

Human activity and climate variability impacts on sediment discharge and runoff in the Yellow River of China

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Received: 4 February 2015 / Accepted: 2 April 2016 / Published online: 22 April 2016
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Abstract We analyze the variability of sediment discharge and runoff in the Hekou–Longmen segment in the middle reaches of the Yellow River, China. Our analysis is based on Normalized Difference Vegetation Index (NDVI), sediment discharge, runoff, and monthly meteorological data (1961–2010). The climate conditions are controlled via monthly regional average precipitation and potential evapotranspiration (ET_0) that are calculated with the Penman–Monteith method. Data regarding water and soil conservation infrastructure and their effects were investigated as causal factors of runoff and sediment discharge changes. The results indicated the following conclusions: (1) The sediment concentration, sediment discharge, and annual runoff, varied considerably during the study period and all of these factors exhibited larger coefficients of variation than ET_0 and precipitation. (2) Sediment discharge, annual runoff, and sediment concentration significantly declined over the study period in a linear fashion. This was accompanied by an increase in ET_0 and decline in precipitation that were not significant. (3) Within paired years with similar precipitation and potential evapotranspiration conditions (SPEC), all pairs showed a decline in runoff, sediment discharge, and sediment concentration.

(4) Human impacts in this region were markedly high as indicated by NDVI, and soil and water measurements, and especially the soil and water conservation infrastructure resulting in an approximately 312 Mt year^{-1} of sediment deposition during 1960–1999.

1 Introduction

The Yellow River is the second largest river in China and the surrounding area has significant cultural and archeological importance. The Yellow River has extremely large sediment discharge, yet it has relatively low water discharge. Significant changes have recently taken place in the Yellow River basin environment under the influences of intensive human activities and global climate change coupled with the fragile ecosystem (Wang and Cheng 2000). For example, the sediment discharge and water discharge of the Yellow River have significantly declined during the past 50 years (Yang et al. 2004a; b; Liu and Zheng 2004; Fu et al. 2004; Xu 2005a; b; Miao et al. 2010; Gao et al. 2011; Mu et al. 2012; Liu et al. 2013; He et al. 2015a). Because the middle reaches of the Yellow River run through the Loess Plateau, they have become the main source of sediment due to the improper land use and excessive exploitation in the surrounding area. In one study, the sediment from the middle reaches accounted for 88.2 % of the Yellow River sediment, while the water from the same area only accounted for 44.3 % of the Yellow River streamflow (Gao et al. 2011). The average yearly streamflow from Toudaoguai to Longmen station (located in the middle reaches of the Yellow River) was $48.8 \times 10^8 \text{ m}^3$ during 1950–2005, while it was $37.7 \times 10^8 \text{ m}^3$ during 1987–2005. The decrease in streamflow between these two periods ($11.1 \times 10^8 \text{ m}^3$) represents 22.7 % of the yearly mean streamflow during 1950–2005 (The Ministry of Water Resources of the People's Republic of China 2009). The main causes of runoff

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and sediment discharge change are related to human activities (e.g., dam construction and land-use change) and natural climatic variability. These factors have caused significant changes to the runoff and sediment discharge of many rivers, e.g., the Nile (Fanos 1995), the Colorado (Carriquiry and Sanchez 1999), the Yangtze (Xu 2009), and the Yellow Rivers (Miao et al. 2011). Many recent studies on runoff and sediment discharge have been based on comparative analyses (Walling and Fang 2003; Restrepo and Syvitski 2006) or modeling (Lørup et al. 1998; Nearing et al. 2005). While these two methods have assisted in understanding runoff and sediment discharge variability, there are large differences between the methods with regard to the underlying theory and parameters. For example, the rainfall-runoff and rainfall-sediment statistical models are still controversial when dividing the distinct transition point of runoff or sediment discharge time series according to the impacts of human activities, resulting in different division periods that exhibit differing results (Xiong 1986; Mu et al. 2007; He et al. 2011). Furthermore, although the mechanisms of runoff and discharge are clear in distributed hydrological models (Yang et al. 2004a; b; Cong et al. 2009; Liu et al. 2011; Bai et al. 2014), there are significant spatial differences in the model parameters and their selection is too variable. Current models do not comprehensively account for the variation of precipitation and evaporation in the divided period.

It is necessary to select temporal periods with similar climatic characteristics to better capture the influence of human activities and climate change on runoff and sediment discharge. Comparable climatic characteristics also reduce the uncertainty in the selection of model parameters and improve the accuracy in the evaluation of effects. The objectives of this investigation are to illustrate how sediment yield and discharge from the middle reaches of the Yellow River, China, varied from 1961 to 2010; to quantitatively evaluate the impact of human and climate factors on runoff and sediment discharge; and to discuss implications for watershed management.

