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Runoff and sediment variation in the areas with high and coarse sediment yield of the middle Yellow River

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Abstract. Massive water and soil conservation works (WSCW) have been conducted in the areas with high and coarse sediment yield of the middle Yellow River since 1982. With the impending effects of climate change, it is necessary to reconsider the effects of WSCW on runoff and sediment variation at decadal and regional scales. Using long-term official and synthesized data, the WSCW impacts on reducing water and soil loss were studied in Sanchuanhe River watershed. Results showed that the sediment and runoff generated from this area showed a decreasing trend in the past 50 years. A great progress has been achieved in erosion control since the 1970s. After the 4 soil and water conservation harnessing stages during the period from 1970 to 2006, the sediment and runoff yield showed decreases with the extension of harnessing. The results revealed that human activities exerted the largest effects on the sediment reduction and explained 66.6% of the variation in the specific sediment yield. The contribution of rainfall variation to runoff reduction was as large as human activities. A great benefit have been obtained in water and soil loss control in this area.

1. Introduction

Soil erosion is one of the most serious environmental threat to our terrestrial ecosystems (Singer et al., 1996; Yang et al., 2003; Sun et al.,2013). It reduces topsoil and fertility of farmland (Verstraeten et al., 2002; Ward et al., 2009) and affects the delivery of eroded sediments from agricultural areas carrying nutrients, pesticides, and heavy metal contaminants to rivers and channels (Boers, 1996; De Wit et al., 1999; Verstraeten et al., 2002), which can affect the quality of river water and of water in coastal areas (Yan et al., 2015). The Loess Plateau, as one typical area of serious soil erosion in China has received much attention from both the government and academic spheres (Ritsema, 2003; Ostwald et al., 2006; Hou et al., 2014; Liu et al., 2015). In this region, soil erosion by water during the rainy season is the main source of the Yellow River sediment accompanied with broken terrain, crisscross gulley, severe soil loss and complex mechanism of soil erosion and sediment yield, which leads to this region characterized by a long agricultural history, ragged topography, severe soil erosion, and a fragile environmental status (Wang et al., 2011). Sustainable development in Loess Plateau depends upon techniques such as soil and water conservation (Zhang et al., 2016). To control the serious soil erosion and to guarantee the food security for the local people in this region, a great deal of water and soil conservation works (WSCW) has been made in the past century, such as plant trees and grass, implement tillage and dry-land farming techniques, build terraces and soil-retaining dam (Wei et al., 2015). WSCW are generally built in uplands to face erosion and water scarcity problems, they consist of hillslope works reducing surface runoff and increasing local infiltration, and of small reservoirs collecting headwater flow and providing supplemental water for irrigation (Guillaume et al., 2008), were put into practice in the 1950s, and enlarged to a large-scale after the 1970s（Shi et al., 2012). Since the later 1970s, soil–water conservation-based strategy of watershed management has been implemented to gain soil erosion control (Li, 1997), and a few areas of forest plantation or agro forestry systems were established (He et al., 2003). It is obvious that a land-use change of such a magnitude must have large effects on infiltration, runoff and sediment yield, resulting in global changes of soil and fluvial hydrology and of erosion rates. But it is not easy to predict the sense of these changes (Lasanta et al., 2000).

The areas with high and coarse sediment yield of the middle Yellow River is well known for its severe erosion, high sediment yields. Since 1982 when the 8 key soil and water conservation harnessing regions has been built, the ecological environment has been gradually improved and the amount of sediment and runoff entering the Yellow River has been reduced continuously. Some researchers considered that it was owing to the water and soil conservation works (WSCW), while others believed that it was caused by the rainfall variation, but this has not been quantified for the effect respectively. Therefore, in this study the Sanchuanhehe River of Yellow River watershed was chosen as the case study area. The quantitative analysis model and monitoring data were used to explore the the influence of human activities and rainfall variation on sediment and runoff yield. The objectives of this study is to determine how the specific sediment and runoff yield is related to rainfall variation and human activities at the watershed scale.

