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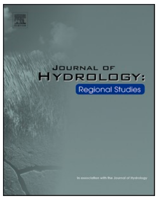

Effects of land uses and rainfall regimes on surface runoff and sediment yield in a nested watershed of the Loess Plateau, China

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ABSTRACT

Study region: The Loess Plateau, China.
Study focus: Land-use and rainfall characteristics are two crucial influencing factors that affect the surface runoff and soil loss process; however, less attention has been paid to nested watersheds in vulnerable geo-ecosystems. Here we analyzed rainfall characteristics impacts on runoff and sediment in one of the nested watersheds, which contains six sub-watersheds with different land uses. According to rainfall amount, duration, and maximum rainfall intensity within 30 min (I_{30}), 180 rainfall events during 2004–2019 were categorized into four types using *K*-means clustering method, and different hydrological years were distinguished.
New hydrological insights for the study region: The runoff coefficient and sediment yield under the rainfall regime I (little precipitation, moderate duration of precipitation, low intensity of precipitation) were the lowest; under the rainfall regime IV (high precipitation, short duration of precipitation, high intensity of precipitation), these values were the largest. The average runoff coefficient among the six sub-watersheds analyzed varied as follows: farmland watershed > farming-pastoral watershed > closed watershed > secondary forest watershed > mixed forest watershed > plantation watershed. The closed watershed had the lowest average sediment yield, while the farming-pastoral watershed showed the highest one. In addition, the runoff coefficient and sediment yield also changed differently in various hydrological years. The results of this study suggest that natural restoration measures are the optimal choice for coordinating the relationship between surface runoff and sediment yield. Enhanced long-term monitoring is needed to accurately describe watershed processes.

1. Introduction

Water erosion has been identified as one of the main causes of soil deterioration and land degradation worldwide (García-Ruiz et al., 2015). Soil erosion has become a severe global problem hindering sustainable economic and societal progress (Feng et al., 2010; Wuepper et al., 2020). Rainfall-runoff processes, as well as the resulting soil erosion, are influenced by many factors (Chen et al., 2013;

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Ziadat and Taimeh, 2013; Yu et al., 2019). Land-use and rainfall characteristics are two crucial influencing factors that affect the surface runoff and soil loss process (Mohamadi and Kavian, 2015; Yin et al., 2017; Guzha et al., 2018; Martínez-Mena et al., 2020). For this reason, in order to better adjust land use to achieve soil and water conservation goals, it is essential to understand the dynamics of runoff and soil loss and their causes across different land uses.

Proper land-use pattern adjustments can significantly improve soil water infiltration (Neris et al., 2012; Biro et al., 2013) and reduce sediment output to acceptable levels (Fu et al., 2009; Gao et al., 2017). In China (Chen et al., 2007) and northwest Ethiopia (Assaye et al., 2021), cropland areas have historically expanded at the expense of forests, shrublands, and grasslands, even on steep slopes. Soil erosion has intensified due to unsustainable land use and management measures (Borrelli et al., 2017). Mismanagement of forests has resulted in severe water loss and soil erosion on mountain slopes, as well as the formation of gullies, which has led to an increase in sediment loads in rivers (Kasai et al., 2005). Rain causes splashing and surface runoff, which can lead to erosion on the soil surface (Kinnell, 2005). The intensity and duration of precipitation play an important role in ecohydrological processes (Ran et al., 2012). Rainfalls with greater intensity or duration result in a greater peak runoff, leading to greater total runoff in watersheds (Wei et al., 2014). Moreover, rainfall patterns and regimes are important factors in both water conservation and soil erosion (de Lima and Singh, 2002; Peng and Wang, 2012; Mohamadi and Kavian, 2015; Chen et al., 2018). Different rainfall regimes causes different surface runoff and sediment yield, as shown in one of the runoff plot in a loess region of Gansu province, China (Wei et al., 2007). Peng and Wang (2012) showed that the response of runoff and sediment yield to rainfall characteristics had threshold value.

