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Influence of Vegetation on Runoff and Sediment in Wind-water Erosion Crisscross Region in the Upper Yellow River of China

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Abstract: All characteristics of vegetation, runoff and sediment from 1960 to 2010 in the Xiliu Gully Watershed, which is a representative watershed in wind-water erosion crisscross region in the upper reaches of the Yellow River of China, have been analyzed in this study. Based on the remote sensing image data, and used multi-spectral interpretation method, the characteristics of vegetation variation in the Xiliu Gully Watershed have been analyzed. And the rules of precipitation, runoff and sediment's changes have been illuminated by using mathematical statistics method. What′s more, the influence mechanism of vegetation on runoff and sediment has been discussed by using the data obtained from artificial rainfall simulation test. The results showed that the main vegetation type was given priority to low coverage, and the area of the low vegetation coverage type was reducing year by year. On the country, the area of the high vegetation coverage type was gradually increasing. In a word, vegetation conditions had got better improved since 2000 when the watershed management project started. The average annual precipitation of the river basin also got slightly increase in 2000–2010. The average annual runoff reduced by 37.5%, and the average annual sediment reduced by 73.9% in the same period. The results of artificial rainfall simulation tests showed that the improvement of vegetation coverage could increase not only soil infiltration but also vegetation evapotranspiration, and then made the rainfall-induced runoff production decrease. Vegetation root system could increases the resistance ability of soil to erosion, and vegetation aboveground part could reduce raindrop kinetic energy and splash soil erosion. Therefore, with the increase of vegetation coverage, the rainfall-induced sediment could decrease.

Keywords: vegetation coverage; runoff; sediment; infiltration rate; wind-water erosion crisscross region

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1 Introduction

There are serious soil erosion problems in China. According to the data from national survey of soil and water conservation (Liu, 2013), the soil erosion area is 2 949 100 km^2, which accounts for 30.7% of the total territory area of China. The area of wind-water erosion crisscross region is about 260 000 km^2, accounting for 8.8% of the total soil erosion area. In the Loess Plateau region, which is the main sand source area of the Yellow River, wind-water erosion crisscross region has the most intense soil erosion (Tang, 2000). It is harmful to not only to the Yellow River but also the local economy. Therefore it is necessary to study the mechanism of soil erosion in this complex environment region. The underlying surface and vegetation coverage are important factors affecting in the progress of soil erosion (Li *et al.*, 2007; Ludwig *et al.*, 2007). Soil and water conservation work has been carried out nationwide in China since the 1990s. Studies showed that the soil erosion in the Loess

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Plateau has been effectively and significantly reduced since 1997 (Yao *et al.*, 2011). Vegetation recovery played a critical role in reducing the erosion (Liu *et al.*, 2008; Wang *et al.*, 2011; Gao *et al.*, 2016), especially in the Loess Plateau region. Many experimental studies on typical plots in the Loess Plateau region have been carried out. Guo *et al.* (2012) took the experiments to study the effect of water flow on the shallow gully erosion in the loess hilly-gully region. Zhao *et al.* (2009) took many experiments to study the effects of vegetation on erosion, and the results showed that vegetation can effectively hold runoff, and damage to the grass irrigation in loess hilly-gully region can cause serious soil erosion. The artificial simulated rainfall experiments were carried out by Wang *et al.* (1991) to research the relationship between the rainfall intensity and the infiltration rate. All the studies mentioned above were carried out in plot, and large scale studies on the impact of vegetation coverage on runoff and sediment were rare.

In this study, vegetation changes of a typical river basin, Xiliu Gully Watershed, in the wind-water erosion crisscross region was interpreted by analyzing remote sensing data in 1998, 2002, 2007, and 2010. The research on precipitation, runoff, and sediment was carried out according to the observed data from 1960 to 2010. The response of the runoff and sediment export from the watershed to the vegetation change was investigated to study the role of vegetation in soil and water conservation.

