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Analysis of changes in characteristics of flood and sediment yield in typical basins of the Yellow River under extreme rainfall events

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ABSTRACT

The future trend of water and sediment variation is closely related to the governance of the Yellow River. The increasingly frequent occurrence of extreme rainfall events has rendered the future water and sediment situation of the Yellow River uncertain. Understanding the characteristics of flood and sediment yield of the river basin under extreme rainfall conditions at different times is a prerequisite and foundation for accurate prediction of water and sediment situation in the Yellow River in the future period. We here used the July 26 extraordinary rainstorm event in 2017 in the Wuding River as a starting point for revealing the law of flood and sediment yields changes under extreme rainfall conditions around the year 2000. The results indicated that, during the period from 1960 to 2016, the average proportion of extreme rainfall depth in the middle Yellow River region over the total precipitation depth increased by 5.1%. Areas where extreme rainfall events frequently occur showed a trend of developing from localized regions in the Toudaoguai–Longmen reach to the majority of the middle reaches. There were obvious changes in the rainfall-flood and rainfall-sediment relations under extreme rainfall conditions. Compared with historical extreme rainfall events, the decline in flood and sediment yield in the river basin after 2000 under similar rainfall and intensity conditions was obvious. Among these results, flood decreased by 30.4–78.2%, sediment yield was decreased by 53.0–88.2% and sediment content in flood was decreased by > 47.2% on average when compared with the same rainfall conditions in the previous century. Comparative watershed studies showed that, during extreme rainfall events, areas under soil and water loss management programs suffer 57.2% and 75.7% less flood runoff modulus and sediment transport modulus, respectively, than non-managed areas. This indicates that soil and water loss management is the major driving factor for changes in rainfall-flood and rainfall-sediment relations under extreme rainfall conditions. This study highlights the importance of soil and water loss management in the flood control and sediment reduction. We concluded that, with the implementation of soil and water conservation measures, the probability of large flood and sediment events will greatly decrease and the amount of sediment entering the Yellow River under extreme rainfall will further decrease in the next 30 years.

1. Introduction

Global warming and the frequent occurrence of extreme meteorological and hydrological events caused by it results in great impact on society, economy, and ecosystems (Coskun et al., 2010). It has drawn a great deal of attention from various governments and international organizations (Ren et al., 2014; Jiang et al., 2016). This is particularly so for extreme rainfall events because their frequency and intensity have increased, resulting in changes in flood runoff and serious damages to economic production and people's lives. Due to the severity of extreme rainfall events and the disaster chain it causes, research on its variation characteristics and effects has attracted widespread attention (Huang et al., 2014; Hibino et al., 2016).

The Yellow River being the second largest river in China is famous for its highest sediment content in the world and disastrous floods (Mu, 2010). It only accounts for 2% of the total water volume of China, but

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irrigates 15% of China's farmland and supplies water to 12% of the population. > 400 million people live in the Yellow River basin. The Yellow River plays a decisive role on the national economy. Excessive sediment and insufficient water is the basic characteristics of the Yellow River (Hu, 2016). This distinct characteristic causes complexity and difficulty in management. Considering the trend of runoff and sediment in the Yellow River directly affects the planning of the Western route of the National South–North Water Transfer Project and the direction of governance for the downstream broad beach region, the future water and sediment situation of the Yellow River have long been a major concern of water resource management agencies and disaster prevention and mitigation departments. A lot of studies show that the runoff and sediment load of the Yellow River showed a sharp reduction in the past few decades due to the change in climate and human activities. According to He (2017), compared to the period of 1919–1959, the mean yearly runoff volume after 2010 decreased by 46%, and the mean yearly amount of sediment yield was decreased by nearly 94%, while precipitation only decreased by 4.5%. The changes in runoff and sediment in the Yellow River is so greater and faster that it exceeds people's imagination, which would bring a great influence on practices of Yellow River harnessing such as river regulation and layout of large-scale hydraulic project (Yao et al., 2017). Therefore, under this new sediment-runoff change condition, predicting the average sediment yield and annual runoff for the future years is the most urgent, and has received more attention. However, influenced by human activities and extreme climate events (especially extreme precipitation events), no consensus has been reached hitherto (Liu, 2016). Under the background of global climate change, the frequent occurrence of extreme rainfall events has added uncertainty to the prediction of the future runoff and sediment situation in the Yellow River. To revealing study the effects of extreme rainfall events of the future runoff and sediment situation in the Yellow River, it becomes urgent to identification of the changes in flood and sediment yield characteristics under different extreme rainfall events across different time periods and discusses the main driving factors.

The middle reaches of the Yellow River, lies in the core of the Loess Plateau, is well known for its severe soil erosion around China (Li et al., 2012). It is an important source of Yellow River sediment and also a key administrative region of water and soil loss management. Approximately 90% of the sediment originates from the middle Yellow (Chen et al., 2007). Severe soil erosion and sediment discharge have led to challenges in relation to the reservoir operation and river management of the lower Yellow River (Xin et al., 2014). Under the background of global climate change, extreme rainfall occurs frequently and it aggravates the situation of regional soil erosion control (Wei et al., 2007). Huang et al. (2014) suggested that extreme rain events are significantly increasing in Yellow River basin of China in the past 50 years. Gao and Xie (2014) reported that the intensity of rainfall and amount of heavy rainfall have increased during the last decades over the Yellow River basin. Liu et al. (2012) suggested that extreme rainfall is the key factor affecting soil erosion in this region. Zhou and Wang (1992) reported that soil erosion of the Loess Plateau is caused mainly by a few times of heavy rain or rainstorms. Li et al. (2012) found that soil erosion caused by a heavy rainstorm often accounts for > 90% of the total annual amount. Sun (2015) and Liu (2016) conducted that extreme rainfall events have a decisive impact on soil erosion and sediment in the Yellow River. Carrying out a study in the flood and sediment yield characteristics in the middle reaches of the Yellow River basin under extreme rainfall events across different time periods has considerable significance to the scientific prediction of the effects of extreme rainfall on future water and sediment situation of the Yellow River.

Extraordinary rainstorm event occurred in the Wuding River watershed (the second major tributaries of the middle reaches of the Yellow River) on July 26, 2017. The maximum daily rainfall was 256.8 mm. The rainstorm caused severe flooding in Suide Couny and Zizhou County, Shanxi Province, China. This rainstorm event has provided us with an important case study for studying the characteristics of flood and sediment yield under extreme rainfall events. In view of this, we here used the July 26 extraordinary rainstorm event in 2017 in the Wuding River as a background, and compiled nearly 60 years of flood and sediment yield characteristics and its evolution characteristics in the typical basins (Wuding river, Qiushui River, Huangfu Rvier) in the middle Yellow River under extreme rainfall events at different time periods. The comparative watershed method was applied to quantitatively evaluate the effects of changes in the underlying surface caused by soil and water retention measurements on flood and sediment yield in the basin during extreme rainfall events. The results of the study aimed to provide a scientific basis for the accurate prediction of future Yellow River flood and sediment trends through the identification of the runoff and sediment dynamic variation characteristics, patterns, and their driving factors during extreme rainfall events across different periods. This will also provide support for decisions for soil and water loess management and ecological construction in the basin.