2 Methods and data

2.1 Study area

The Yellow River is ranked fifth among the longest rivers in the world and is the second longest river in China. The segment between Hekouzhen and Longmen Stations (He-Long) (35°–41° N, 108°–113° E) represents the middle reaches of the Yellow River. This segment is 517-km long and is 1.13×10^5 km² in area (Fig. 1). This region is located in the Loess Plateau. The area has deep (20–30 m or deeper) loess layers. The loess soil is susceptible to erosion as it is highly permeable and loose. Severe soil erosion is the primary origin of coarse sediment within the middle reaches of the Yellow River.

The study area is located in a semi-arid/arid transition zone. The area is subject to a continental monsoon climate. The average yearly precipitation ranges from 260 to 600 mm, the mean annual temperature is within the range of 6 to 14 °C, and the mean yearly pan-evaporation ranges between 900 and 1400 mm (Ran et al. 2006).

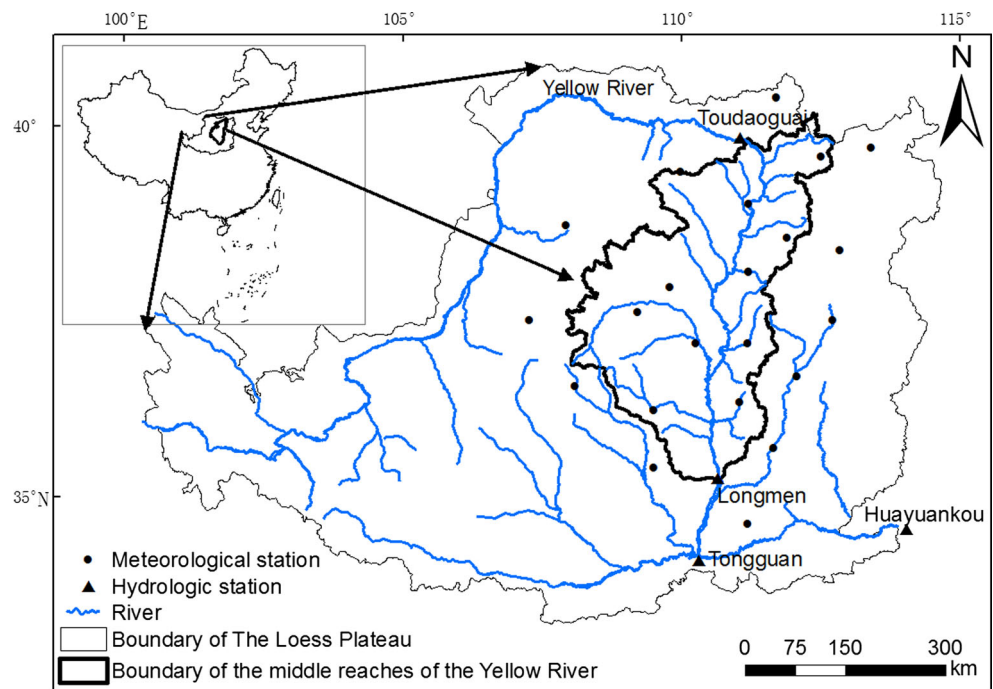
Data for the study was obtained from the Toudaoguai and Longmen hydrological gauge stations, which cover a 1.13×10^5 km² watershed. The mean annual sediment discharge and runoff were 527.2 million tons and 4306.8 million m³, respectively, during 1961–2010. The mean sediment concentration is reported to be 19.5 kg m⁻³ (Ministry of Water Resources of China 2011).

2.2 Data

We obtained the available daily data during 1961 to 2010 from 22 national climatic stations within and proximate to the study area. This data was provided by the National Meteorological Information Centre (NMIC). However, we analyzed monthly data in this paper (Fig. 1). The monthly data, include monthly precipitation (P_m , mm), maximum temperature (TMX, °C), minimum temperature (TMN, °C), sunshine duration (SD, h), relative humidity (RH, %), and wind speed (WS, m s⁻¹). We then performed standard error correction and quality assessment procedures according to Peterson et al. (1998). There were few missing values. The missing data points which were interpolated via values estimated from multiple regression relationships established from up to five highly correlated and spatially proximate stations (Fan et al. 2011). The potential evapotranspiration of the Middle Yellow River was derived using the Penman–Monteith (PM) method promoted by the Food and Agriculture Organization (FAO) (Allen et al. 1998). The potential evapotranspiration and precipitation were spatially averaged using the spatial interpolation method according to the monthly data from the study area. Annual potential evapotranspiration and precipitation (P) were cumulative monthly data. Annual streamflow (in Mm³) and sediment discharge (in Mt) data at the He-Long section of the study region from 1961 to 2010 were provided by the Chinese River Streamflow and Sediment Communiqués, Ministry of Water Resources, China (MWR).