The Loess Plateau is a typical fragile environmental region and a key area of soil and water conversation in China and the world (Shi and Shao, 2000). Scholars have paid close attention to the region's water erosion, but most studies of soil erosion are based on measurements within runoff plots and large river catchments (Poesen, 2018). Because the characteristics of the underlying watershed surface are extremely complex, when extrapolating runoff-plot scale to watershed scale, there is less information available about topography, slope (gradient), soils, land cover, land use, and land management (Sidle et al., 2017). The need for small watershed studies continues to be great for understanding and modeling hydrological relationships. Watershed-based approaches have promoted a variety of measures to control surface runoff and soil losses over time, including check dams, terraces, grass strips, natural vegetation restoration, and various shrub and tree plantations (Zhao et al., 2013). In particular, in the 1990s, the Chinese government initiated a large-scale "Grain-for-Green" project to combat soil erosion and improve the environment (Deng et al., 2014; Yu et al., 2020). Due to the phenomenon of water and soil losses in recent decades, water runoff changes in the Yellow River basin have attracted much attention, especially in the middle reaches of the river (Zuo et al., 2016).

Numerous studies on the response of surface runoff to different land uses have indicated significant variability with rainfall regimes at different scales (López-Tarazón and Estrany, 2017; Guastini et al., 2019; Yu et al., 2022). Nonuniform variations in land-use/vegetation coverage have been linked to hydrological responses across watersheds (Roa-García et al., 2011; Warburton et al., 2012; Salemi et al., 2013; Gao et al., 2018). Watershed hydrological processes (canopy interception, runoff, vegetation transpiration, and soil evapotranspiration) can all be significantly influenced by tree planting (Wang et al., 2011a, 2011b; Jia et al., 2017; Jin et al., 2020). Moreover, the nested watershed is a complete watershed containing various types of sub-watersheds, however, long-term responses of surface runoff and sediment yield on land use and land management are still poorly understood.

Runoff and sediment yields are highly variable. Long-term monitoring has been found to be necessary to accurately characterize

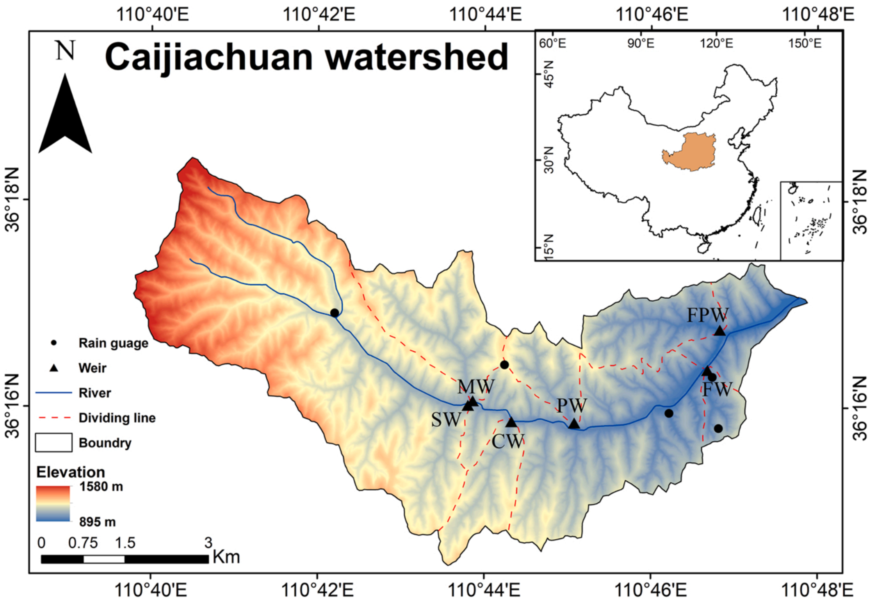

Fig. 1. Location of the study sites. Note: SW, secondary forest watershed; MW, mixed forest watershed, CW, closed watershed, PW, plantation watershed; FW, farmland watershed; FPW, farming-pastoral watershed. The same below.

watershed processes. Considering these research gaps, we analyzed surface runoff and sediment yield during rainfall events (2004–2019) in one of the nested watersheds contained six sub-watersheds and located in the Loess Plateau, China. The specific aims of the study were (1) to compare the differences in surface runoff and sediment yield across the six sub-watersheds and (2) to examine surface runoff and sediment yield in relation to different rainfall regimes and hydrological years.