2. Materials and methods

2.1 Study area

Sanchuanhe River watershed (36°55′-38°10′N, 110°33′-111°36′E) is located in the areas with high and coarse sediment yield (AHCS) of the Loess Plateau and covers 4161 km^2, in the reach from Hekouzhen to Longmen in the middle reaches of Yellow River (Fig.1). This watershed is representative of the AHCS in terms of its natural resources, land-use patterns, and population. Gauge records of the watershed's discharge and sediment yield have been collected since 1957. The area is influenced by dry and continental climates with an average annual precipitation of 506.3mm. 73% of this precipitation occurs in the period of May to September. In this area, the mean annual temperature is 7.3～10.5 °C, with a minimum mean temperature of −9.5 °C in January and a maximum of 24.3 °C in July. In the summer, intense storms erode much soil; average annual sediment delivery in this area measured 10510 $t/km^{-2} y^{-1}$.

The topography of the watershed is characterized by mountain ranges, deep valleys, and loess hilly and gully region; and the elevation ranges from 650 to 1900 m. According to the Chinese soil classification system, the major soil types include brown loamy soil, loessial soil, grey cinnamonic soil, and meadow soil (National Soil Survey Office, 1998). The principal land cover type in this watershed is forest occupying 39.8% of the watershed area.

In the early 80s of last century, the soil erosion in local places was very serious, which resulted in riverbed sediment deposition and soil fertility decline and made the ecological environment very fragile. Since 1983 when Sanchuanhe River watershed was listed as one of the 8 key soil and water conservation harnessing regions, the state and local government have done a lot of hard work and effectively carried out many soil and water conservation measures such as soil and water conservation forest, closed forest, aerial tree planting, planting commercial fruit forest and grass, soil-retaining dam construction, etc. Those significant results have been achieved and the ecological environment has been gradually improved. During the period of 1970-2006, large-scale soil and water conservation harnessing was carried out in four stages in Sanchuanhe River watershed. namely, 1st stage: 1970-1979, 2nd stage:1980-1989, 3rd stage:1990-1996, 4th stage:1997-2006. By the end of 2006, the measures of soil and water conservation management area occupies 1735km^2.