We utilized the Global Inventory Monitoring and Modeling Studies (GIMMS) Normalized Difference Vegetation Index (NDVI) dataset as collected from the NOAA Advanced Very High Resolution Radiometer (AVHRR) (<http://www.noaa.gov>, downloaded from <http://westdc.westgis.ac.cn>). This dataset includes records of the monthly variation in terrestrial vegetation from August 1981 to December 2006. Because of incomplete information for 1981, we used data from 1982 to 2006. The GIMMS data have a spatial resolution of 8 km and a temporal resolution of 15 days (Tucker et al. 2005). To eliminate the influences of solar

Fig. 1 Location of the middle reaches of the Yellow River, China



altitude angle, atmosphere, and clouds, we used the method of maximum value composites (MVCs) to calculate monthly maximum NDVI (Stow et al. 2007). At each pixel, this technique chooses the highest NDVI from the GIMMS NDVI dataset (15-day interval) (Zhou et al. 2003). The vegetation in the study area is most developed during the productive months of June to September. The vegetation exhibits little variation during the period of October to May. The NDVI values of the four productive months are the best reflection of the long-term variation in vegetation cover during a year. Therefore, we calculated the NDVI between June and September of each year using the MVCs method. This value was then utilized as an indicator of the yearly vegetation growth in the study area.

We obtained water and soil conservation data from the Soil and Water Conservation Data Compilation of the Yellow River that covered the period from 1960 to 1999. The data includes some general characteristics of the study region; biological conservation measures, e.g., area of man-made forest, hillside closures (natural remediation area with little to no human disruption), and grass planting; and structural measures, such as reservoirs, terraces, key projects for gully control, and check dams.

2.3 Theoretic framework and methods

2.3.1 Theoretic framework

The water balance of the watershed can be expressed as:

$$P + W_i + R + W_g + W_s + ET_c + \delta W \quad (1)$$

where, P is the areal precipitation, W_i is the water input from other watersheds, δW is the change in water storage of engineered structures (e.g., reservoirs), R is the surface runoff, W_g is the underground runoff, W_s is the soil water storage, and ET_c is the actual evapotranspiration.

This equation can be simplified by considering the specific hydrogeological conditions of the study area. (1) There is no water input from other watersheds in this study area, and W_i can therefore be ignored. (2) There is a thick soil layer, a deep water table (Shangguan and Zheng 2006), and little recharge of underground runoff from the limited infiltration (Gates et al. 2011), and thus, W_g is assumed to be approximately 0. (3) There is little vegetation cover in the study area, the surface soil exhibit weak infiltration capacity, and the surface runoff is primarily generated by infiltration-excess rainfall which is characterized by heavy rainfall with high intensity and short duration (Zhu et al. 1997), and therefore, W_s can be ignored. (4) The water in reservoirs mainly supplies the demands of the human population, and δW can therefore be considered as the anthropogenic impact. Therefore, for long-term analyses, Eq. (1) can be simplified to:

$$P = R + ET_c \quad (2)$$

where, R is the surface runoff, P is the areal precipitation, and ET_c is the actual evapotranspiration.

$$ET_c = k \times ET_0 \quad (3)$$

where, ET_c is the actual evapotranspiration, k is the coefficient, and ET_0 is the potential evapotranspiration. If there is adequate water supply, then $k = 1$ and $ET_c = ET_0$. We assume

that the k does not change for the same land under similar weather conditions, and we conjecture that the human-induced vegetation change can change k . We analyze ET_0 in the study instead of ET_c that implies the faster change than the natural evolution of ET_c is also the result of anthropogenic impact.

2.3.2 Penman–Monteith methodology

The FAO Penman–Monteith (PM) approach of estimating evapotranspiration (ET_0 , mm day^{-1}) is considered an international standard and is included in the FAO-56 report (Allen et al. 1998). In this study, monthly potential evapotranspiration was derived according to Allen et al. (1998). We calculated monthly potential evapotranspiration via the product of the number of days in a month and ET_0 .

