water discharge from a catchment to the amount of precipitation received in that catchment during a certain period. $AMSC$ [kg/m^3] represents the relationship between long-term discharge and sediment at an inter-annual scale. Cr and $AMSC$ are expressed as:

$$Cr = \frac{\frac{\overline{Q}}{A}/1000}{\overline{P}} \tag{6}$$

$$AMSC = 1000 \cdot \overline{S}/\overline{Q} \tag{7}$$

where $\overline{Q}$ [m^3/year] is the annual mean discharge, $\overline{P}$ [mm] is the annual mean precipitation in the control area for each hydrological station and A [km^2] is the control area of hydrological station. 1000 in Eq. (6) is the conversion factor between meter and millimeter, 1000 in Eq. (7) is the conversion factor between ton and kilogram. $\overline{S}$ [t/year] is the annual mean sediment load for n years.

2.4.4. Sediment identity factor assessment

From the processes for producing sediment, we can determine the sediment identity:

$$S = P \cdot \frac{Q}{P} \cdot \frac{S}{Q} = P \cdot Cr \cdot A \cdot AMSC \tag{8}$$

Deriving time [t] on the left and right sides of the above equation, and then dividing by the variable itself gives us:

$$\frac{\frac{dS}{dt}}{S}/A = \frac{d(P \cdot Cr \cdot AMSC)}{dt} = \frac{\frac{dP}{dt}}{P} + \frac{\frac{dCr}{dt}}{Cr} + \frac{\frac{dAMSC}{dt}}{AMSC} \tag{9}$$

Next, we define a function $r(X)$:

$$r(X) = \frac{\frac{dX}{dt}}{X} \tag{10}$$

And then insert the function $r(X)$ from Eq. (10) into Eq. (9):

$$\frac{r(S)}{A} = r(P) + r(Cr) + r(AMSC) \tag{11}$$

Here, we treat P1 and P2 as different time periods in the above time series, and calculate the rates of annual change in P, Cr, and $AMSC$ by linear regression, giving values for the slope. Then, the slope is divided by the respective variable mean values to calculate the proportional change ($r(X)$). In theory, the proportional change in sediment load divided by the basin area should be equal to the sum of the proportional changes in the three factors (P, Cr, $AMSC$).

3. Results

3.1. Changes in sediment load and water discharge

Figs. 2 and 3 show the changes in sediment load and water discharge between the P1 and P2 periods at each hydrological station on the Loess Plateau. There was a significant reduction in both sediment load and water discharge at most hydrological stations (Figs. 2c and 3c). 13% of stations experienced a sediment-load reduction of >0.1 Gt sediment load per year and 44% experienced a water-discharge reduction of >0.1 Gm^3 per year. Only 18% of stations showed a >50% decrease in water discharge; however, 86% of stations had a >50% decrease in sediment load. In general, the reduction in sediment load tended to be more extensive and more significant than the reduction in water discharge. As expected (Miao et al., 2010), the farther the mainstream station is from the Huayuankou station, the greater is the reduction in water discharge (Fig. 3c). All stations except three showed a decrease in sediment load (Fig. 2c and d). Stations with an increase in sediment load were: Zhangcunyi (Beiluo River) – 82%, Luolicun (Wei River) –0.064%, and Wenyuheshuiku (Fen River) – more than 100%.

Compared with P1, we found a 22% reduction in annual water discharge in P2 on the plateau, and a 29% reduction in wet-season water discharge. In addition, an important characteristic can be observed by examining Figs. 2 and 3: the changes in annual sediment load were essentially the same as the changes in wet-season sediment load (Fig. 2c and d), but did not match the changes in discharge (Fig. 3c and d). Only 9 stations showed an increase wet-season discharge but 17 stations showed an increase in annual mean discharge (Fig. 3c and d). In total, the wet-season sediment load across all stations accounted for 96% of the annual sediment load in P1 and 95% in P2, on average. For water discharge, the corresponding percentages were 72% (P1) and 65% (P2).

3.2. Temporal and spatial variations in suspended sediment yield

Suspended sediment yield (SSY) is one of the indicators of the intensity of soil erosion in a basin. It is influenced by geomorphology, ground composition, climate, vegetation coverage, and human activities. Fig. 4 shows the temporal and spatial variations in SSY across the Loess Plateau: 56% of stations had a >80% decrease in sediment yield in P2 compared with P1, and 86% of stations had a >50% decrease. SSY decreased in all basins except Zhangcunyi (Beiluo River) and Luolicun (Wei River) station. And on average, the SSY across the Loess Plateau reduced by 74%.

During P1, the sediment-production capacity of upstream of the Toudaoguai gauging station was relatively weak and the SSY was under 1000 t/(km^2·a) for all stations except Jingyuan station (Zuli River basin), where the SSY reached 3984 t/(km^2·a). The areas with high sediment yield (>5000 t/(km^2·a)) were mainly concentrated in the north of the Toudaoguai–Longmen region, as well as in the northeast Beiluo River basin and the Jing River basin. The areas with the most serious soil erosion formed a band across the central region of