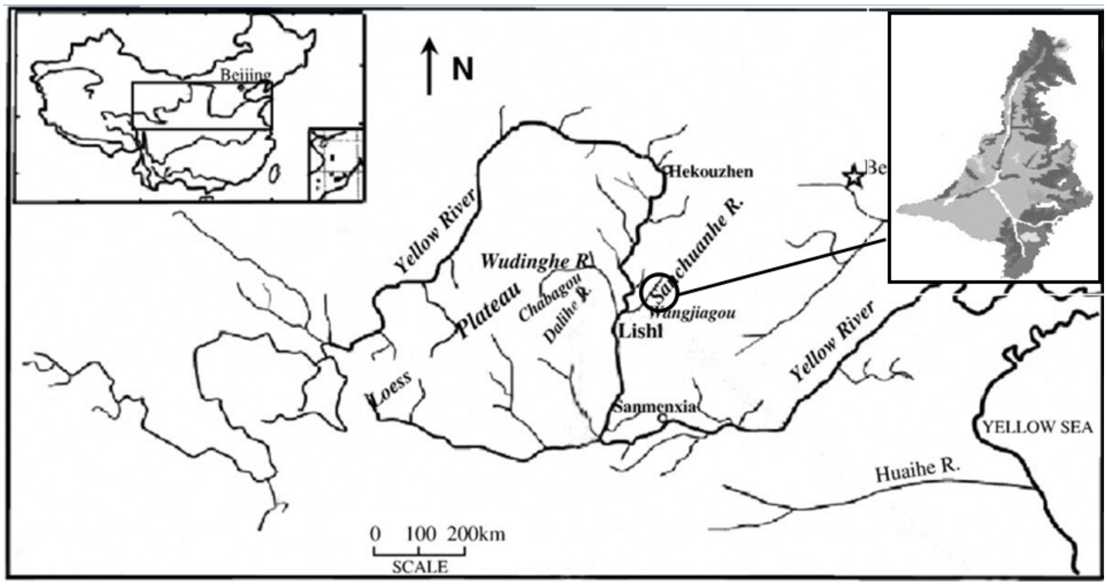

Figure 1. Location of the Sanchuanhe River watershed

2.2. Data collection

The hydrological data used in this research included precipitation, runoff, and sediment. The data sources for this study included the monthly and annual runoff and sediment load of Houdacheng hydrological station (1957 – 2006), mean daily precipitation, mean daily temperature of 20 hydrologic stations, and 4 meteorological stations within and surrounding the study area. The areas of soil and water conservation measures in several periods (1982, 1989 and 1999). The rainfall and runoff data come from the Hydrological Data of the Yellow River Basin issued yearly by the Yellow River Conservancy Commission (YRCC), and the bulletins of Chinese River Sediment from 1957 to 2006 (BCRS, 1957 – 2006), which were compiled by the Ministry of Water Resources (MWR). According to Yan (1984), the procedures used for the hydrological survey at hydrometric stations in China follow the national standards issued by the MWR and are basically the same as those used internationally. The data of soil and water conservation measures contain the areas of terrace, soil-retaining dam, forestation, grass sowing, farmland irrigation and reservoir capacity. They are among the basic data of soil and water conservation in the Yellow River basin collected from the local governments on the Loess Plateau by the Bureau of Middle Yellow River Management of the Yellow River Conservancy Commission (Shi, 2012). The Houdacheng hydrological station is the terminus in Sanchuanhe River watershed. A few of the 24 stations had been observably relocated in the study period, and the longest series of annual runoff recorded at a location of each of these stations was kept.

3. Results and discussions

3.1 Runoff and sediment yield characteristics

3.1.1 Temporal variation of runoff. The difference of annual runoff in Houdacheng station, the entrance and outlet of Sanchuanhe River watershed, is shown in Fig. 2. It represents the runoff generated from the watershed.A clear decreasing trend of runoff can be seen in Fig. 2, with a reduction gradient of 4.8 million m^3 per year. Moreover, the curve of the 10-year moving average of runoff displays a decline in an obvious staircase form. Sequential Cluster and rank-sum test (Sun et al., 2008) detected a primary abrupt change around the year 1970 and a secondary around the year 1981. Runoff reduced by about 22.7% after 1st harnessing stage (1970 – 1979) than before, and by about 22.8% after 1980 than in the period of 1970 – 1979. Since 1997, the annual runoff had declined to only 1.06 billion m^3 per year, which was about one-third of that before harnessing stage (3.23 billion m^3 per year). The causes for the occurrence of the runoff variation will be discussed later after the impacts of influencing factors on runoff being investigated.

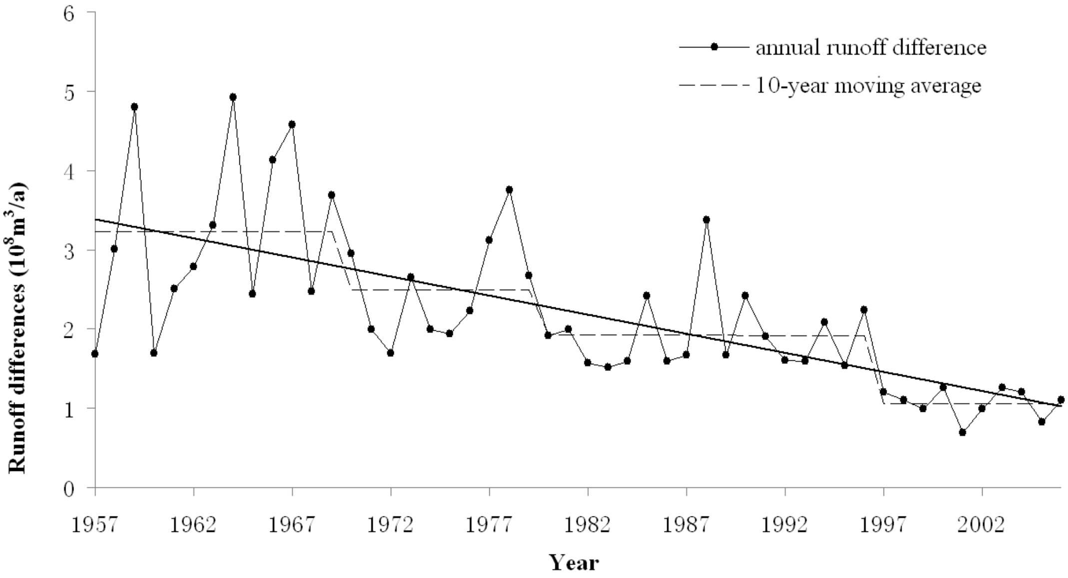

Figure 2. The annual runoff difference of Houdacheng station in the period of 1957-2006