2.3.3 Spatial interpolation method

Spatial interpolation methods have been generated for specific variables and data types (Journel and Huijbregts 1978; Burrough and McDonnell 1998). In this study, we selected the inverse distance weighted (IDW) spatial interpolation technique to calculate spatially averaged precipitation and the potential evapotranspiration for the study area.

2.3.4 Trend detection

A linear regression method was used to identify trends in the potential evapotranspiration, precipitation, sediment concentration, sediment discharge, and runoff.

2.3.5 Analysis for comparable weather conditions

Years with similar precipitation and potential evapotranspiration conditions (hereafter referred to as SPEC) were selected to facilitate the analysis (Wang et al. 2008; Wang et al. 2013; He et al. 2015b; He et al. 2016). Paired years with SPEC were selected according to three conditions: (1) annual precipitation for the 2 years should differ by <2 %, (2) the potential evapotranspiration should differ by less than 2 %, and (3) the selected years should differ by at least 5 years. Due to the slow evolution of vegetation and natural landforms, we conclude that the changes to sediment discharge and runoff in a SPEC pair are primarily anthropogenic. We selected four pairs of years based on the above-mentioned conditions. It should be emphasized that this methodology assumes similar weather conditions in paired years. This is an important assumption for the middle reaches of the Yellow River, because individual rainfall events in the area can account for approximately 60–90 % of the total annual precipitation (Li et al. 2010).

Although data on individual rainfall events can be used to describe the impacts of rainfall on sediment generation and runoff, the rainfall events in the study area exhibit high spatial heterogeneity. It is therefore difficult to use rainfall event data for the whole study area. Utilizing the monthly precipitation and ET_0 data to identify similar weather conditions for 2 years at the regional scale is a rational alternative.

3 Results

3.1 Sediment discharge and runoff statistics

The sediment discharge, runoff, sediment concentration, precipitation, and potential evapotranspiration statistics are presented in Table 1. The mean sediment concentration, annual runoff, and sediment discharge were 19.5 kg m^{-3} , 4306.8 M m^3 , and 527.2 Mt , respectively. There was a large difference between the minimum and maximum values of each variable. The sediment discharge in 1967 was 197.87 times that in 2008; the sediment concentration in 1977 was 145.64 times the level in 2008; and the runoff in 1967 was 10.86 times that in 2009. The coefficients of variation (CVs) of sediment discharge, runoff, and sediment concentration were 0.851, 0.437, and 0.719, respectively. This indicates that the changes in sediment concentration, runoff, and sediment discharge are highly unstable.

3.2 Potential evapotranspiration and precipitation variation

Precipitation and potential evapotranspiration are the primary meteorological factors that influence sediment and runoff. Precipitation is the driving force for soil erosion

Table 1 Sediment concentration (SC), sediment discharge (S), runoff (R), precipitation (P), and potential evapotranspiration (ET_0) statistics for the study area from 1961 to 2010

Statistic	R M m ³	S Mt	SC kg m ⁻³	P mm	a.ET ₀ mm
Mean	4306.8	527.2	19.5	440.3	1032.0
Minimum	870.0	10.8	0.39	247.0	881.5
(Year)	(2009)	(2008)	(2008)	(1965)	(1964)
Maximum	9450.0	2137.0	56.8	712.5	1126.4
(Year)	(1967)	(1967)	(1977)	(1964)	(1972)
Median	3980.0	402.6	15.5	435.6	1033.3
Standard deviation	1880.1	448.5	14.0	85.3	49.7
Confidence levels (95.0 %)	534.3	127.5	3.98	24.24	14.12
Coefficients of variation	0.437	0.851	0.719	0.194	0.048

and sediment delivery, as well as, the water source for runoff and soil moisture in this region. In the study area, the average annual precipitation and potential evapotranspiration were 440.3 and 1032.0 mm, respectively (Table 1). The maximum P (712.5 mm) in 1964 was 2.88 times the minimum P (247.0 mm) in 1965, and the CV for P was 0.194. The maximum recorded mean potential evapotranspiration in 1972 (1126.4 mm) was 1.28 times the minimum recorded value in 1964 (881.5 mm), with a low CV of 0.048. The precipitation and potential evapotranspiration exhibited relatively more stability as compared to runoff, sediment discharge, and sediment concentration.

3.3 Sediment discharge and runoff trends

The annual runoff, sediment concentration, and sediment discharge exhibited significant linear reductions during the study period (Fig. 2). The mean rates of decline for annual runoff, sediment concentration, and sediment discharge were $94.07 \text{ Mm}^3 \text{ year}^{-1}$, 0.433 kg m^{-3} , and $19.28 \text{ Mt year}^{-1}$, respectively. There is a significant ($P < 0.001$) synchronized variation among annual runoff, sediment discharge, and sediment concentration.