2 Materials and Methods

2.1 Study area

The Xiliu Gully Watershed is a typical watershed in the wind-water erosion crisscross region in the upper reaches of the Yellow River of China. The Xiliu Gully originates from Dongsheng District of Ordos City of Inner Mongolia, and flows into the Yellow River in Zhaojunfen County, Inner Mongolia. The river's total length is 106.5 km, and its total drainage area is 1356.3 km^2. The upstream watershed in the loess hilly-gully region covers an area of 876.3 km^2, accounting for 64.6% of the total area. The middle part is in the Hobq Desert, with low ridge of fixed and semi-fixed dunes, which accounts for 20.7% of the total area. The downstream part is a pluvial fan, accounting for 14.7% of the total area. The watershed has a typical continental monsoon climate. The average annual precipitation is 267 mm, and the average annual evaporation is more than 2000 mm, 7 times the amount of precipitation. The main soil types are chestnut soil and coarse osseous chestnut soil, and the soil thickness is between 10 cm and 30 cm. The vegetation coverage is low. Soil and water conservation work in this watershed started from the 1960s, and the aim of the project is increasing the vegetation protection area. As we all know, the climate condition is very serious in the study area, so the effect of recovering vegetation is not good. But large-scale and comprehensive treatment has been carried out mainly since 2000.

2.2 Data collection

The daily precipitation data from 1960 to 2010 were collected from four meteorological stations (namely Gaotouyao Station, Hanjiata Station, Chaidenghao Station, and Longtouguai Station) (Fig. 1). The monthly precipitation and annual precipitation were calculated and statistically analyzed according to the daily precipitation. The daily runoff and sediment data from 1960 to 2010 were collected from Longtouguai Hydrological Station (Fig. 1).

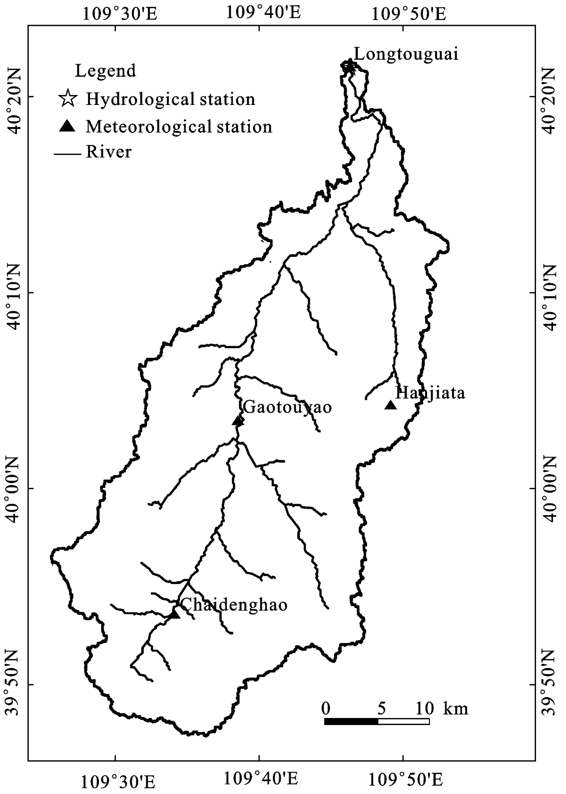


Fig. 1 Position of meteorological stations and hydrological station in Xiliu Gully Watershed

Vegetation coverage in the Xiliu Gully Watershed was interpreted and analyzed by multi-spectral remote sensing interpretation methods, using TM and ETM remote sensing data (image data from http://glovis.usgs.gov) on July 2, 1998, August 29, 2002, August 3, 2007, and July 10, 2010.

2.3 Methods

2.3.1 Anomaly percentage

Anomaly percentage (Y_i): anomaly percentage is an important index in climate prediction, and it refers to the departure from average annual percentage. The formula is as follows:

$$Y_i = \frac{\left(x_i - \overline{x}\right)}{\overline{x}} \times 100\% \qquad (1)$$

in this study, x_i is variable′s value in the i th year, $\overline{x}$ is the average from 1960 to 2010.

2.3.2 Variation coefficient

Coefficient of variation (C_v) represents the inter-annual variations. C_v is defined as:

$$C_v = \frac{\sqrt{\frac{1}{n}\sum_{i=1}^{n}(x_i - \overline{x})^2}}{\overline{x}} \qquad (2)$$

where the average $\overline{x} = \frac{1}{n}\sum_{i=1}^{n} x_i$, and n is the length of the time series (from 1960 to 2010).