3.1.2 Temporal variation of sediment. The difference of annual sediment in Houdacheng station is shown in Fig. 3. A clear decreasing trend of sediment can be seen in Fig. 3, with a reduction gradient of 0.72 million t per year. Moreover, the curve of the 10-year moving average of sediment also displays a decline in an obvious staircase form. Sequential Cluster and rank-sum test (Sun et al., 2008) detected a primary abrupt change around the year 1970 and a secondary around the year 1981 (Fig. 3). Sediment reduced by about 49.7% after 1st harnessing stage (1970 – 1979) than before, and by about 47.3% after 1980 than in the period of 1970 – 1979. Since 1997, the annual sediment had declined to only 2.58 million t per year, which was about 7% of that before harnessing stage (36.7 million t per year).

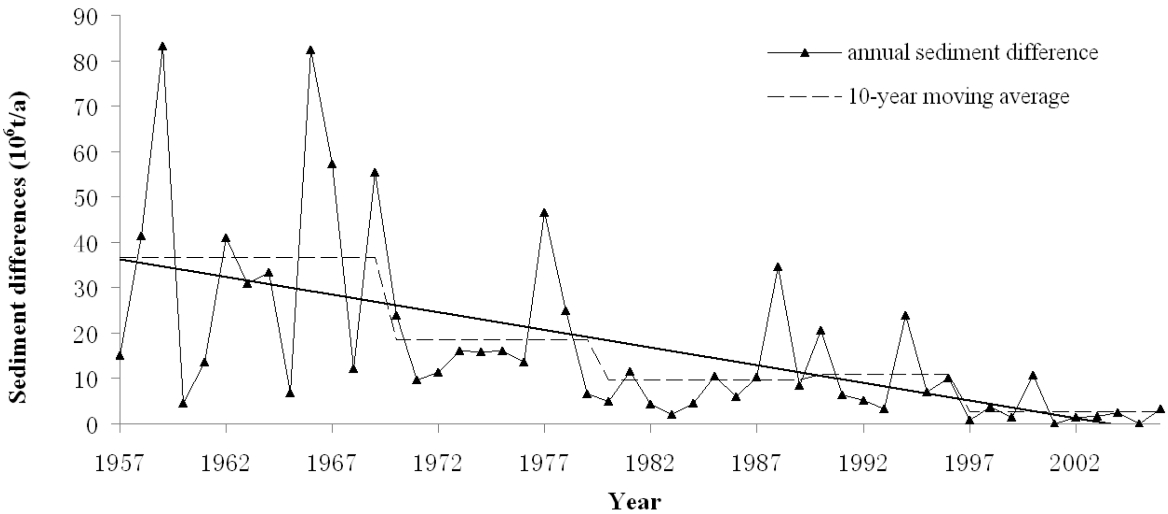

Figure 3. The annual runoff difference of Houdacheng station in the period of 1957-2006

3.2 Runoff and sediment yield modulus

3.2.1 Calculation model. Catchment runoff and sediment yields have typically been derived by empirically scaling measured specific runoff and sediment yield from a gauged river to the contributing catchment area (Hicks et al., 2011). This is because of the difficulty in quantifying the variability in 'erosion-affected areas' for landscapes (Marden et al., 2014). Currently, calculation model for water and sediment variation is under development to better quantify erosion process contribution to runoff and sediment yield specifically for small watersheds. This model requires data that better represent the characteristics of erosion rainfall of small watershed, which can account for the effect of runoff and sediment yield.