3.4 Precipitation and potential evapotranspiration trends

The annual precipitation declined, while the annual potential evapotranspiration increased. However, neither of these trends was significant (Fig. 3).

3.5 Precipitation and ET_0 between paired years with SPEC

The four pairs of years with similar weather conditions (Table 2) range from 1970 to 2009, and the temporal difference between each pair varies from 9 to 28 years. The differences in P and ET_0 between the paired years were within the ranges of -4.6 – 5.2 and -15.4 – 6.7 mm, respectively (Table 2), and the percent difference in P and ET_0 were within the ranges of 0.00–1.15 and 0.65–1.46 %, respectively.

3.6 Sediment discharge and runoff for pairs of SPEC years

The SPEC analysis of the changes in sediment discharge (S), runoff (R), and sediment concentration (SC) are shown in Table 3. There is a general decreasing trend in R , S , and SC for SPEC paired years, which is in agreement with the statistical results (Fig. 2). The relative amplitudes of R , S , and SC between the paired years ranged from 13.74 to 77.69, 30.27 to 97.97, and 20.00 to 96.58 %, respectively. The R , S , and SC for pair 4 exhibited the most dramatic change among the four

pairs, with amplitudes of R , S , and SC at 77.69, 97.97, and 96.58 %, respectively.

3.7 An example of NDVI changes in pair 4

NDVI is an effective indicator of green plant material and an index of the vegetation cover of a region (Carlson et al. 1994), which directly affects water yield and sediment discharge. Considering the availability of NDVI data, we analyzed NDVI data from 1982 and 2006 for pair 4. The mean annual NDVI for 1982 and 2006 were 0.631 and 0.662, respectively. The NDVI decreased in 35.45 % of the study area and increased in 64.55 % of the area. The vegetation cover increased mainly in the lower and upper and regions of the study area (Fig. 4), and it may be the main reason for the runoff reduction in this area (Xin et al. 2009).

3.8 Soil and water conservation engineering

In addition to NDVI changes, engineering projects likely impact the sediment concentration, runoff, and sediment discharge of the study area. Based on the Soil and Water Conservation Data Compilation of the Yellow River Basin (Table 4), 258 reservoirs have been built in this region, with 77, 49, 19, and 113 reservoirs in Ningxia, Inner Mongolia, Shanxi, and Shaanxi, respectively. The total area controlled by reservoirs is $33,843.7 \text{ km}^2$. The amount of siltation measured was 1005.4, 277.5, and 7951.6 M m^3 in the reservoirs, the key projects for gully control, and check dams, respectively. Using a dry bulk density of sediment of 1.35 t m^{-3} (Ran et al. 2004), we arrive at 12,467.0 Mt of sediment as the estimated level, or $311.68 \text{ Mt year}^{-1}$ over the 40-year period between the start of the implementation and 1999. This accounts for 59.12 % of the mean $527.2 \text{ Mt year}^{-1}$ that is transported from the middle reaches of the Yellow River as sediment discharge (Table 1). The trend in the total amount of siltation (12,467.30 Mt) or the annual average rate ($311.68 \text{ Mt year}^{-1}$) may explain the decreased trend of sediment discharge in Fig. 2.

3.9 Causal factors for decreases in sediment discharge and runoff

The variability in the sediment discharge, sediment concentration, and runoff in the middle reaches of the Yellow River has been illustrated earlier. A relatively small increase in ET_0 and a relatively small reduction in rainfall caused a marked decrease in the sediment discharge and runoff. NDVI data indicates an increase in vegetation cover, which should have an effect on runoff and erosion. Finally, soil and water conservation engineering projects sequestered large amounts of sediment.

Fig. 2 Annual variation in SC (sediment concentration), R (runoff), and S (sediment discharge) during 1961–2010 in the study area