2.3.3 Artificial rainfall test

The artificial rainfall test was carried out in the study area by using the rainfall simulation device designed by Xi'an University of Technology. The device is mainly divided into three parts, namely, water supply, voltage regulator, and rainfall. The raindrops from the device are nearly to the natural rainfall and the drops′ effective height was 6 m. According to the test, the rainfall uniformity coefficient reaches more than 85%. It can meet the requirements of artificial rainfall test. Test methods and plot layout were reported in Wang *et al*. (2012).

3 Results and Discussion

3.1 Temporal characteristics of runoff and sediment

The average annual precipitation between 1960 and 2010 was 267 mm with significant inter-annual variability. The maximum is 490 mm, which occurred in 1967, and the minimum is 26 mm, which occurred in 1962. The 1980s was a very dry period (the average annual precipitation in the 1980s was 11.6% less than that from 1960 to 2010), while the 1990s was a wet period (Table 1).

The average annual runoff is 2.91 × 10^7 m^3 from 1960 to 2010. The inter-annual variability of runoff is more obvious compared to that of precipitation. The maximal annual runoff appeared in 1961, which is 9.299 × 10^7 m^3, while the minimum was only about 9 × 10^6 m^3 in 2010. The characteristics between precipitation and runoff have been analyzed, and the heavy precipitation and large floods, which usually caused the serious runoff, are the main characteristics in the Xiliu Gully Watershed (Wang *et al.*, 2014). Table 1 shows that the runoff variability was similar to the precipitation variability. But since 2000, there has been a significant decrease in runoff, while a slight increase in precipitation.

As Table 1 shows, the change of sediment was more significant than those of precipitation and runoff. The annual sediment reached 47 487 000 t in 1989, clogging the Yellow River, while it was only 573 t in 2009. The sediment dropped sharply after 2000. During 2000-2010, the sediment is 69% less than the average level (Table 1).

Table 1 Decadal variation characteristics of annual average precipitation, runoff and sediment

Period	Precipitation		Runoff		Sediment	
	Average (mm)	Change (%)	Average (×10^7 m^3)	Change (%)	Average (×10^6 t)	Change (%)
1960–1969	279	4.7	3.330	14.4	3.19	–17.6
1970–1979	260	–2.5	3.475	19.4	4.38	13.4
1980–1989	236	–11.6	2.598	–10.7	6.73	74.2
1990–1999	283	6.1	3.260	12.0	4.10	6.0
2000–2010	275	2.9	1.980	–31.9	1.20	–69.0
1960–2010	267	0.0	2.910	0.0	3.87	0.0

Cumulative precipitation values have been calculated from 1960 to 2010, just as the runoff and sediment. The precipitation cumulative curve showed in Fig. 2a is the most continuous and smooth compared with the runoff cumulative curve (Fig. 2b) and sediment cumulative curve (Fig. 2c). That is to say, the variation of annual precipitation is not very obviously.

The jump points in the runoff cumulative curve and sediment cumulative curve are very clearly and obviously compared with the precipitation cumulative curve. The jump points show abrupt variation of runoff or sediment, and the value in the jump point year is larger than the year before. We can judge the variation of the runoff and sediment evidently according to the cumulative curve. The reason of the appearing of the jump points is that the river is seasonal river, and the runoff is high in the flood reason and is low in the drought reason. Heavy rain is the major factor to the runoff and sediment, and runoff is the main carrier to the sediment (Wang *et al.*, 2014).

We further used coefficient of variation (C_v) to represent the precipitation, runoff and sediment's inter-annual variations. C_v is calculated by Equation (2), The C_v of precipitation from 1960 to 2010 was 0.32, the C_v of runoff was 0.67, and the C_v of sediment was the largest, 1.91.

3.2 Temporal characteristics of vegetation coverage

The characteristics of vegetation coverage condition and vegetation type have been analyzed in the sampling area before the vegetation coverage classification of the whole river basin has been defined. Vegetation coverage classification was based on density threshold segmentation method, and five vegetation types have been identified in the study area, as shown in Table 2.

The area proportions of different coverage types in this watershed are shown in Fig. 3 for different periods. Major observations from the figure include the following.