2. Materials and methods

2.1. Description of the study area

The middle reaches of the Yellow River are located in the Loess Plateau hinterland (33°40′N–41°30′N, 103°50′E–113°50′E), with an area of 362,000 km^2 (Fig. 1). This region lies mostly on the transitional border between the monsoon climatic zone and the continental arid climate zone, and is one of main resources of storm floods in the Yellow River. The mean annual precipitation is only 526 mm, and 60% of precipitation occurs in the form of rainstorms. Rainstorm here is frequent, intensive and with a short duration. The arid and low rainfall characteristics, unique geological and geomorphological characteristics, and soil characteristics, have caused the middle reaches of the Yellow River to become a region with the greatest severe soil and water loss in the Loess Plateau. The extreme erosion modulus is 59,000 t/km^2. Three major hydrologic stations are primarily involved in the mainstream Yellow River in its middle reaches, namely the Toudaoguai, Longmen, and Tongguan hydrologic stations. Using Longmen hydrologic station as a demarcation point, the middle reaches of the Yellow River (Toudaoguai–Tongguan reaches) are diviede into the Toudaoguai–Longmen and Longmen–Tongguan reaches. Toudaoguai–-Tongguan reaches is an important source of Yellow River sediment and controls > 90% of sediment yield at the Tongguan station in the Yellow River (Zhang et al., 2012). In recent years, with the continued management of soil and water loss at the Loess Plateau, the underlying surface of this region has undergone drastic changes.

2.2. Data collection and processing

Flood runoff and suspended sediment concentration data from 1956 to 2017 were obtained from the “Compiled Yellow River Basin hydrological and sediment data” by the Yellow River Conservancy Commission. Flood runoff was computed using a velocity–area method from automatic measurements of velocity using a current meter (LS68–2) and water depth at a natural cross-section. Sediment data were accumulated by hour sediment yield calculated from half hour streamflow and suspended sediment concentration (SSC) data. Daily precipitation data from 46 national weather stations in the middle reaches of Yellow River were obtained from the State Meteorology Bureau (http://cdc.nmic.cn/home.do). Annual precipitation was calculated using daily data. ArcGIS 10.1 was used to interpolate annual precipitation data for the middle reaches of Yellow River. Figures and tables were processed and plotted using Origin 9.0 software.

2.3. Extreme rainfall index

The threshold value method that is commonly used internationally

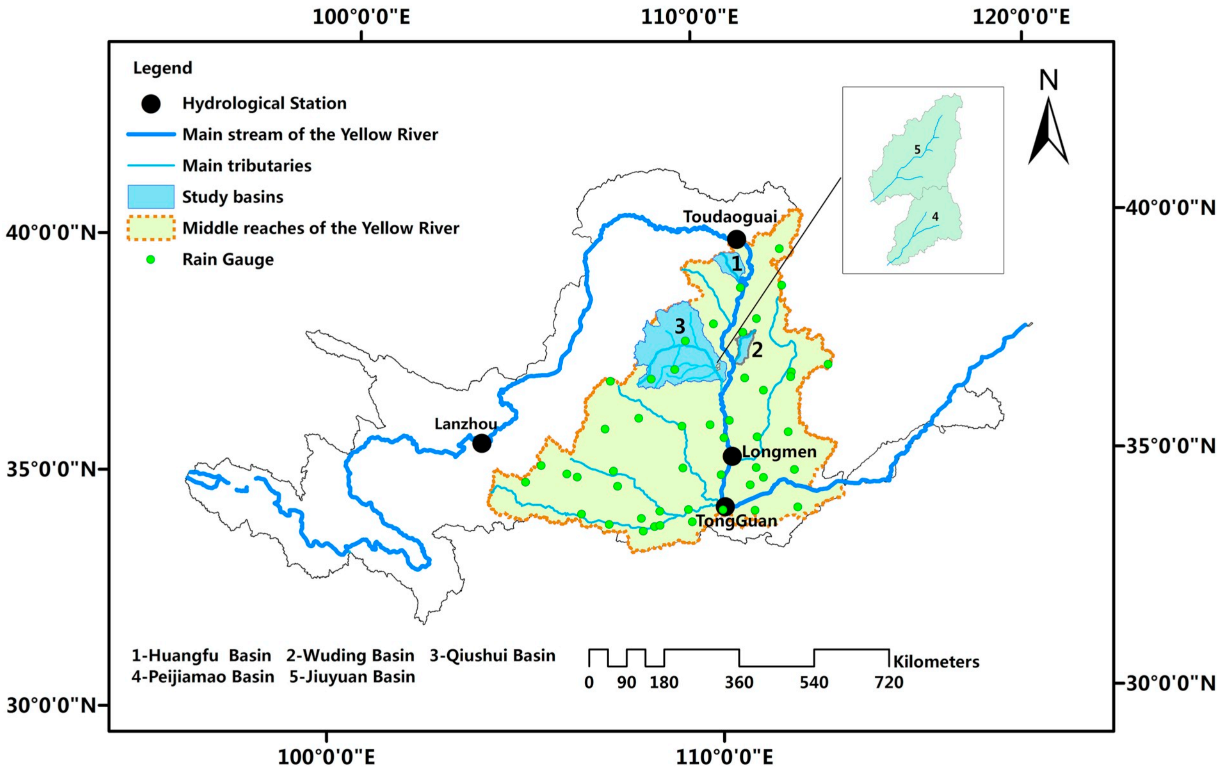

Fig. 1. Geographical location of the middle reaches of the Yellow River.

for changes in extreme climate values was used to convert percentage values into extreme values, as defined by extreme rainfall index for daily precipitation (Gao and Xie, 2014). Specifically, days with precipitation over 0.1 mm during in the period from 1956 to 2016 were arranged in ascending order. The 90th percentile for precipitation was taken to be the threshold value for extreme rainfall in that weather station. When the daily precipitation of that station exceeded its threshold, that station was considered to have experienced an extreme rainfall event. To study the change law of extreme rainfall in the middle reaches of Yellow River, referring to related research results (Wang et al., 2015; Zhao et al., 2017), annual sediment discharge in Yellow river showed a significant decreasing trend from 1956 to 2016 ($P < 0.01$), and two inflection points in 1980 and 2000 were identified, respectively. With this result, the extreme rainfall study period may be divided into three periods: the first period (1960–1980), the second period (1980–2000), and the third period (2000–2016).