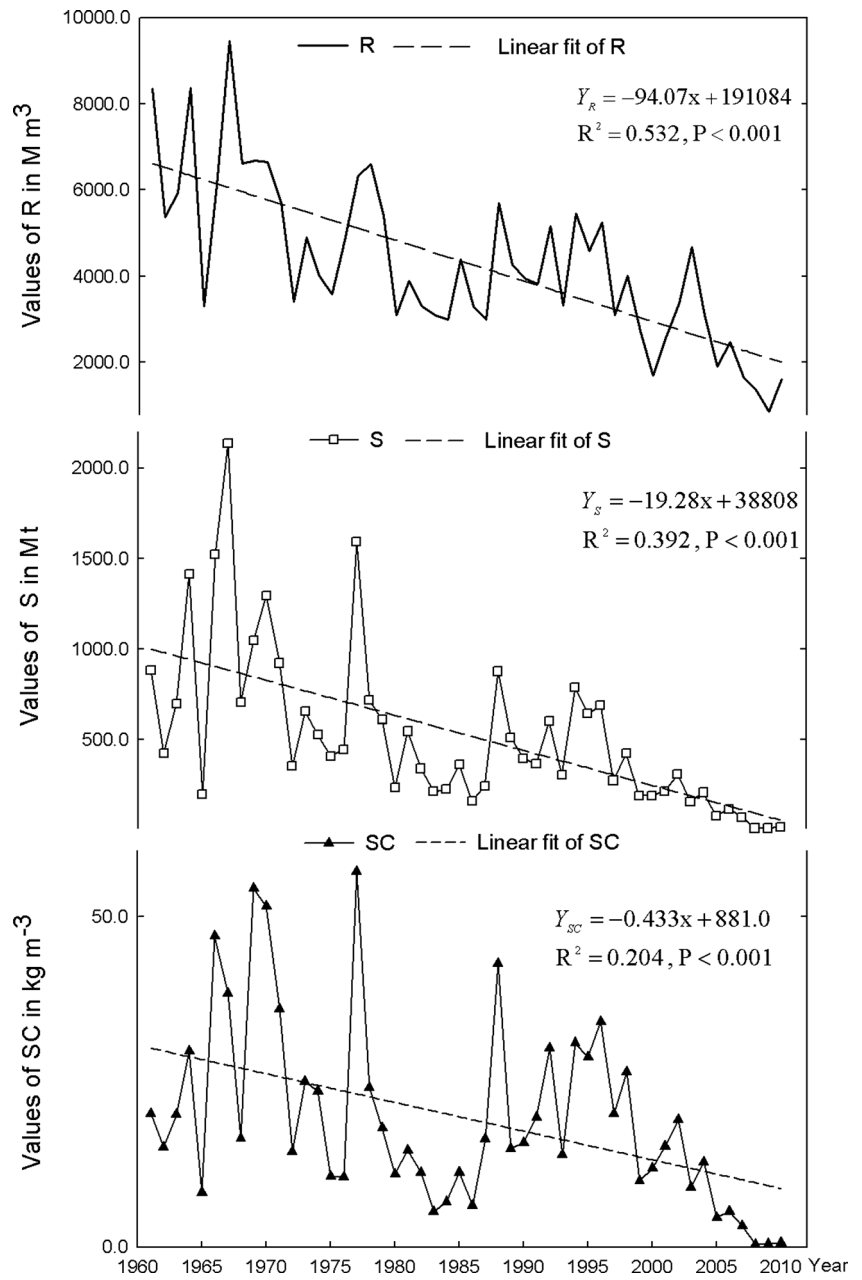


Fig. 3 Yearly ET_0 and precipitation variation during 1961–2010 in the middle reaches of the Yellow River

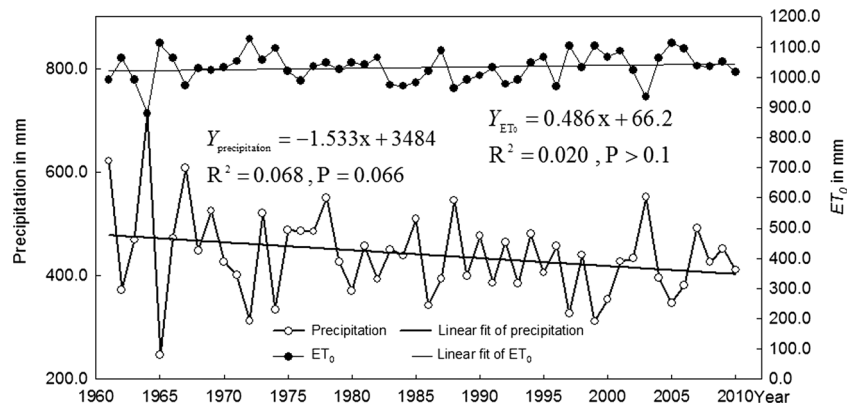


Table 2 Precipitation and ET_0 of the paired years

Number	Paired years with SPEC			P/mm				$a.ET_0/mm$			
	Year 1	Year 2	D-year	Year 1	Year 2	D-P	a (%)	Year 1	Year 2	D-a. ET_0	a (%)
1	1970	1979	-9	426.8	426.8	0.0	0.00	1031.6	1024.9	6.7	0.65
2	1971	1995	-24	401.2	405.8	-4.6	-1.15	1051.8	1067.2	-15.4	-1.46
3	1977	1994	-17	485.1	480.3	4.8	0.99	1035.6	1046.6	-11.0	-1.06
4	1981	2009	-28	457.5	452.3	5.2	1.14	1040.6	1051.2	-10.6	-1.02