(1) Low vegetation coverage area showed a decreasing trend. Area proportion of low vegetation coverage was 46.2% in 1998, and reduced to 14.7% in 2010. The area decreased significantly during 1998 to 2002, from 512.28 km^2 to 335.1 km^2, and the reduction accounted for 16% of the total area. The difference between 2002 and 2007 was small, only 0.7% of the total area. The most dramatic change occurred during 2007 to 2010, from 326.7 km^2 to 163.11 km^2, representing a reduction of above 50%.

(2) The area of middle coverage, high-middle coverage and high coverage of vegetation types increased year by year. From 1998 to 2010, the proportion of middle coverage to total area increased from 9.4% to 21.4%, the proportion of high-middle coverage increased from 5.3% to 13.1%, and the proportion of high coverage increased from 10.0% to 13.3%.

(3) The area of middle-low vegetation coverage fluctuated from 1998 to 2010. The proportion of middle-low coverage in 1998 was 29.1%, increased to 38.3% in 2002, then slightly decreased to 34.8% in 2007, and finally increased to 37.4% in 2010.

Overall, from 1998 to 2010, the low vegetation coverage area decreased most significantly, from 512.28 km^2 to 163.11 km^2, and the rate of decrease was about 68.2%. The area of middle coverage and high-middle had a rising trend, and the rate of increase was more than 50%. All the numbers show that the vegetation coverage changed significantly in the study area, and the vegetation in the Xiliu Gully Watershed was recovered in 1998–2010, but still was given priority to with low and middle-low coverage (Fig. 3).

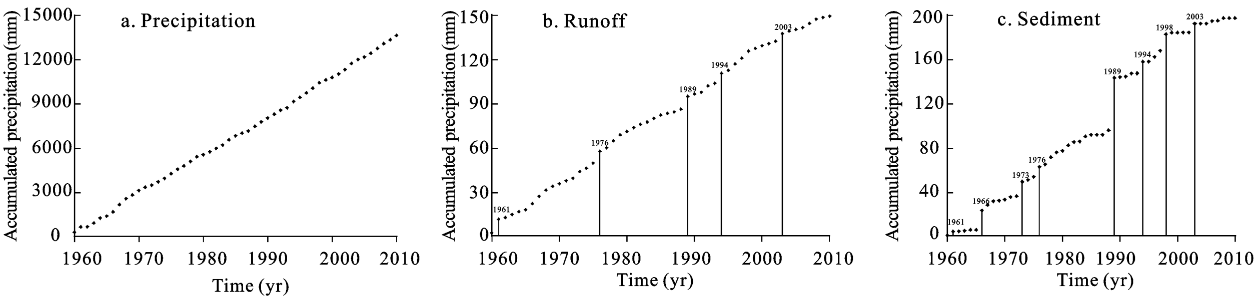


Fig. 2 Cumulative curve of precipitation, runoff and sediment in Xiliu Gully Watershed

Table 2 Vegetation coverage type and classification standard

Serial number	Vegetation type	Vegetation coverage (%)
L1	Low coverage	Vegetation coverage <25
L2	Middle-low coverage	25≤ Vegetation coverage <45
L3	Middle coverage	45≤ Vegetation coverage <60
L4	High-middle coverage	60≤ Vegetation coverage <75
L5	High coverage	Vegetation coverage ≥75

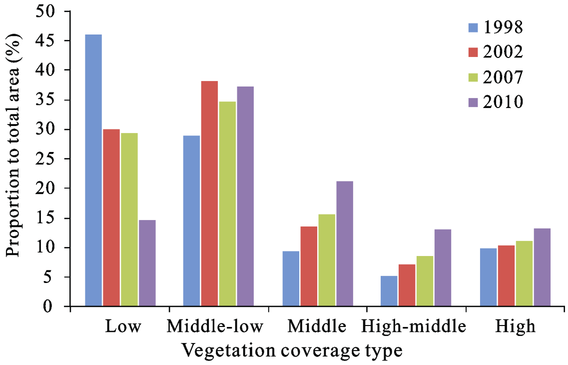


Fig. 3 Vegetation coverage changes in Xiliu Gully Watershed

3.3 Spatial characteristics of vegetation coverage

As illustrated by Fig. 4, the vegetation coverage in the upper watershed was higher than that in the middle and lower parts. The middle part has a very low coverage because of the desert area. Vegetation coverage along the river was higher than that far away from the river. Figure 5 shows the area proportions of different coverage types in 1998, 2002, 2007, and 2010.