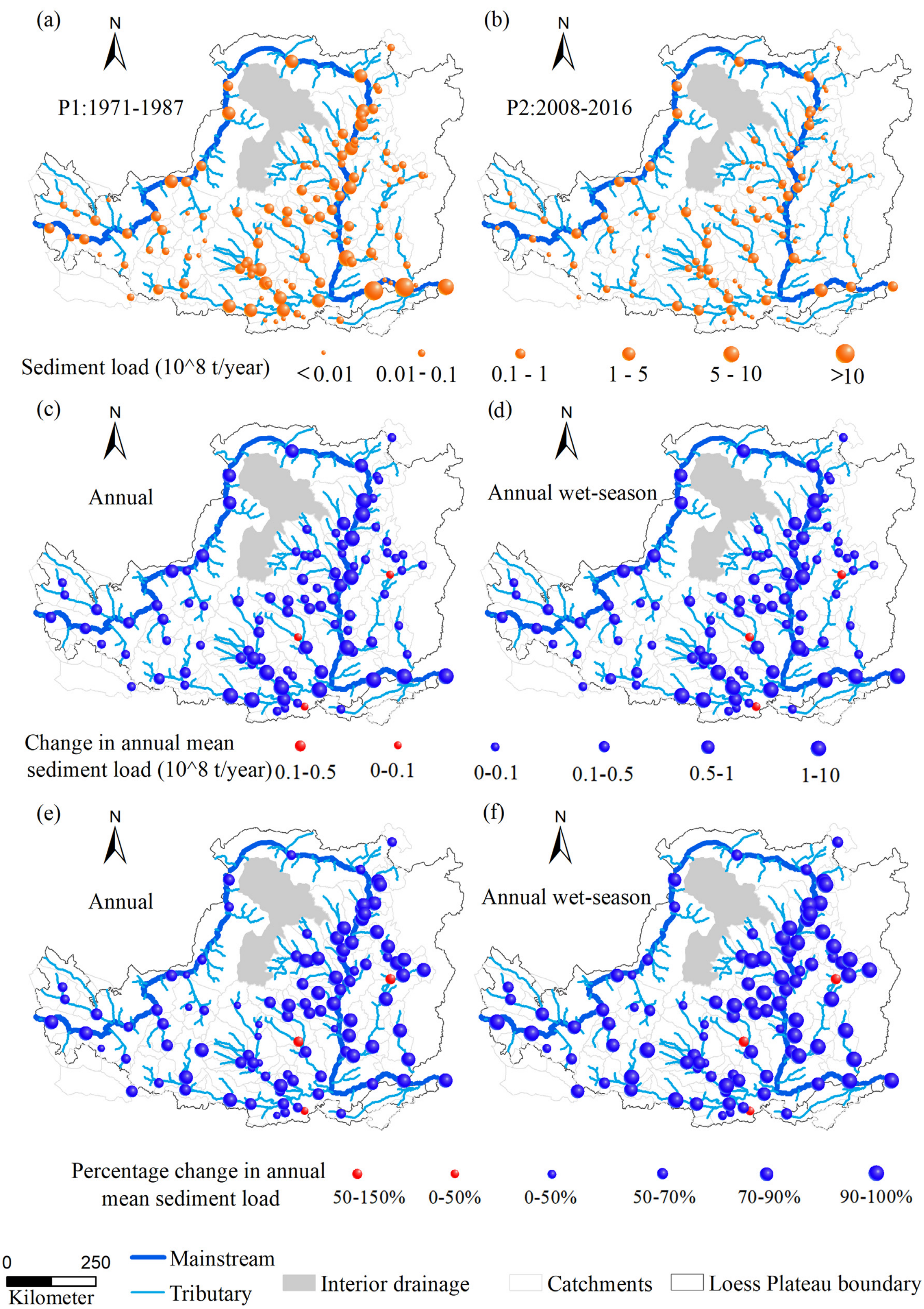

Fig. 2. Each point represents the location of a hydrological station on the Loess Plateau. (a, b) Annual mean sediment load during the two periods, P1 (1971–1987) and P2 (2008–2016). (c, d) Changes in the annual mean sediment load and the annual mean wet-season sediment load (i.e. $S_{P2} - S_{P1}$). (e, f) Percentage changes in the annual mean sediment load and the annual mean wet-season sediment load (i.e. $(S_{P2} - S_{P1}) / S_{P1}$). Subscripts indicate the corresponding period. (c, d, e, f) Red points indicate increases and blue points indicate decreases. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

the Loess Plateau. The areas with the greatest sediment production during P1 were the Huangfuchuan basin (Huangfu station) and the Kuye River basin (Wenjiachuan station), where *SSY* values reached 15,055 t/(km^2·a) and 11,940 t/(km^2·a). The Huangfuchuan and Kuye River basins are both located in the transition zone between the southeastern part of the Ordos Plateau and the Loess Plateau in northern