D -year difference in years between years 1 and 2, $D-P$ difference in precipitation between years 1 and 2, $D-a.ET_0$ difference in ET_0 between years 1 and 2, and a amplitude (%)

4 Discussion

In this paper, we selected discrete time periods based on similar weather conditions to investigate the impact of human activities on erosion and runoff. This method helped control for precipitation, which generates runoff and erosion, and the technique also improved the objectivity and accuracy of the analysis and results. Compared with the traditional hydrologic method, our method does not use distinct transition points for to divide the hydrological series, which avoids divergence that results from different division points for the “unaffected” hydrological series period (Xiong 1986; Mu et al. 2007; He et al. 2011). Once this condition for the runoff and sediment yield is followed, the variation of sediment discharge and at a watershed hydrological control station can be used to distinguish between natural and human impacts via applying traditional statistics and basic principles of hydrology. This can avoid the influence of the calibration of key parameters in a distributed hydrological model (Yang et al. 2004a, b; Cong et al. 2009; Liu et al. 2011; Bai et al. 2014). In addition, the results from our method can be compared to and verify the results

from a distributed hydrological model, and thereby improve our understanding of the anthropogenic influence on runoff and erosion.

The annual sediment discharge and runoff in the middle reaches of the Yellow River exhibited significant declining trends during the study period, which is consistent with former studies (Xu 2005a; Gao et al. 2011; Mu et al. 2012; He et al. 2015a). A partial reason for this is the regulation of the 258 reservoirs (Ran et al. 1999; Zhu and Hu 2004; Ran 2006). The sediment concentration also presented a significant decrease during the study period. The reason for this may be explained by landscape pattern change in the study area (Suo et al. 2005). These findings have important consequences for integrated basin management.

There are two alternatives for the analysis of anthropogenic influence using the similar weather condition method. The first option considers the impact of human activities on runoff and erosion as a whole and does not distinguish between different human activities. If sufficient data is available, the effect of the different types of activity, such as irrigation and industrial water consumption, could be distinguished in the runoff

Table 3 Changes in runoff and sediment discharge within the four pairs of SPEC years

Character	Number	1	2	3	4
Pairs of years with SPEC	Year 1	1970	1971	1977	1981
	Year 2	1979	1995	1994	2009
Runoff($M m^3$)	Year 1	6650	5720	6330	3900
	Year 2	5400	4590	5460	870
	Difference	1250	1130	870	3030
	a(%)	18.80	19.76	13.74	77.69
Sediment discharge(Mt)	Year 1	1296.3	922.0	1590.8	547.0
	Year 2	610.0	642.9	787.4	11.1
	Difference	686.3	279.1	803.4	535.9
	a(%)	52.94	30.27	50.50	97.97
Sediment concentration($kg m^{-3}$)	Year 1	51.5	36.0	56.8	14.6
	Year 2	18.0	28.8	30.8	0.5
	Difference	33.5	7.2	26.0	14.1
	a(%)	65.05	20.00	45.77	96.58

a amplitude (%)