2.4. Area rainfall analysis

The kriging interpolation method uses spatial autocorrelation as a basis. Raw data and the semi-variorum structure were used to carry out unbiased interpolation for unknown sampling points for regional variables. This method is widely used in spatial distribution analysis for basin rainfall (Oliver and Webster, 1990). Duan et al. (2009) reported that using kriging method for interpolation of precipitation in the Loess Plateau has the highest accuracy and optimal results.

2.5. Comparative watershed method

The comparative watershed method is widely recognized as the most effective method for studying hydrological responses at underlying surfaces changes (Wei et al., 2008; Wang et al., 2011). We here used the Jiuyuan (managed basin) and Peijiamao (unmanaged basin) in Wuding River as regions for comparison (Table 1). Comparison of flood and sediment yield characteristics in the basins under similar extreme rainfall events was used to quantify the contributions of soil and water retention to the effects on flood and sediment yield in the basin under extreme rainfall conditions. Additionally, to eliminate the effects of spatiotemporal heterogeneity of rainfall on flood and sediment yield in the basin, comparative analysis was carried out using flood runoff modulus per unit rainfall and sediment transport modulus per unit rainfall.

3. Result

3.1. Spatiotemporal changes in extreme rainfall in the middle reaches of the Yellow River

The spatiotemporal distribution patterns of extreme rainfall events in 3 periods in 1960–2016 at the middle reaches of the Yellow River were analyzed using data from 46 national rainfall stations and the definition of extreme rainfall indices. Table 2 lists the threshold values for extreme rainfall of different rainfall stations. Fig. 2 shows that the proportion of extreme rainfall to total rainfall in the middle reaches of the Yellow River showed a significant increasing trend over time ($P < 0.05$). This proportion was increased from 47.6% in the Toudaoguai–Tongguan reach in 1960–1980 to 52.7% after 2000, with an increase of 5.1%. From spatial distribution results, we can see that regions with a higher proportion of extreme rainfall events are mainly concentrated in the northwest part of Toudaoguai–Longmen reach (Kuye River and Huangfu River), while the proportion of extreme rainfall events in the Longmen–Tongguan reaches are relatively low. After 2000, regions with a higher proportion of extreme rainfall events extended from parts of the Toudaoguai–Longmen reach to most of the Toudaoguai–Tongguan reach, with the Toudaoguai–Tongguan reach showing an obviously increased proportion of extreme rainfall events. In summary, the center of extreme rainfall events showed a spatial distribution characteristic of shifting from the northwest part of Toudaoguai–Longmen reach to Wuding River in the Toudaoguai–Longmen reach and the Longmen–Tongguan reach.

Table 1
Comparison of major characteristics in the compared basins.

Name	Catchment area (km^2)	Level of soil-erosion remediation (%)	Main water and soil conservation measures					
			Decades	Check dam	Terrace (km^2)	Forestland (km^2)	Damland (km^2)	Grassland (km^2)
Jiuyuan	70.7	18.1	1960s	148	1.62	2.72	0.54	1.73
		30.0	1970s	237	7.04	5.93	1.47	2.00
		62.4	2000s	253	12.85	24.73	2.80	1.26
		70.1	2015s	263	16.94	28.31	3.04	1.27
Peijiamao	39.5	11.7	2015s	61	0.71	5.18	0.38	11.78

Note: level of soil-erosion remediation refers to the percentage of soil-erosion remediation area over the soil erosion area in the river basin.

Table 2
Extreme rainfall threshold values in different rainfall stations.

Id	Station name	90% threshold	Id	Station name	90% threshold
1	Taiyuan	17.24	24	Yan an	18.3
2	Taigu	16.31	25	Luochuan	18.9
3	Youyu	15.2	26	Hengshan	15.25
4	Mengjin	21.6	27	Jingbian	15.3
5	Yangcheng	19.74	28	Qindu	16.6
6	Anze	18.6	29	Wugong	18.1
7	Jiexiu	17.3	30	Wuqi	15.8
8	Wuzhai	14.1	31	Yongshou	17.1
9	Yuanqu	19.88	32	Changwu	16.9
10	Linfen	18.6	33	Xifeng	16.3
11	Houma	18.03	34	Fengxiang	17.4
12	Sanmenxia	19	35	Huanxian	14.8
13	Hequ	15.3	36	Longxian	16.57
14	Xingxian	16.8	37	Kongtong	15.05
15	Lishi	17.7	38	Xiji	12.6
16	Xixian	17.7	39	Huajialing	15.95
17	Jixian	17.48	40	Liupanshan	19.90
18	Hancheng	20.3	41	Jinghe	16.50
19	Shenmu	16.23	42	Yaoxian	17.3
20	Huashan	19.7	43	Yongji	19.23
21	Yanchang	17.8	44	Dingbian	15.01
22	Yulin	16.6	45	Yuncheng	15.61
23	Pucheng	18.52	46	Shuozhou	15.35

3.2. Characteristics of sediment transport by flood in basins under classical extreme rainfall events

Extreme rainfall events are often closely associated with floods (Merz et al., 2014). Conducting an analysis of the flood and sediment transport characteristics during extreme rainfall events has considerable significance for the in-depth understanding of the effectiveness of soil and water loss management. By combining the results of rainstorm distribution in previous section, Huangfu River, Wuding River, Qiushui River where extreme rainfall events are frequent were selected to explore the flood and sediment yield characteristics in typical floods under similar extreme rainfall events at different time periods in history (Table 3). The results showed that, in the years after 2000, the volume of flood and amount of sediment load in extreme rainfall events of the same grade in various basins was much lower than in the 1960s–1990s. The volumes of flood decreased by a range of 30.4%–78.2% while the amount of sediment decreased by a range of 53.0%–88.2%, which was greater than the decline in flood volume. Further analysis showed that after 2000, the maximum sediment concentration in floodwaters in extreme rainfall events showed an overall decreasing trend. Take Wuding River as an example, the maximum sediment concentration in the flood events has been reduced by > 47.2% (Fig. 3), which indicated that changes in the underlay surface induced by soil and water loess management play an important role in reducing sediment concentration in floods.