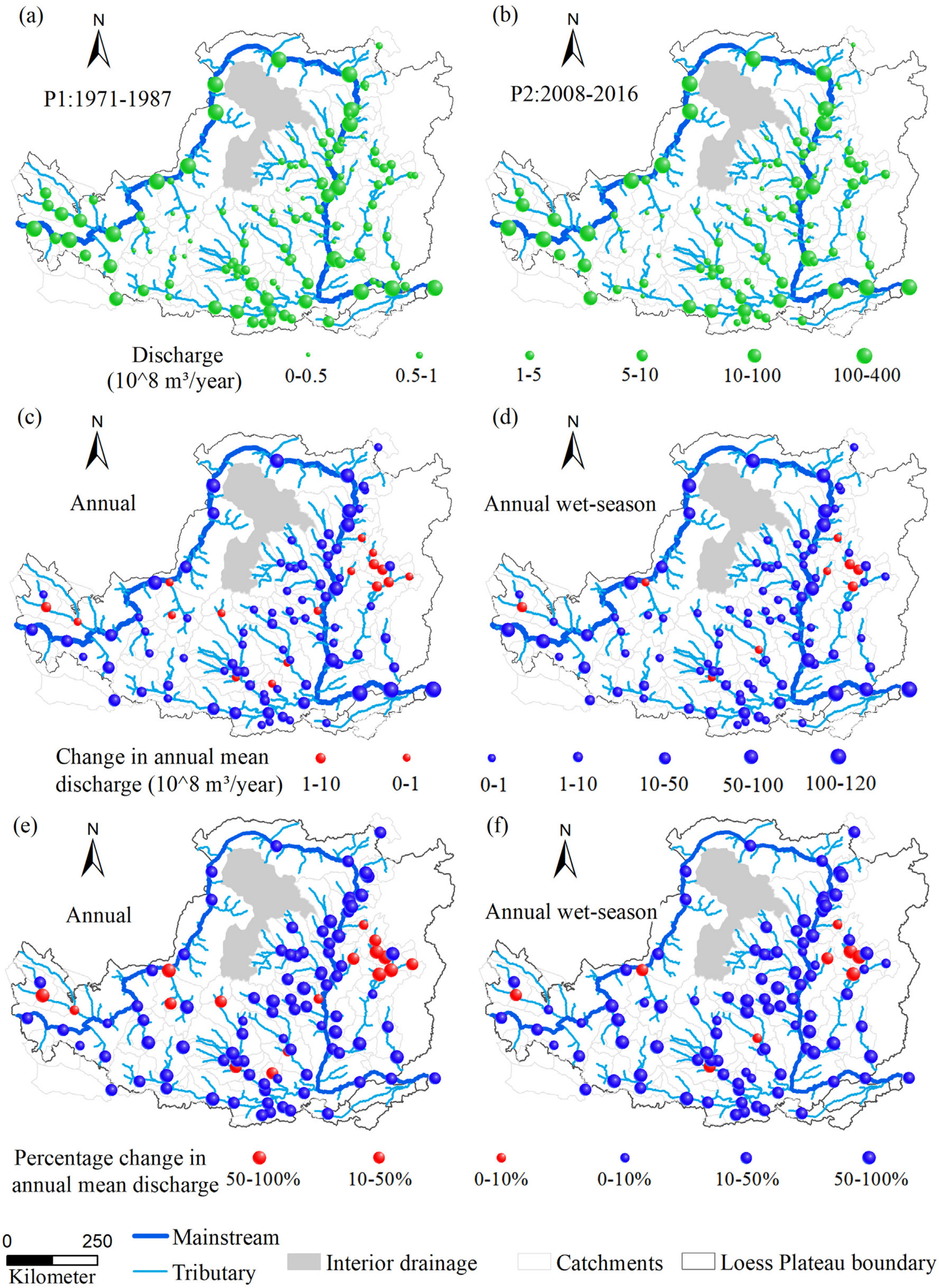

Fig. 3. Each point represents the location of a hydrological station on the Loess Plateau. (a, b) Annual mean water discharge during the two periods, P1 (1971–1987) and P2 (2008–2016). (c, d) Changes in the annual mean water discharge and the annual mean wet-season water discharge (i.e. $Q_{P2} - Q_{P1}$). (e, f) Percentage changes in the annual mean water discharge and the annual mean wet-season water discharge (i.e. $(Q_{P2} - Q_{P1}) / Q_{P1}$). Subscripts indicate the corresponding period. (c, d, e, f) Red points indicate increases and blue points indicate decreases. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Shaanxi. The two basins are both primary tributaries of the middle reaches of the Yellow River and have complex natural conditions.

During P2, the *SSY* did not exceed 1000 t/(km^2·a) for 83% of hydrological stations (Fig. 4b). The sediment yield from the northern Beiluo River basin (Wuqi, Zhidan, and Liujiahe stations) decreased by 90% from P1 to P2. In the western part of the Jing River basin, the sediment yield decreased by >90%. All catchments in the Wei River basin, excluding the Jing River and the Beiluo River, had decreases in *SSY* to below 1000 t/(km^2·a). Moreover, the Qingjian River (Yanchuan station), the Yan River (Ganguyi station), and the rivers on the right-hand side of

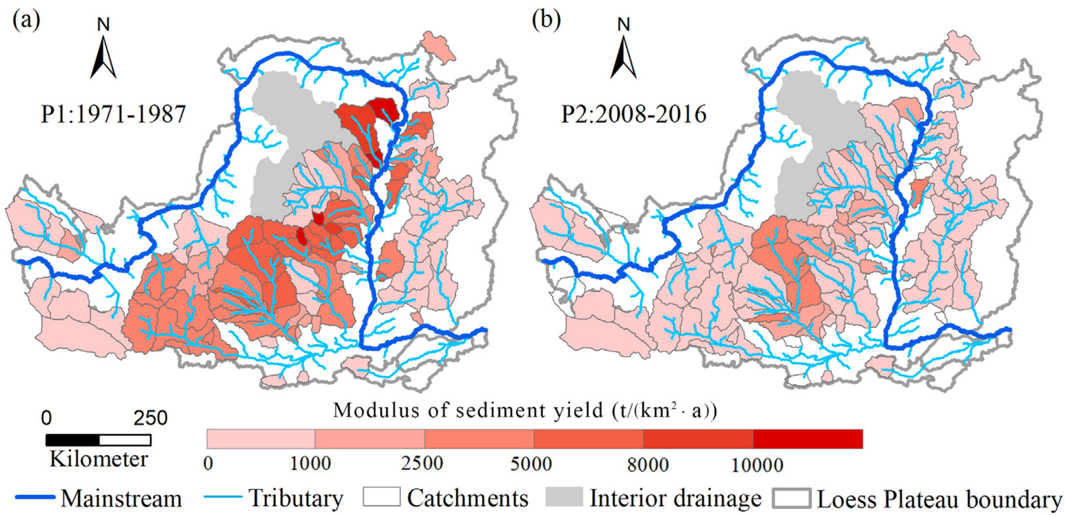

Fig. 4. Spatial pattern of suspended sediment yield (*SSY*) across the Loess Plateau during (a) P1 (1971–1987) and (b) P2 (2008–2016). The *SSY* of the control areas, for six hydrological stations in the Wei River basin whose control-area boundaries were not obtained due to the relatively flat terrain, are not shown in the figure.

the Toudaoguai–Longmen section all controlled soil erosion well in P2. However, for half of the Jing River basin (Zhangjiashan station), the sediment transport intensity remained high.