In the upper reaches of Xiliu Gully Watershed (Fig. 5a), the main type of vegetation coverage was the low coverage in 1998, and the proportion of high-middle coverage area to whole basin was the minimum, 5.52%. The area with low coverage was significantly reduced in 2002, but the area with middle-low coverage, which acts as the main type of vegetation coverage during that period, was increasing. The area with middle vegetation coverage increased, and the area with middle-low vegetation coverage reduced in 2007. The area with low vegetation coverage obviously decreased in 2010, which reduced to 12.63%, on the country, the area with middle coverage, high-middle coverage and high coverage increased, and the proportion of their total area approximately amounted to 50%. All the variations of the vegetation coverage were caused by the policy 'returning grazing land to grassland, returning farmland to forest'.

In the middle reaches of the watershed (Fig. 5b), low coverage type dominated in all periods, and the proportions were higher than 50%. That is to say, the main vegetation coverage characteristic is low coverage because of the special geographical environment.

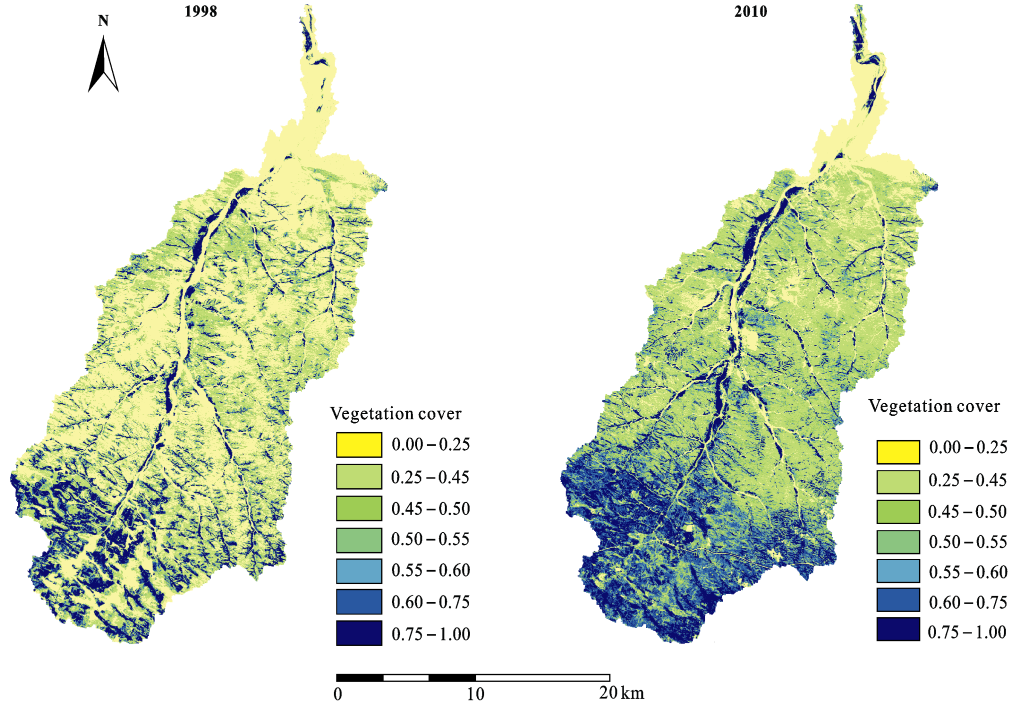
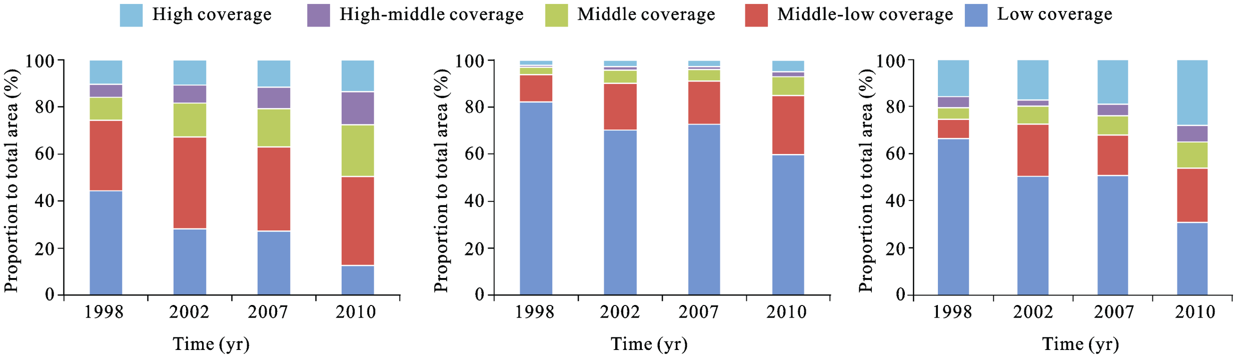