3.3. Changes in the rainstorm-flood and rainstorm-sediment relations in different time periods and basins

In order to further examine the differences in flood and sediment yield under similar extreme rainfall events and identify the change characteristics of rainfall-flood and rainfall-sediment relations under extreme rainfall conditions, flood events with a peak discharge of > 1000 m^3/s in different basins were selected for analysis. Fig. 4 shows that the rainstorm-flood and rainstorm-sediment relations exhibited obvious changes after 2000. The floodwater volume and sediment yield per flood in Wuding River, Huangfu River, and Qiushui River after 2000 were located below the fitting curve. This showed that obvious changes in the rainfall-flood and rainfall-sediment relations under extreme rainfall events in the middle reaches of the Yellow River took place after 2000. We further used the July 26 torrential storm event in Wuding River in 2017 as a study subject to analyze changes in the relationship between rainstorm flood and rainstorm sediment for flood events with peak discharge > 2000 m^3/s in observation data from the Baijiachuan station in Wuding River. Results also showed that compared with the 1977 torrential rainstorm event and under conditions of similar areal rainfall and twice the rainfall intensity, the amount of floodwater in the July 26 torrential rainstorm and flood event was decreased by 34.3% while the decrease in the amount of sediment produced was more pronounced (53.01%) (Fig. 5). Combined with the results of the trends of maximum sediment concentration in the flood events of Wuding River in previous section, we conducted that, with the marked improvement of the sediment production environment in the river basin, the phenomenon of large amounts of sediment produced by heavy rain has improved significantly. More importantly, changes in the underlying surfaces of the basin due to soil and water retention and ecological construction played an active and important role in decreasing sediment during extreme rainfall flood events.

4. Discussion

Changes in the frequency and intensity of extreme rainfall events will greatly affect social and natural environments (Xu et al., 2009; Zhao et al., 2017). The July 26 torrential rainstorm event in Wuding River provides a case study suitable for understanding the effects of extreme rainstorms on the amount of sediment entering the Yellow River. Research on this event showed that the rainfall-flood and rain-sediment relations in the basins of middle Yellow River were significantly different from that of torrential rainstorm events with similar characteristics in the 1970s. Under similar extreme rainfall conditions, the amount of sediment entering the Yellow River was greatly decreased. The runoff modulus and sediment transport modulus in basins with higher soil and water loss management were 57.2% and 75.7% lower, respectively, than in regions with no management. This shows that changes in the underlying surfaces caused by water and soil

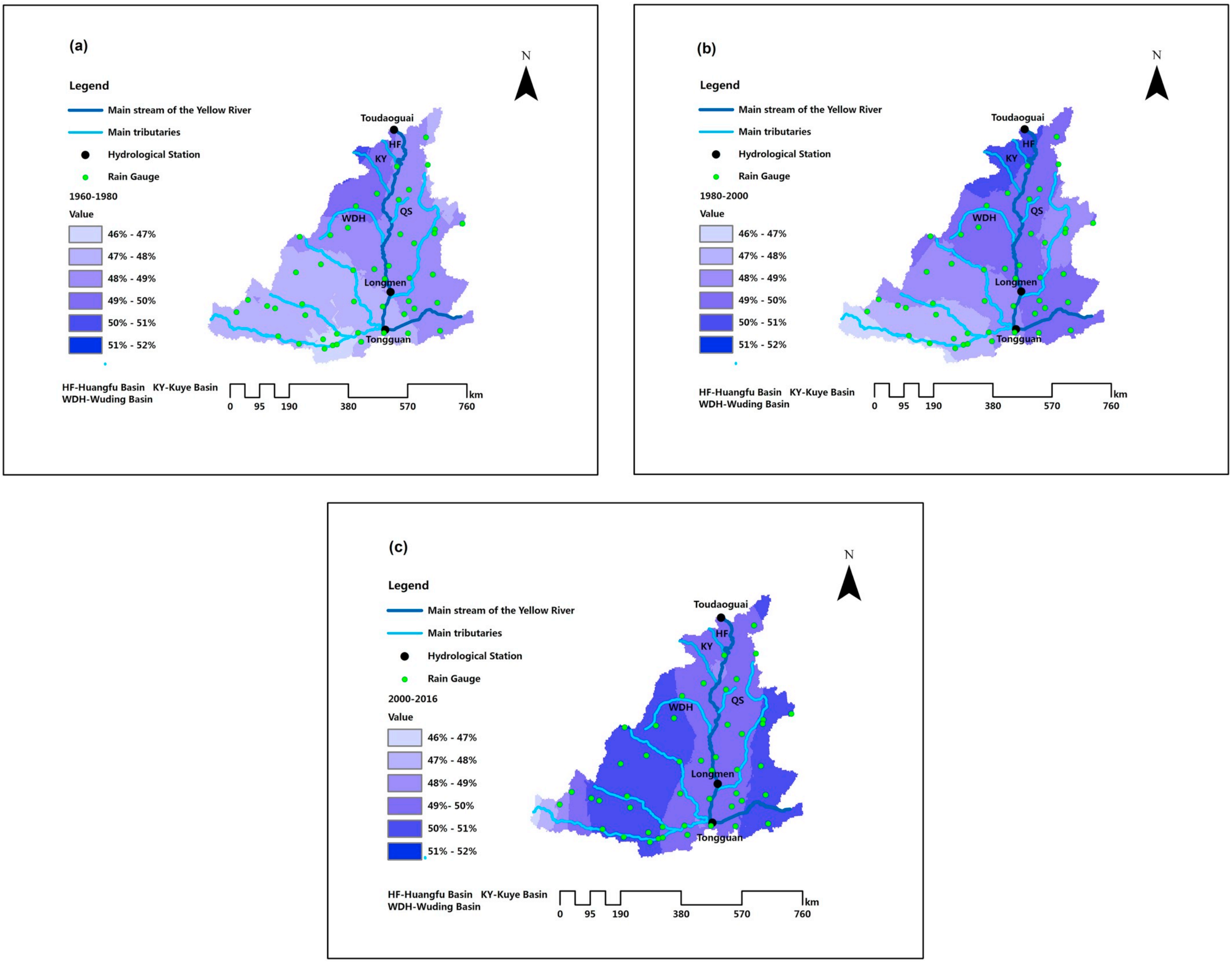

Fig. 2. Spatiotemporal distribution map of the proportion of extreme rainfall to total rainfall in the middle reaches of the Yellow River over the period 1960–1980(a), 1980–2000(b), 2000–2016(c), respectively. Here, the proportion is expressed as a percentage.

retention and ecological construction play important roles and that the effects of soil and water loss management are extremely significant. Hence, a quantitative assessment of the hydrological effects of soil and water conservation, especially on flood and sediment yield under extreme rainfalls, is critical for the sustainable soil and water loess management development within this dry region.

Table 3
Characteristics of extreme rainstorm events in the typical basin in the last 60 years.