3.3. Tributary contribution rates to the sediment load at Tongguan station

Historical data showed that just 10% of the total sediment load was derived upstream of Toudaoguai station (Rao et al., 2001); whereas the sediment load at Tongguan station accounted for 98.1% of that of Lijin station (Hu et al., 2005), which is the last station along the Yellow River. The basin between Toudaoguai and Tongguan stations is critical for the production of suspended sediment in the Yellow River. The spatial pattern of sediment yield on the Loess Plateau was essentially the same in P2 as P1 (Fig. 5), with the sediment sources still mainly concentrated in several important tributaries. Fig. 5a shows that the contribution rates differ greatly between different rivers: during P1, the sediment load from Toudaoguai–Longmen section was 49% of the sediment load at Tongguan station, and the percentages were 31% and 20% for the Wei River and the Jing River, respectively. During P2, the percentage rates changed to 25%, 42%, and 43%, respectively.

Although the Huangfuchuan basin and Kuye River basin have a strong capacity for sediment production (see Fig. 4), the total contribution from these two rivers to the sediment-load value at Tongguan station was small (8% in P1 and 1.5% in P2) because the total basin area of the two rivers accounts for just 3.7% of the area in the Toudaoguai–Tongguan section (the yellow area in Fig. 5). In other words, a low contribution value does not mean that the sediment production capacity is weak. When implementing soil and water conservation measures on the Loess Plateau, gully slopes with a strong capacity for sediment production are the key locations to target.

3.4. Changes in *Cr* and *AMSC*

Fig. 6 illustrates the *Cr* and *AMSC* at each hydrological station for P1 and P2. Most points are below the diagonal line in both panels, which indicates that the *Cr* and *AMSC* were larger during P1 than P2. For the *Cr*, 85% of hydrological stations showed a reduction in P2 compared

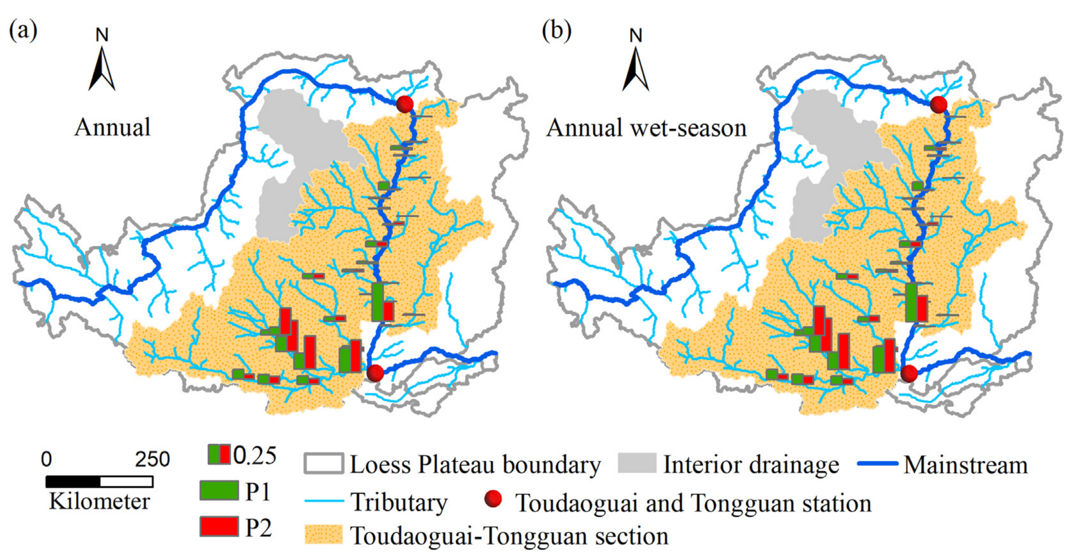

Fig. 5. Tributary contribution rates to the sediment load for the region between the Toudaoguai and Tongguan hydrological stations for (a) annual sediment load and (b) annual wet-season sediment load. The height of the column indicates the magnitude of the contribution rate; height of the column in the legend indicates a contribution rate of 25%. Here, the Toudaoguai–Tongguan section mainly comprises the Toudaoguai–Longmen section, the Jing River basin, the Beiluo River basin, the Wei River basin, and the Fen River basin. (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)

with P1. For the *AMSC*, 90% of stations showed a decrease. The decreases in *Cr* were similar to the reductions in water discharge for most stations (Fig. 2). The runoff coefficient was below 0.6 for all hydrological stations on the Loess Plateau and was below 0.2 for most stations; however, the *AMSC* for the different tributaries showed spatial heterogeneity across the Loess Plateau, varying greatly from catchment to catchment. Furthermore, the *AMSC* was <400 kg/m^3 at most stations during P1 and <200 kg/m^3 at most stations during P2. In Fig. 6b, the points are relatively close to the horizontal axis, which illustrates that the *AMSC* was much lower in P2 than in P1. Fig. S1 illustrates that the sediment load decreasing is not because of the discharge decrease for the tributaries on the Loess Plateau, but the *AMSC* becomes small. For the mainstream, the water discharge and sediment load both have a significant tendency, which means the water discharge reduction may also contribute to the decrease in sediment load.