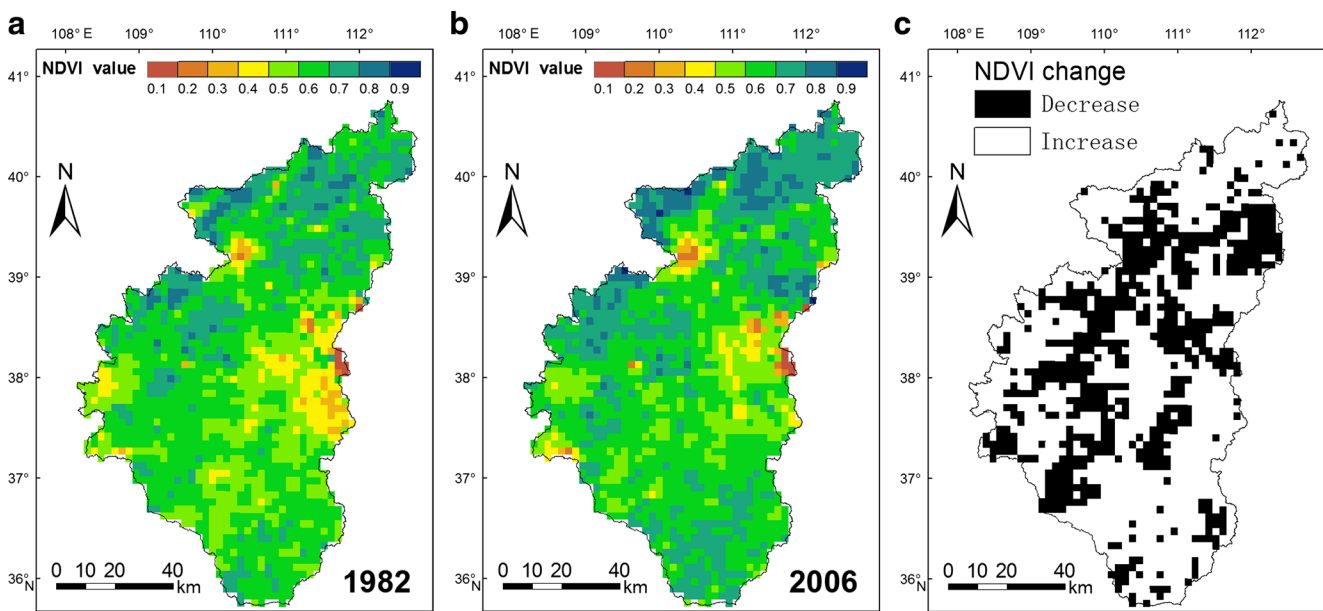


Fig. 4 NDVI change in 1982 and 2006 of the Middle Yellow River

and sediment discharge. The second option is to consider the same human activities occurring in the paired years as a net change instead of as a new effect on runoff and erosion, which makes it easier to describe the influence of human activities between the paired years.

5 Conclusions

The river runoff and sediment discharge have decreased substantially from 1961 to 2010. The precipitation declined, while potential evapotranspiration exhibited a small increase

during the study period. However, these two trends were not significant.

Four pairs of years were selected from the period of the 1970s to the 2000s using the SPEC method. All paired years showed reductions in the sediment discharge, sediment concentration, and runoff. These results are consistent with the trend detected by regression analysis.

There were important anthropogenic impacts related to soil and water measures as well as NDVI change in the middle reaches of the Yellow River. There was a change in NDVI, and 12,467.0 Mt of silt collected in reservoirs and behind check dams during 1960–1999.

Table 4 Area of engineering measures in the middle reaches of the Yellow River till 1999

Type	Character	Unit	Ningxia	Inner Mongolia	Shanxi	Shaanxi	Amount
Reservoir	Number	Set	77	49	19	113	258
	Control area	km ²	10,589.5	5419.3	8809.9	9025	33,843.7
	Capacity	Mm ³	562.4	431.0	120	1369.5	2482.9
	Siltation	Mm ³	357.8	109.9	34.2	503.5	1005.4
Key projects for gully control		M t	483.0	148.3	46.2	679.8	1357.3
	Number	Set	24	195	266	191	676
	Control area	km ²	697.1	950.6	1286.3	2083.1	5017.1
	Capacity	Mm ³	59.5	169.5	224.6	270.7	724.3
Check dam		Mm ³	0	22.7	109.4	145.4	277.5
		M t	0	30.7	147.8	196.3	374.8
	Number	Set	15,149	137	9045	19,766	44,097
	Siltation	Mm ³	5.3	11.7	477.5	7457.1	7951.6
Total amount of siltation		M t	7.2	15.9	644.7	10,067.1	10,734.9
		Mm ³	363.1	144.3	621.1	8106	9234.5
		M t	490.2	194.9	838.7	10,943.2	12,467.0

The technique developed herein can precisely distinguish impacts from anthropogenic activities and climatic changes. This method could help reveal the non-linear relationships among climate, human activities, runoff, and sediment discharge in rivers. It may be able to produce superior results as compared to traditional methods (e.g., hydrologic method). This method is extendable. This method could also be used in different regions or scales.

Acknowledgments This research was supported by the National Science Foundation of China [41171420 and 41271295], the External Cooperation Program of BIC, Chinese Academy of Sciences [16146KYSB20150001], the European Commission Programme Horizon 2020 project [635750], the West Light Foundation of the Chinese Academy of Sciences [2013-165-04], and the National Key Basic Research Special Foundation of China [2014FY210100].

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflicts of interest.

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