Name (site)	Flood number	rainfall (mm)	Average rainfall intensity (mm/h)	50 mm covered area (km^2)	100 mm covered area (km^2)	Flood peak discharge (m^3/s)	flood volume /10^{8}m^3	Sediment load /10^{8}t	Maximum sediment concentration (kg/m^3)
Wuding River	20,170,726	64.0	3.5	13,687	4573	4480	1.67	0.78	873
(Baijiachuan Station)	19,940,805	49.6	2.8	11,848	2238	3220	1.70	0.80	526
	19,770,805	62.1	1.7	14,945	2979	3840	2.54	1.66	737
	19,640,706	57.3	1.7	13,543	1783	3020	1.48	0.84	633
Qiushui River	20,150,802	58.8	5.83	1549	0	1400	0.16	0.06	428
(Linjiaping Station)	19,770,706	55.3	4.95	1297	0	1860	0.27	0.15	582
	20,120,727	64.7	5.34	1230	332.9	1350	0.14	0.05	497
	19,700,809	64.3	4.35	897	394.5	2760	0.63	0.43	741
Huangfu River	20,160,818	80.8	2.88	3004	358.6	2220	0.31	0.09	510
(Huangfu Station)	19,880,805	81.0	2.10	1227	256	6790	1.54	0.91	802
	19,790,810	85.1	1.98	3198	574.5	4960	1.34	0.66	1400

Note: Gauging station at Baijiachuan, Linjiaping and Huangfu were selected as they are located at the outlet of the Wuding River basin, Qiushui River basin, and Huangfu River basin, respectively.

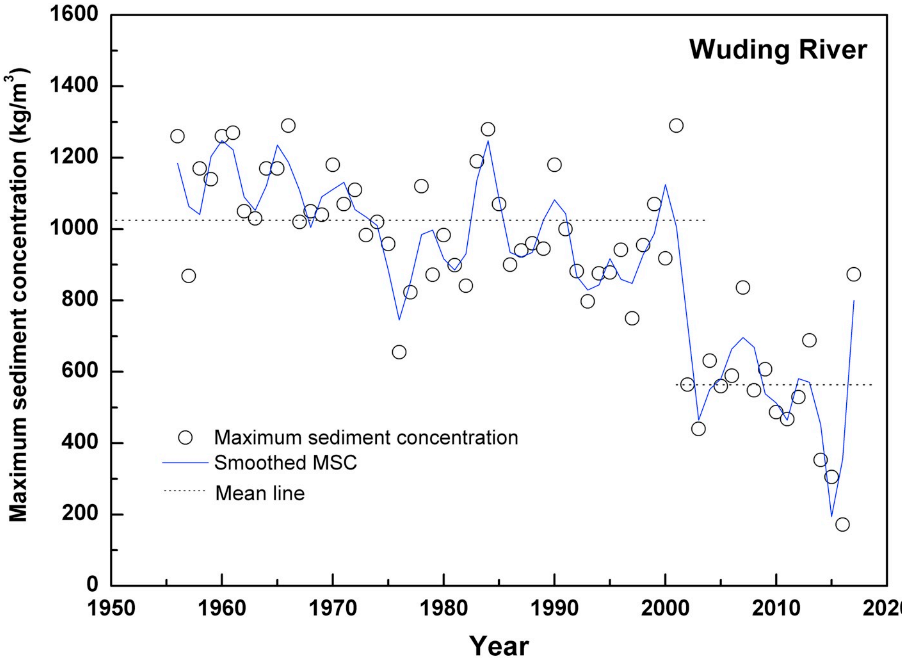

Fig. 3. Maximum suspended sediment concentration of floods changes in the Baijiachuan hydrologic station of Wuding River basin over the years. Here, the gauging station at Baijiachuan was selected as it is located at the outlet of the Wuding River basin.

4.1. Changes in the underlying surfaces of the middle reaches of the Yellow River

Changes in underlying surface conditions will result in changes in runoff generation and confluence characteristics in the basin (Gabris et al., 2003; Halhuber, 2003). As shown in the previous section, obvious changes were occurred in the rainfall-flood and rainfall-sediment relations under similar extreme rainfall events after 2000. The amount of floodwater and sediment transport in the basin was greatly reduced. This is closely associated with changes in underlying surfaces under the effects of human activities. The middle reaches of the Yellow River lie in the core of the Loess Plateau, which is an important area of national soil and water retention and ecological construction. In the last 40 years, significant changes have taken place in the underlying surfaces of the middle reaches of the Yellow River (Table 4). Relevant research showed that there were far more classical soil and water retention facilities, such as check dams, terraced fields, and forested and grassy areas in the Toudaoguai–Tongguan reach after 2000 than there had been during the 1970s, with increases of 1384%, 338.6%, and 18.3%, respectively (Tian et al., 2014; Liu, 2016). There were also 346.2% more reservoirs. Liu (2016) reported that, during the period of 2000–2014, check dams in the middle reaches of the Yellow River intercepted an annual average of 105 million tons of sediment, terraced fields reduced sediment by 422 million tons. Tian et al. (2014) argued that reservoirs in the middle reaches of the Yellow River intercepted an annual average of 98 million tons of sediment. Implementation of soil and water conservation measures plays important roles in reducing peak floodwater levels, decreasing overall flood volume, and decreasing the amount of sediment discharge, by modifying water distribution between evaporation, infiltration, runoff, and groundwater to affect the runoff/confluence flow and sediment transport processes in the basin.

4.2. Effectiveness of soil and water retention measures on reduction in flood and sediment volume under extreme rainfall

In order to further demonstrate the effects of changes in underlying surfaces caused by soil and water loess management on sediment transport by flood in the basin during extreme rainfall events, Jiuyuan (governed basin) and Peijiamao (non-governed basin) were selected for comparative analysis of soil and water retention effectiveness in 15 typical rainstorm events since 1954. Table 5 shows that in the July 26 torrential rainstorm event, the rainfall amounts of the two basins are close to each other. The runoff depth of Peijiamao was 2.47 times that of Jiuyuan. The peak discharge of Peijiamao was 3.49 times that of Jiuyuan. These results are inseparable from the flood peak reduction and flood detention effects of the soil and water conservation measures (such as check dams) in Jiuyuan. In addition, the maximum amount of sediment amount in Jiuyuan and Peijiamao was 170 kg/m^3 and 382 kg/m^3, respectively. This shows that soil and water conservation measures have huge effects in decreasing sediment content in flood. Fig. 6 is a contour map, which is an XYZ map. A two-dimensional (2D) graph was used to present 3D results by using different colors to differentiate between different Z values. From Fig. 6, one can see the differences in flood runoff modulus and flood sediment transport modulus and their ranges under similar rainfall events in the Peijiamao and Jiuyuangou watersheds since historical observation data became available. Specially, a summary analysis of historical rainstorm events in the basins showed that, under similar extreme rainfall events, the ranges of the runoff modulus and sediment transport modulus in Jiuyuan were much lower than the unmanaged Peijiamao, with an average reduction in runoff modulus and sediment transport modulus by 57.2% and 75.7%, respectively (Fig. 6). This result also shows that soil and water loss management have an important effects in regulating water flow and decreasing sediment in the basin. Through comparison of the flood and sediment characteristics of the July 26 torrential rainstorm and historical rainstorm events, we can see that the runoff modulus and sediment transport modulus of Jiuyuan were drastically lower than in the 1977 torrential rainstorm event, with the difference in sediment being particularly pronounced. In addition, through comparison of the runoff modulus per unit rainfall, we find that the runoff modulus per unit rainfall and the sediment transport modulus of Jiuyuan peaked in 1977, before becoming stable or decreasing (Fig. 7). This result indicated that as the degree of soil and water loss management increases, basin erosion and sediment continuously decrease.