3.5. Sediment identity factor assessment

By splitting the sediment load into the product of precipitation (P), runoff coefficient (*Cr*), and annual mean sediment concentration (*AMSC*), we found that the degree of sediment transport in the river was affected to some extent by all three factors. Fig. 7 shows that the control areas for 59 hydrological stations had a slight increase in precipitation between P1 and P2, 67 stations showed a decrease in *Cr*, and 75 stations showed a decrease in *AMSC*. For 82 hydrological stations, the average proportional rate of change was 0.14% for precipitation, −1.00% for *Cr*, and −2.21% for *AMSC*. This demonstrates that the *AMSC* and the *Cr* were the main driving forces for the decrease in sediment load. Moreover, there was clear variation in the proportional change for *AMSC* among the hydrological stations (Fig. 7); for 8 stations, the proportional change in *AMSC* even increased by a large margin.

4. Discussion

4.1. Impact of climate change on sediment load and water discharge

Precipitation and temperature are two major climatic factors that influence ecological hydrology processes in catchments, including water discharge, evapotranspiration, and sediment load (Vörösmarty et al., 2018). Generally, river flows in arid and semi-arid regions are sensitive to changes in precipitation. Tang et al. (2018) utilized daily precipitation data at 170 meteorological stations on the Loess Plateau to analyze the changes in precipitation, and showed that the decrease in annual precipitation over the past fifty years was mainly due to a decrease in erosive rainfall. Sun et al. (2015b) used a gridded dataset and found an overall downward trend in wet-season precipitation that was mostly due to a decrease in the frequency and intensity of precipitation over 38% of the plateau. However, Fig. S2 shows that the annual mean precipitation during P2 was slightly higher than that during P1 for most of the controlled areas. The fact that these precipitation characteristics differ from those reported by Tang et al. (2018) and Sun et al. (2015b) may be due to the use of a different research period. Miao et al. (2010) indicated that there is a strong correlation between annual precipitation and water discharge but no significant relationship between annual precipitation and sediment load. However, the results presented here show that, despite a lack of significant change in annual precipitation across the Loess Plateau (Fig. 8a), the water discharge and sediment load at most stations has decreased considerably (Figs. 2e and 3e). This inconsistency may be due to intensive human interference in the region, as discussed further in the next section.

Extreme precipitation largely determines the sediment load and runoff on the Loess Plateau (Li and Gao, 2015). Climate change may cause increases in the frequency of extreme precipitation (Huntington, 2006; Schiermeier, 2011). Although the total amount of annual precipitation on the Loess Plateau has not changed significantly since 1960, nearly 37% of the total area on the Loess Plateau has experienced decreases in the frequency of precipitation together with increases in the intensity of precipitation (Fu et al., 2017). The risk of both severe flooding and drought on the Loess Plateau increased between 1960 and 2011, with the northwestern areas of the plateau showing increased threat of drought and the southeastern areas an increased risk of flooding (Miao et al., 2016). When the intensity of rainfall is high, it has strong kinetic energy and can break up the loose loess, making it easy to carry away, which leads to very high sediment concentrations in the river.

Temperature is also a key climatic factor that can affect the hydrologic regimes of rivers: temperature can influence the erosion rate (McCave, 1984). An increase in temperature of 2 °C can lead to a 20% increase in water discharge and a 30% increase in sediment load for some specific watersheds (e.g., the Colville River), although this does not necessarily generalize (Syvitski et al., 2003). Fig. 8b indicates that the average annual mean temperature across the Loess Plateau has significantly increased over the past few decades, from 6.4 °C to 7.6 °C. Fig. 8b also shows that the average temperature fluctuates from year to year. This warming trend on the Loess Plateau should, in theory, be accompanied

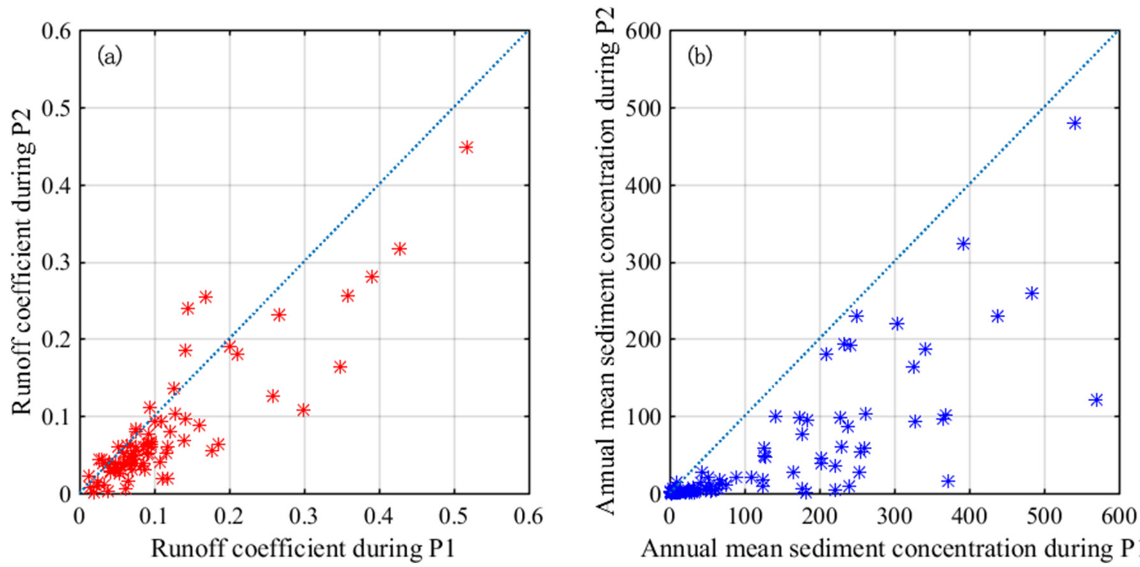

Fig. 6. Changes in (a) the runoff coefficient (*Cr*) and (b) the annual mean sediment concentration (*AMSC*, kg/m^3) at each station. Blue dotted lines indicate the line of equality. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