Fig. 4 Spatial distribution of vegetation coverage in Xiliu Gully Watershed in 1998 and 2010



a. Upper reaches b. Middle reaches c. Lower reaches

Fig. 5 Distribution of vegetation coverage in different reaches of Xiliu Gully

In the lower reaches of the watershed (Fig. 5c), low coverage and middle-low coverage were the main types in 1998, and the proportion was 66%. The proportion of high-middle and high coverage was over 20%. Low and middle-low coverage remained the main types in 2002 and 2007, and the proportion is higher than 60%. But proportion of the low coverage reduced significantly to 30.76% in 2010. On the other hand, the proportion of high-middle and high coverage was up to 35.22%.

3.4 Influence of vegetation change on runoff and sediment

Soil and water conservation work in the Xiliu Gully Watershed began from the 1960s. The control measures, such as engineering measures, plant measures, were mainly adopted in the upstream. The main control measures were the plant measures, but the vegetation growth and the improvement of vegetation coverage were not very obvious because of the climate condition. As we all know, it is very drought in the study area. The area of comprehensively harnessing soil and water loss in 2000 was 134.7 km^2, reaching 10.6% of the whole area. As disasters caused by frequent flood damaged to the Yellow River, central and local governments have paid more attention to the soil and water conservation. The implementation of the World Bank Loan Project for soil and water conservation has been carried out since 2000, and treasury bond project and warping dam system construction project for soil and water conservation also have been done in this area. At the end of 2007, the soil erosion area controlled is about 306.9 km^2, 37.8% to the whole river basin (Chen *et al.*, 2008). The comprehensive governance areas of soil and water loss are shown in Table 3.

Two periods before and after 2000 were defined in order to analyze the influence of vegetation on runoff and sediment. Table 4 shows the changes of precipitation, runoff and sediment in the two periods. The average annual precipitation increased by 3.7%. The average annual runoff and average annual sediment reduced significantly after 2000, and the reduction amplitude were 37.5% and 73.9%, respectively.

Table 3 Comprehensive governance area of soil and water loss in Xiliu Gully Watershed in different times

Time	Governance area (km^2)	Planting crop (ha)	Planting water conserved forest (ha)	Planting grass (ha)	Closing hill for reforestation (ha)	Dam (number)
2000	134.7	2786	8938	1234	500	15*
2007	306.9	1591	26020	976	2100	47

Note: *: Pond dam; Governance area is the area sum of planting crop, water conserved forest, grass and closing hill for reforestation

Table 4 Average annual precipitation, runoff and sediment in different periods

Period	Precipitation		Runoff		Sediment	
	Average (mm)	Change (%)	Average (× 10^7 m^3)	Change (%)	Average (× 10^6 t)	Change (%)
1960–1999	265		3.166		4.60	
2000–2010	275	3.7	1.980	–37.5	1.20	–73.9

In the second period (2000–2010), runoff and sediment decreased more significantly compared with those in the early period (1960–1999) even though with the same precipitation. Runoff and sediment discharge reduction was influenced by many factors, such as the dammed-up effect of warping dam, agriculture, animal husbandry, vegetation, *etc*.

In order to analyze the impact of the change of vegetation coverage on runoff and sediment's variation, the artificial precipitation test has been carried out. The quantitative analysis of the effects of vegetation coverage on runoff and sediment were studied.

The measured data got from artificial precipitation test showed that sediment was more in the plot without vegetation than that in other plots. Table 5 shows the differences of runoff and sediment in different test plots. The sediment yield in Plot 2 without vegetation was the largest, 5–10 times larger than that in plots with vegetation coverage. There were two reasons, firstly, vegetation roots can consolidate soil, which reduces soil erosion. Secondly, vegetation can abate the kinetic energy of raindrops, and weaken water drops splash erosion.