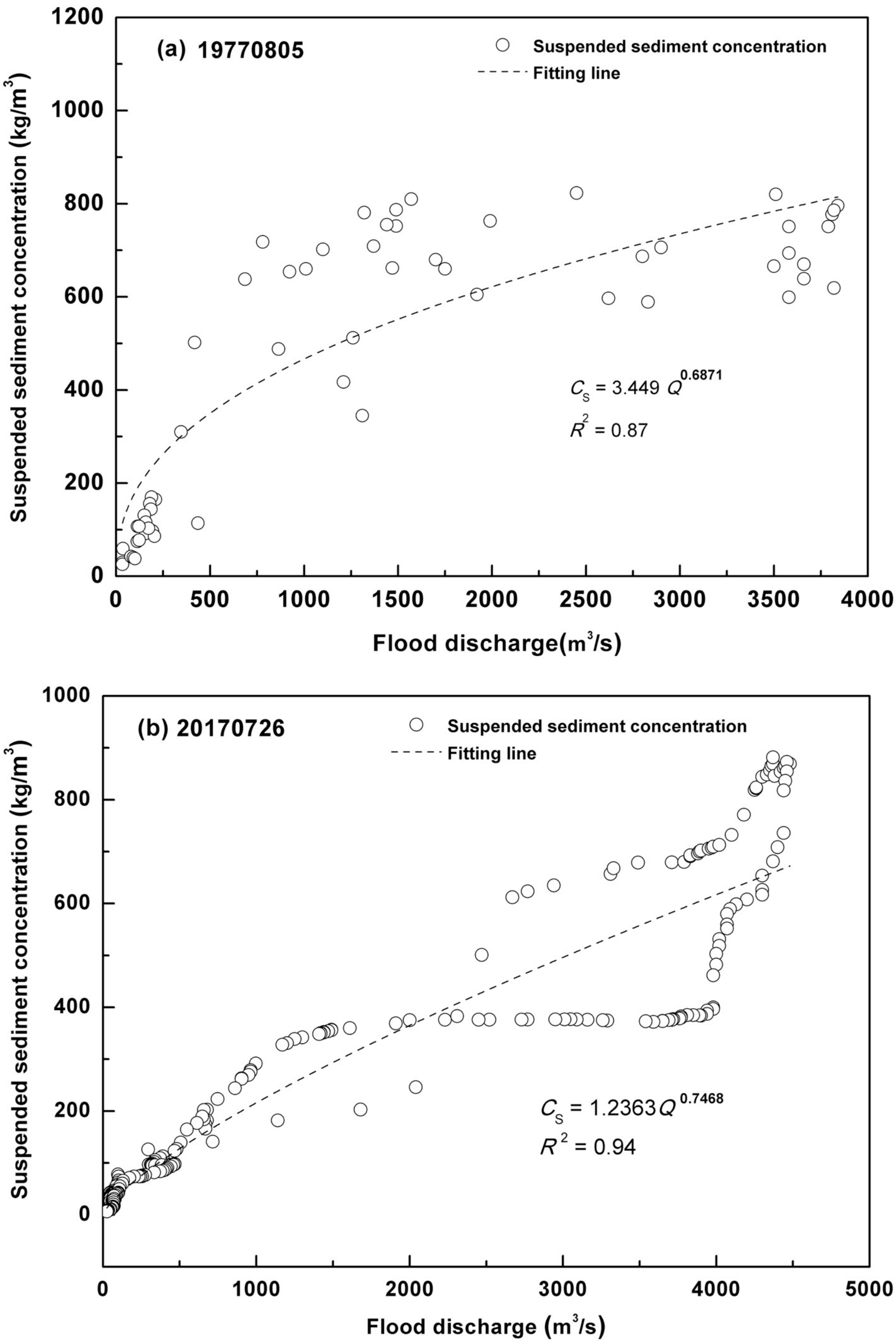

Fig. 4. Sediment rating curve under extreme rainstorm on August 5, 1977 (a) and July 26, 2017 (b) in Wuding River Basin.

4.3. Impact of soil and water retention measures on future water and sediment in the Yellow River

Check dams and reservoirs exhibit significant temporal effects in sediment retention, and their sediment-retention effects are mainly dependent on residual active reservoir capacity in the reservoirs and check dams (Zhang et al., 2010). By referring to Yao et al. (2017), it can be seen that underlying surface changes are the primary cause of drastic reduction in water and sediment in the Yellow River in recent years. They pointed out that the contribution of forest and grass vegetation, terraced fields, and other slope factors accounts for approximately 80% of sediment reduction, while that of reservoirs, check dams, and gully-channel measures account for approximately 20%. This shows that the effects of forest and grass vegetation and terraced fields on water and sediment changes in the Yellow River are greater than those of reservoir projects. Liu (2016) predict that in the next 30 years the developmental potential of forest and grass vegetation area in the Loess Plateau will be extremely small. However, optimization of forest and grass vegetation community structure will continue. As structure determines function, optimization of these vegetation communities will inevitably play important roles in controlling soil erosion and in reducing the amount of sediment entering the Yellow River. Furthermore, due to key national remediation projects on slope transformation and soil erosion, the area of terraced fields in the Loess Plateau will inevitably increase and their water-transfer and soil-conservation effects will be further amplified. In addition, during 2007–2014 the actual volume of sediment retained by check dams above the Tongguan hydrologic station was approximately 125 million t/a. Through 2011, there were 4397 of 5470 key dams that