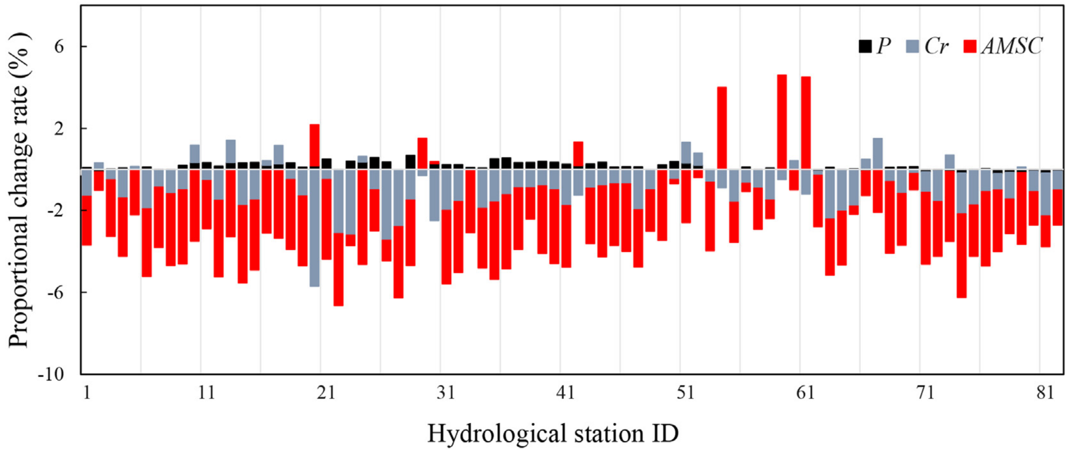

Fig. 7. Proportional changes in the forces driving the dynamic processes underlying sediment reduction, displayed for each hydrological station on the Loess Plateau. *P* is precipitation, *Cr* is the runoff coefficient, and *AMSC* is the annual mean sediment concentration. The bar ID numbers correspond to the hydrological station ID numbers listed in Supplementary Table 1.

by increases in water discharge and sediment yield, given a lack of change in other external conditions. However, increases in temperature can strengthen the evaporation capacity of a region (Hatfield and Prueger, 2015) and result in decreases in runoff. This may affect the microclimate and vegetation growth in a region (Moufida and Djamel, 2012). Therefore, the relationships between temperature and water yield or sediment yield are complex.

Meteorological and hydrological drought can influence the sediment load in a river (Ahmadi et al., 2019). Over the past few years, meteorological and hydrological droughts have intensified on the Loess Plateau (Wu et al., 2018). However, our research results show that the influence of droughts on changes in sediment load is not significant (Figs. 2 and 3). Instead, water conservation measures (dams, reservoirs, afforestation, etc.) are the key factors underlying the decrease in AMSC.

4.2. Impact of human activities on the Loess Plateau

The impact of human activities on the Loess Plateau is extensive and far-reaching (He et al., 2014). Over the past 50 years, the main purpose of human transformation of the surface environment has been to reduce soil erosion on the plateau and downstream sedimentation in the Yellow River. The interventions can be divided into two types: water and soil conservation measures and the construction of reservoirs and large- to medium-sized dams. Sediment-trapping measures can be divided into

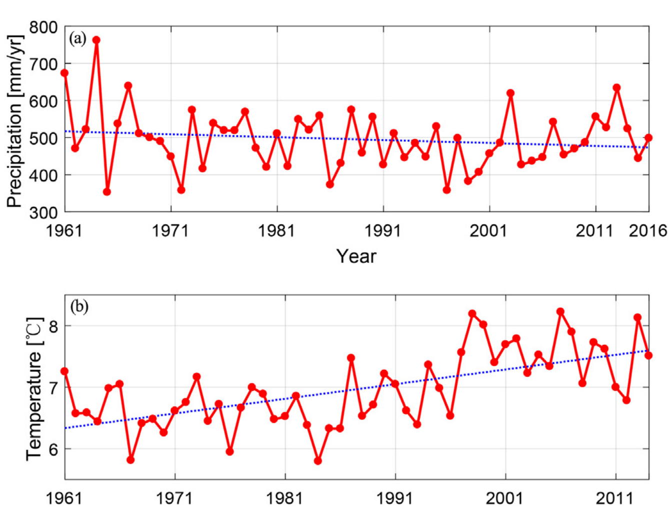

Fig. 8. Climate change on the Loess Plateau. (a) Annual mean precipitation between 1961 and 2016. (b) Annual mean temperature between 1961 and 2014.

two main types on the basis of their location (Gao et al., 2016): slope measures (e.g., planting of trees and grass, no-till approaches, terracing, and the construction of fish-scale pits) and channel measures (e.g., the construction of check dams, key dams, and warping dams).