In recent years, many scholars have studied the calculation model of runoff and sediment variation in small watershed. For example, Zhang et al. (1994) established the formula to estimate the annual runoff and sediment in the flood season, dry years, precipitation, precipitation index and annual runoff sediment discharge based on correlation analysis. Wang et al. (2002) considered that runoff was composed by surface runoff and underground runoff, and underground runoff associated with antecedent precipitation, so the early water quantity parameter was introduced to estimate the runoff and flood sediment of flood and non flood season separately. Zhao et al. (1993) take effective precipitation in flood season, the effective rainfall intensity in July and August as the main parameters, establishes the model of sediment and runoff yield in flood season. Xu et al. (2000) choose the maximum 1 day rainfall, the maximum 30 day rainfall, the flood season rainfall and annual rainfall as characteristics of precipitation, established the relationship between the precipitation and annual runoff, sediment in a watershed. Ran et al. (2006) considered that sediment is mainly carried by the flood, by splitting the flow process were established a formula to estimate the flood peak and base flow, on this basis established the correlationship between the rainfall and flood sediment. The accuracy of the model needs to be verified. The verification method is statistic the measured data before 1970, calculated the required parameters, and the parameters generation model was calculated. Comparing the calculated results with the measured data, the difference between the calculated value and the measured value is the error. This paper chooses the measured data (1957 – 1969) to verify the formula, the flood and sediment yield calculation model build by Ran et al. has got the best simulation effect of natural runoff and sediment process. There is a good match between the calculated and measured runoff and sediment, as shown in Table. 1, which displays the results of Houdacheng hydrological station on the main stream of Sanchuanhe. All the errors of flood runoff are in the range of 0.4% – 34%, the errors of flood sediment are in the range of 1.6% – 39%, indicating that the models can give good predictions on the annual flood runoff and sediment for some cases. Comparing with the measured runoff, the relatively error of computed average annual runoff for the period of 1959 – 1969 is 18.6%, and it is 22.9% of sediment at Houdacheng station. Therefore, this paper adopts the calculating model of Ran. The formula is as follows:

$$W_H = 0.00365\, P_{7+8}^{2.6665} \tag{1}$$

$$W_C = 21.67\, P_N^{\ 1.9104}\, P_Y^{\ -0.8903} \tag{2}$$

$$W_{HS} = 0.0248\, P_{7+8}^{2.9778} \,/\, P_N^{\ 0.7595} \tag{3}$$

Where: W_H is the annual flood runoff, W_C is the base-flow, W_{HS} is the annual flood sediment, P_{7+8} is rainfall in July and August, P_y is the annual effective rainfall, P_N is the annual rainfall.

Table 1. Comparison between the calculated and measured annual runoff and sediment of Houdacheng hydrological stations on the mainstream of the Sanchuanhe River over the period of 1959–1969.

year	calculating runoff $W_{Hc}(10^8\,m^3)$	measured runoff $W_{Hm}\,(10^8\,m^3)$	error (%)	calculating sediment W_{HSc} (10^6 t)	measured sediment W_{HSm} (10^6 t)	error (%)
1959	2.69	2.68	0.4	84.69	83.32	1.6
1960	0.18	0.16	14.8	6.63	5.49	20.7
1961	0.58	0.49	19.2	17.53	13.82	26.8
1962	1.17	0.92	27.3	49.50	40.72	21.6
1963	0.82	1.24	-33.8	24.80	30.66	-19.1
1964	1.54	1.62	-5.0	41.30	33.46	23.4
1965	0.12	0.14	-16.3	4.72	6.65	-29.0
1966	1.89	1.90	-0.4	62.65	82.47	-24.0
1967	1.49	2.30	-35.0	45.87	57.07	-19.6
1968	0.27	0.34	-22.4	8.95	12.30	-27.2
1969	1.05	1.49	-29.7	34.29	55.86	-38.6

4. Conclusions

In the Sanchuanhe River watershed, the large-scale continuous soil and water conservation harnessing campaign have been carried out to many key regions according to the severity of the soil erosion on the Loess Plateau of China since the 1980s, and great progress has been achieved in water and soil loss control. The effects of water and soil conservation works (WSCW) on runoff and sediment loss were investigated in Sanchuanhe River watershed to analyze 50 years' monitoring data of the outlet station in this watershed, and quantitative analysised the contribution of WSCW harnessing to the runoff and sediment yield of this watershed in different stages by virtue of hydrological simulation model, thus to identify the influence on WSCW harnessing on runoff and sediment yield variation. After many years' harnessing the great benefit have been obtained in the reforestation and effective sediment trapping in this watershed.

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