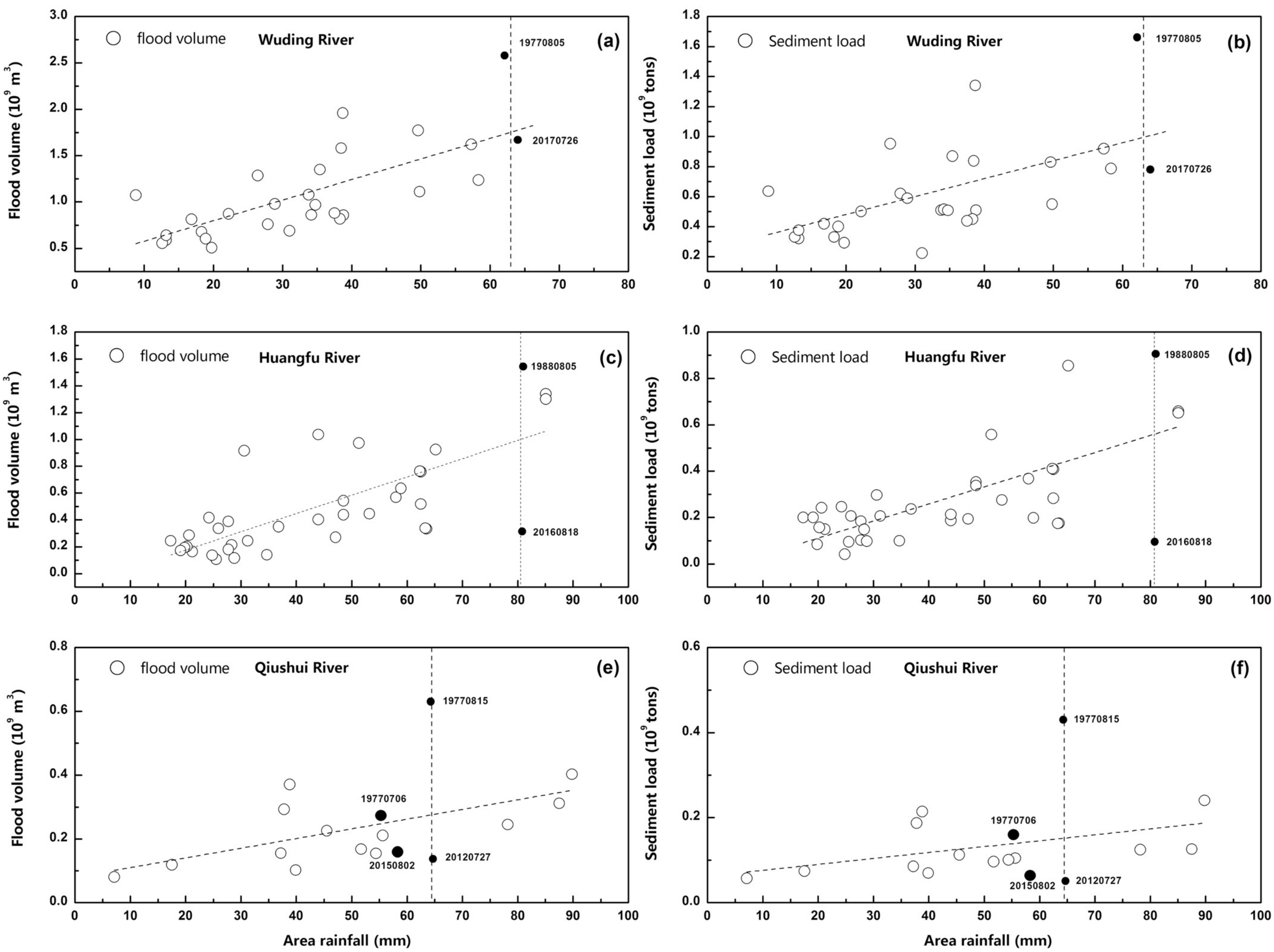

Fig. 5. Changes in rainfall-flood and rainfall-sediment relations during typical extreme rainfall events in Wuding River (a, b), Huangfu River (c, d) and Qiushui River (e, f). Here, flood volume refers to the total water volume flowing out from the exit cross-section of a river basin in a certain time period, and also refers to the total flood water volume during one rainfall event. It was obtained by calculating the instantaneous discharge and time. The instantaneous discharge was obtained from measurements by the hydrologic station, while the temporal resolution was 30 min.

Table 4
Changes in the number of typical soil and water conservation measures in the middle reaches of the Yellow River.

Category	Measures	Year	Number	Source
Typical soil and water conservation measures	Check dams	2011	4898	Li et al., 2012
		1970	330	
	Terrace	2014	21,603(km^2)	Liu, 2016
		1970	4925(km^2)	
	Forestland and grassland	2014	40.6(%)	
		1970	22.3(%)	
	Reservoir	2012	772	Tian et al., 2014
		1970	173	

Table 5
Characteristics of flood and sediment yield during the July 26 torrential rainstorm in the compared regions.

Name (site)	Catchment area (km^2)	Rainfall duration	Rainfall (mm)	Runoff depth (mm)	Runoff coefficient	Flood peak discharge (m^3/s)	Maximum sediment concentration (kg/m^3)	Sediment transport modulus (t/km^2)
Jiuyuan	70.11	51h20m	156.1	18.39	0.12	36.14	170	1914
Peijiamao	39.30	36h30m	156.7	45.50	0.29	126.10	382	7595