By the end of 2007, the area affected by soil and water conservation measures covered 225,600 km^2 (Kong et al., 2016), and the vegetated areas had increased by 119,500 km^2 (Kong et al., 2016). The survey data show that the area of afforestation and grass-plating is generally increasing during the past decades (Fig. 9a). There is a significantly negative correlation between vegetation density and sediment yield (Kong et al., 2018): soil erosion can be more than twenty times less with afforestation than with tilled land (Montgomery, 2007). For a mountainous watershed, the greater the vegetation coverage, the lower the intensity of soil erosion intensity (Zhou et al., 2008).

Terraces were widely used for crop production from 1970s (Zhang et al., 2014). The growth of level terrace area (Fig. 9c) on the Loess Plateau have influenced the sediment delivery. The sediment-interception efficiency of terraces in this region can reach 95% (Chen et al., 2007). By the year of 2000, check dams on the plateau had intercepted 71.27 Gm^3 of sediment load (Zeng et al., 1999). Moreover, 242,000 additional check dams will be built in the future (Huang, 2000). Within their life cycle, dams and reservoirs have the most significant ability to intercept sediment (Miao et al., 2010). By 2000, 11,200 large- to medium-sized dams had been built on the Loess Plateau (Feng, 2000). Meanwhile, a great number of reservoirs have been constructed on the Loess Plateau (Fig. 9d). For the Xiaolangdi reservoir, it alone trapped 3.2 Gm^3 sediment by 2014, accounting for almost half of its capacity (Kong et al., 2017). Due to these measures, both river flow and, especially, the sediment load in the river decreased greatly for most catchments on the Loess Plateau, as shown in Figs. 2c and 3c.

However, these measures all have both advantages and disadvantages. Vegetation restoration can reduce the kinetic energy of rainfall through canopy interception and the litter layer to reduce soil erosion (Liu et al., 1994). Furthermore, vegetation and terraces can increase the slope-convergence time and penetration to reduce sediment movement. Whether it is planting trees or constructing engineering measures on the slopes, the purpose is to stabilize the slope landscape. This does have a great effect on the sediment load, but also decreases the runoff to the rivers (Liang et al., 2014; Wang et al., 2015). Water conservation projects in the river channel, such as check dams, are used to intercept the incoming sediment load and runoff to create additional farmland. The sediment intercepted by check dams is very fertile, which leads to the increasing area created by check dam during the past 40 years (Fig. 9b). It was reported that the created agricultural land reached 320,000 ha by 2002 (Wang et al., 2011). Dams not only intercept the sediment load, but also change the speed of the water flow and the

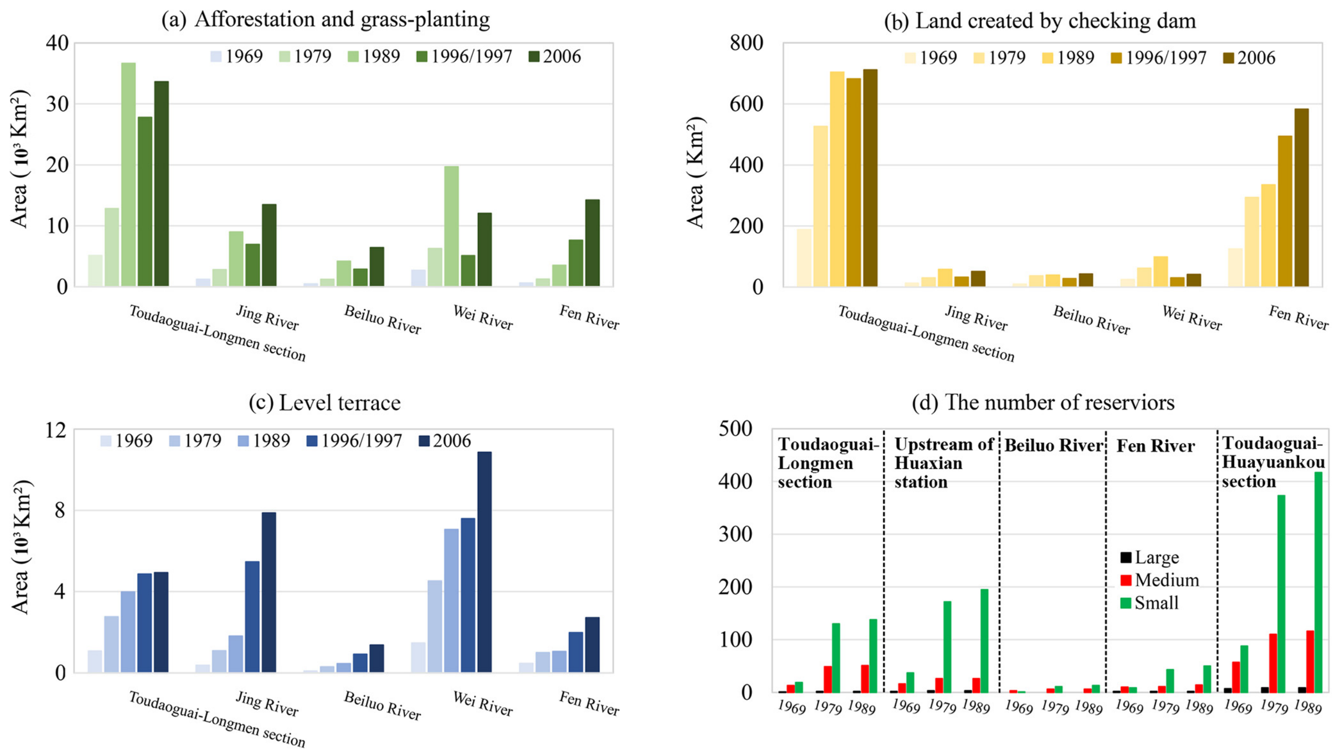

Fig. 9. Statistical data regarding the area covered by water conservation measures in the Toudaoguai–Longmen section and four basins on the Loess Plateau (a, b and c) and the number of reservoirs in important basins or sections across the Loess Plateau (d). The data regarding water conservation measures between 1969 and 1989 and the number of reservoirs are from Xu et al. (2006); data for 1996/1997 and 2006 are from Ran et al. (2012). Note that the range of the Wei River basin in a, b, and c does not include the Jing River basin or the Beiluo River basin.