The runoff is smaller in higher vegetation coverage than in other types of vegetation coverage. The results of soil infiltration experiments showed that the soil infiltration rate was stronger in higher vegetation coverage in all conditions of rainfall, as shown in Fig. 6. The soil infiltration rate in Plot 6 (vegetation coverage was 33%) was 1.6 times than that in Plot 3 (vegetation coverage was 18%) in 1.0 mm/min rainfall intensity condition. Under the condition of light rain intensity rain (0.5 mm/min), the influence of vegetation coverage on soil infiltration rate in the process of runoff was more apparent. Other studies showed that the evapotranspiration capacity increased with higher vegetation coverage after rainfall (Jin *et al*., 2009; Pei *et al*., 2010; Chen and Zeng, 2013), which was another important factor influencing runoff.

Table 5 Runoff and sediment in different artificial rainfall test plots under different vegetation coverage

Plot No.	Coverage (%)	Uniformity (%)	Runoff (L)	Sediment (kg)
2	0	72	281.64	36.29
3	18	77	303.20	7.54
6	33	82	182.17	2.37

Note: test plot area is 100 m^2

4 Conclusions

The spatial and temporal distribution characteristics of vegetation coverage have been analyzed in the Xiliu Gully Watershed in the upper reaches of the Yellow River. The vegetation was developed very well with the carrying out of the soil and water conservation, especially in 2000–2010. The area with low or middle-low vegetation coverage accounted for most of the basin area. From the spatial variation, the vegetation coverage in the upper reaches of the Xiliu Gully was significantly higher than that in the middle and lower reaches.

Inter-annual variation of precipitation, runoff and sediment was obvious, especially the sediment. After 2000, the average annual precipitation increased 3.7% compared with the previous period (before 2000), while the average annual runoff and average annual sediment significantly reduced, the amplitudes of the reduction were 37.5 % and 73.9%, respectively.

The results got from artificial rainfall simulation test showed that the improvement of vegetation coverage could increase not only soil infiltration but also vegetation evapotranspiration, and then made the rainfall-

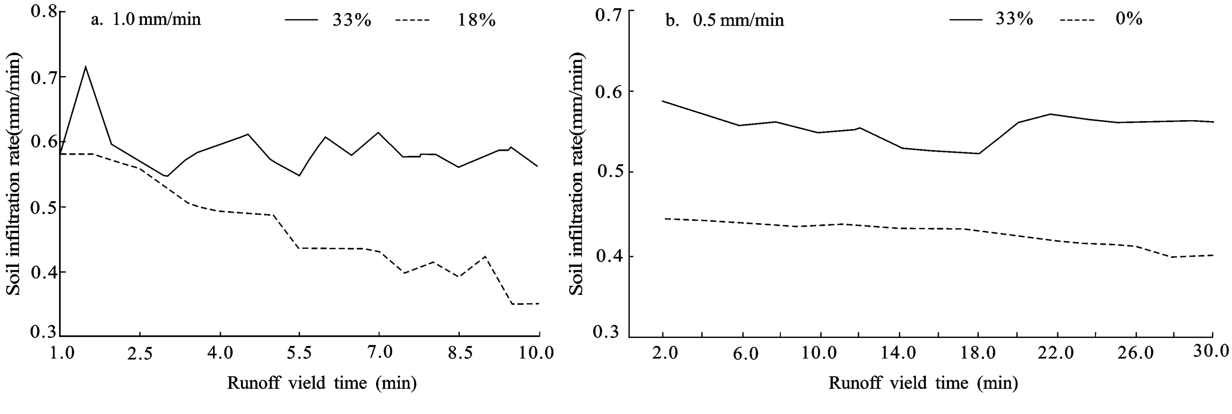


Fig. 6 Rainfall infiltration in different vegetation coverage under different rainfall intensities

induced runoff production decrease. Vegetation root system could increases the resistance ability of soil to erosion, and vegetation aboveground part could reduce raindrop kinetic energy and splash soil erosion. Therefore, with the increase of vegetation coverage, the rainfall-induced sediment could decrease.

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