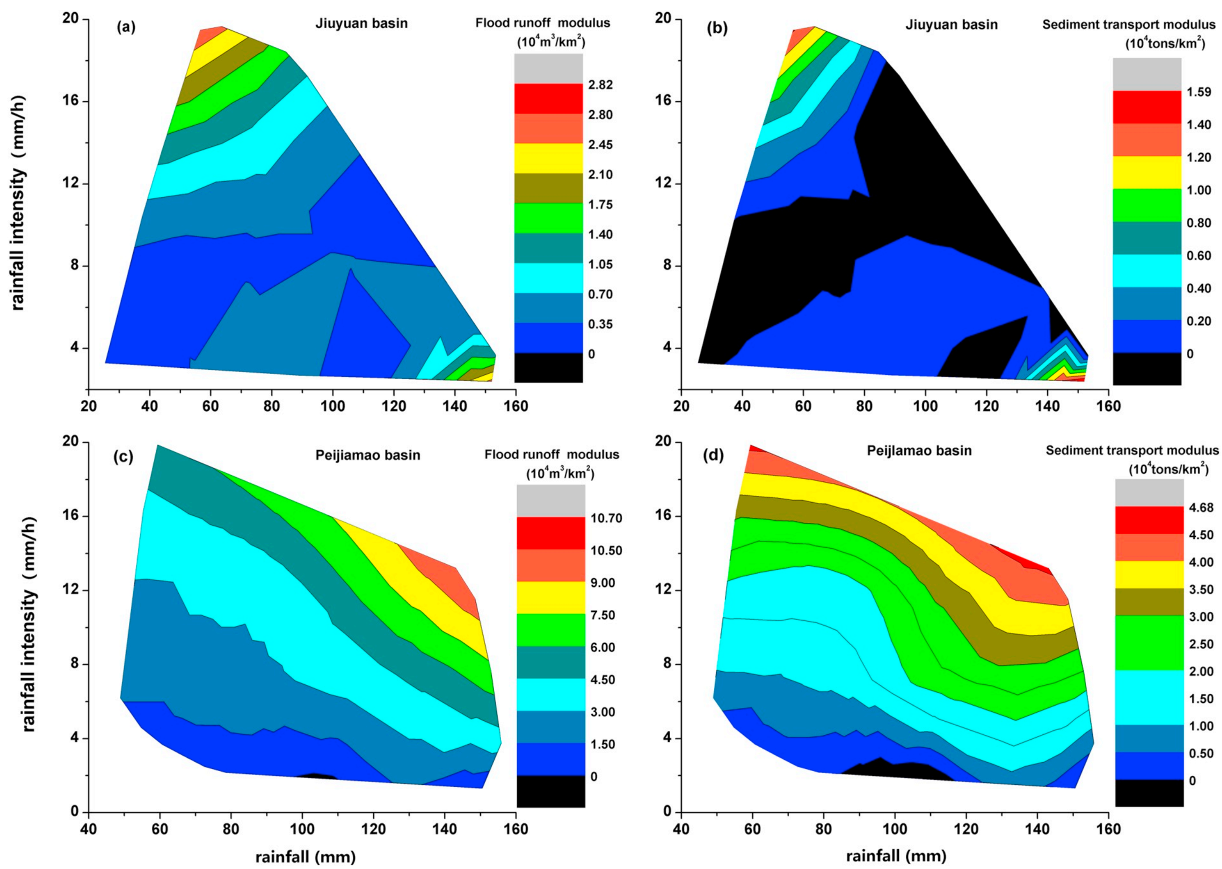

Fig. 6. Contour maps of flood runoff modulus and sediment transport modulus in Jiuyuan Basin (a, b) and Peijiamao Basin (c, d). Here, a two-dimensional (2D) graph was used to present 3D results by using different colors to differentiate between different Z values.

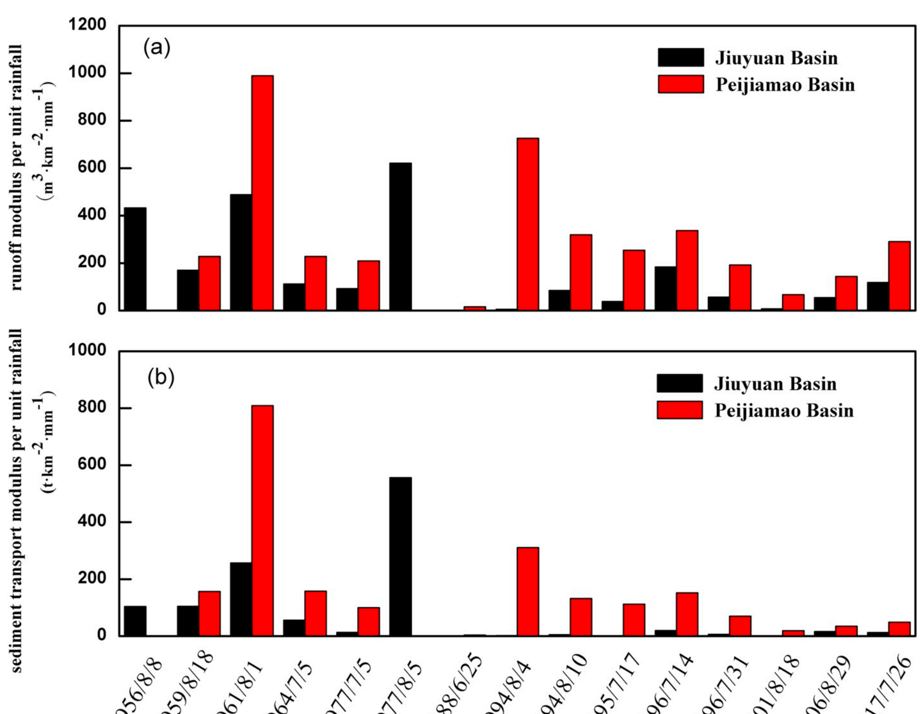

Fig. 7. Runoff modulus per unit rainfall (a) and the sediment transport modulus (b) under similar extreme rainfall conditions in the compared basins.

could still retain sediment, and their sediment retention life exceeded 30 years. In the next 30 years, as the capacity of check dams decreases, the sediment-retention capacity of check dams is expected to reach 13 million t and erosion-reduction capacity is expected to reach 20 million t. In the next 30 years, the mean volume of sediment retained by reservoirs will be approximately 27 million t. With the completion of the Guxian, Dongzhuang, and other reservoirs, the sediment-retention capabilities of reservoirs are expected to increase further. In summary, as soil-erosion remediation measures in the Yellow River Basin continue to improve, the conclusion that the volume of sediment in the Yellow River will further decrease in the next 30 years is generally believable.

5. Summary

The frequent occurrence of extreme climate events, especially rainstorm events, has made the future situation of water and sediment in the Yellow River even more uncertain. To provide scientific and technological support for accurately predicting the situations in runoff and sediment loads in the next 30 years, it's very necessary and urgent to study the changes in characteristics of flood and sediment yield in the Yellow River under extreme rainfall events. Through the study, we found that the proportion of extreme rainfall to total rainfall in the middle reaches of the Yellow River has increased significantly, and regions with a higher proportion of extreme rainfall events were extended from parts of the Toudaoguai–Longmen reach to most of the middle reaches. Under similar extreme rainfall events, the volume of floodwaters was decreased by an average of 30.4–78.2% and the amount of sediment was decreased by an average of 53.0–88.2% since 2000. The effects of water and soil retention engineering works can't be ignored. Further, in similar extreme rainfall events, the ranges of the runoff modulus and sediment transport modulus in basins with a high degree of management were much lower than unmanaged basins, with an average reduction in runoff modulus and sediment transport modulus by 57.2% and 75.7%, respectively. These results strongly indicate that soil and water loess management plays an important role in reducing flood, sediment yield and sediment concentration in the Yellow River.

In summary, under the guidance of the “lucid water and lush mountains” concept in the new age, as China continues to manage soil and water loss in the Loess Plateau, gradually increase the retention of soil and water facilities and their building standards, and strengthen the maintenance of buildings after construction, the underlying surface ecosystem in the basin will continue to improve. This will greatly improve the sediment production environment, resulting in a drastic reduction in the amount of sediment entering the Yellow River under extreme rainfall conditions and the probability of massive flood and sediment events. The uncertainty of the effects on future water and sediment situation in the Yellow River under extreme rainfall is weakening. Hence, the probability of large flood and sediment events will greatly decrease and the amount of sediment entering the Yellow River under extreme rainfall will further decrease in the next 30 years.

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