level of the water, potentially affecting water discharge in the rivers (Arias et al., 2012). Ngo et al. (2016) reported that climate change and reservoirs/dams play opposing roles: reservoirs and dams reduce water discharge extremes, so dams can also to some extent reduce the extreme sediment-transport values in rivers. But once the rivers with check dams become farmlands, the purpose of building these dams is invalidated. The capacity of these dams to intercept sediment has declined in recent years (Ran et al., 2013), and the lifetimes of some dams are only about 10 years (Xu, 2004).

Synchronous decreases in surface runoff and sediment load may lead to many problems, the most distinct of which are slower growth—or even scouring—of the Yellow River Delta (Kong et al., 2015), and downstream drought and degradation of wetland ecosystems. The limited soil water is overused by the non-native vegetation planted on the Loess Plateau, leading to the formation of dried soil layers (Wang et al., 2011), which slows the infiltration of runoff (accelerating evaporation) (Ritchie, 1998), leading to decreases in groundwater (Gao et al., 2015). Considering the current status of water resources and the relatively low runoff coefficient on the Loess Plateau (Fig. 6a), returning farmland to forest is an unsustainable solution. Because the ecosystem of the Loess Plateau is still very fragile (Fu et al., 2017), policymakers need to carefully weigh the advantages and disadvantages of slope-based measures, especially planting trees on the slopes. Replacing non-native species with native trees should be considered. When selecting tree species for afforestation, it is best to take both the integrity of the ecological hydrological process and the economic benefits of the tree species into account to avoid farmers re-cultivating the land, which will lead to aggravation of soil erosion.

4.3. Contributions of human activities and climate change to changes in the sediment load

Over recent decades, human activities and climate change have had a tremendous impact on the Loess Plateau and have fundamentally changed the ecological environment in the region. We presented preliminary findings on the relative contribution human activities and climate change in Fig. 7. The *Cr* is mainly affected by changes in precipitation duration and intensity and underlying surface features (Wu et al., 2006), which are related to both climate change and human activities. The *AMSC* comprehensively represents the relationship between water discharge and sediment load for a basin and it is mainly influenced by human activities (Zhang et al., 2018). For the 82 hydrological stations on the plateau, if we only consider the changes in the *AMSC*, the contribution of human activity to the sediment decrease is 72% (the average proportional rate of change of the *AMSC* was −2.21% and the sum of the three factors was −3.07%; −2.21% divided by −3.07% equals 72%, see the result in Section 3.5 for the specific values). However, if we consider the changes in both the *AMSC* and the *Cr*, the maximum contribution of human activity is 104% ((−1.00% plus −2.21%) divided by −3.07% equals 104%). The contribution rate may be >100% because the precipitation increased while the sediment load decreased (i.e. climate change has a negative effect on the sediment load change), as suggested by Guo et al. (2018). Several previous studies showed that the contribution of human activities to changes in the sediment load has transcended the contribution of climate change, fundamentally altering the characteristics of water discharge and sediment transport on the Loess Plateau (Miao et al., 2011; Mu et al., 2012; Zhao et al., 2013). Wang et al. (2015) reported that, prior to 2000, the main factors responsible for the decrease in sediment load were the construction of terraces and check dams and changes in precipitation, but after the year 2000, the main factor was revegetation. Overall, the impact of human activities has been deepening, but because many hydrological stations have only small control areas, each is influenced to different degrees by different factors. The next step is to find a way to accurately quantify the contribution of human activities and climate change to changes in water discharge and sediment load in small watersheds.

5. Conclusions

The degradation of the Loess Plateau has been the focus of much study. In this study, we analyzed data from 122 hydrological stations between 1971 and 1987 (P1), and from 104 hydrological stations between 2008 and 2016 (P2), to assess changes in water discharge and sediment load during the two periods. The annual water discharge in P2 was 22% lower in P2 than in P1, and the wet-season water discharge 29% lower. We found larger decreases in sediment load: a 74% reduction in the annual sediment load in P2 compared with P1 and a 75% reduction in the wet-season sediment load. Only 18% of stations showed a decrease in water discharge of >50%; however, 86% of stations showed a >50% decrease in sediment load.

The sediment yield results show that soil erosion has weakened on the Loess Plateau. However, there were no fundamental changes in the main sediment resources of the Loess Plateau: the Wei River, Jing River, and the Toudaoguai–Longmen section remained the most important. Using sediment identity factor assessment and 82 hydrological stations, we conducted a systematic analysis of the factors driving sediment reduction. Precipitation increased in the control areas for 59 hydrological stations in recent years whereas the runoff coefficient (*Cr*) decreased in the control areas for 67 stations and the annual mean sediment concentration (*AMSC*) decreased at 75 stations. The main driving forces behind the reduction in sediment load were the *AMSC* and the *Cr*. To briefly conclude, the contribution of human activities to sediment decreases was >72%, with a maximum value of 104%. Through this study, we aim to raise awareness of the complexities involved in soil and water conservation measures. Achieving sustainability of a healthy hydrological cycle on the Loess Plateau remains a challenge.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2019.02.246.

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