2. Materials and methods

2.1. Study area

This study was carried out in the National Forest Ecosystem Field Scientific Observatory Station in Ji County, Shanxi Province, China. The Caijiachuan watershed (110°39′45″–110°47′45″E, 36°17′27″–36°18′23″N) is located in the south-eastern Loess Plateau, China; it belongs to the first tributary of the Yiting River, the second tributary of the Xinshui River, third tributary of the Yellow River (Fig. 1), with altitude ranging from 895 m to 1580 m. The watershed covers an area of 39.8 km^2; it is generally oriented from west to east and is approximately 12.4 km long. The study area is located in a semi-humid region, the average annual potential evaporation is 1723.9 mm, and the annual mean air temperature is 10.2 °C. The average long-term (for 1985–2021) annual precipitation is 575.9 mm; 85 % of precipitation falls mainly from May to October. The primary soil type is alditol, and the topographic features are typical of a loess hilly and gully region. The watershed is 84 % forested. The upstream part of the watershed has natural secondary forests that are primarily composed of *Quercus liaotungensis*, *Populus davidiana* and *Betula dahurica*; the middle part of the watershed has plantations of Chinese pine (*Pinus tabuliformis*), black locust (*Robinia pseudoacacia*), and Chinese arborvitae (*Platycladus orientalis*); and the downstream part of the watershed is dominated by farmland and grassland (Wang et al., 2012).

As stated above, the Caijiachuan watershed contains six sub-watersheds (Fig. 1). At the outflow of each sub-watershed, six compound weirs were constructed. Table 1 summarizes the basic characteristics of each sub-watershed, including the secondary forest watershed (SW), mixed forest watershed (MW), closed watershed (CW), plantation watershed (PW), farmland watershed (FW), and farming-pastoral watershed (FPW). The SW, which consists mainly *Quercus Liaotungensis*, *Populus davidiana* and *Betula dahurica*, has the most common type of vegetation formed by secondary succession. The MW consists of artificially planted vegetation in secondary forests. The artificial vegetation in the PW was planted in the 1990s. The CW has closed farmland and grassland to avoid the impact of human activities. Farmland and grassland are the two main land-use types in the FPW.

2.2. Rainfall monitoring

A tipping bucket rainfall gauge (ISCO 674, Teledyne Company, USA, 0.1 mm) was installed to record the incident rainfall in each weir. At the same time, five rainfall gauges (HOBO RG3-M, Onset Company, USA, 0.2 mm) with an accuracy of 0.2 mm were also set up at other locations in the watershed. In total, eleven rainfall gauges were installed in the Caijiachuan watershed (Fig. 1). The rainfall amount (RA, mm), rainfall duration (RD, h) and maximum rainfall intensity of 30 min (I_{30}, mm h^{-1}) were obtained using these monitoring data. Combined with the location of the rainfall gauges, kriging interpolation was used to calculate the mean rainfall over the entire watershed.

In the Caijiachuan watershed, precipitation from May to October accounted for more than 80 % of the annual precipitation, and erosive rainfall mainly occurred during this time. Thus, rainfall was recorded every 5 min from May to October during 2014–2019. According to our early findings (Zhang et al., 1996), rainfall events with less than 10 mm generally did not cause significant changes in the water level. The rainfall-runoff events included in the study occurred between May and October during 2004–2019, and they were chosen based on the following criteria: a) a total event precipitation of at least 10 mm; b) no precipitation for at least 6 h between two events.

2.3. Surface runoff and sediment yield monitoring

An automatic sampler and ultrasonic water level gauge (ISCO 6700, Teledyne Company, USA) were arranged in each compound weir during May-October from 2014 to 2019, and the water level was measured every 5 min. In addition, an automatic long-term measuring water level gauge (Nissan water research type 62, Japan) was used for correction. We used the velocity area method and the base flow using the linear cutting method to calculate the flow rate and runoff data of the watershed based on the observed water level and calibrated water level flow curve. A rectangular section with a small triangular groove was adopted to effectively solve

Table 1
Characteristics of the six sub-watersheds studied.

Sub-watershed type	Area, km^2	Length, km	Width, km	Channel density, km km^{-2}	Slope gradient, %	Shape factor	Forest coverage, %
Secondary forest	18.57	2.67	2.67	25.90	7.05	2.72	82.60
Mixed forest	3.62	3.30	1.10	0.91	8.89	3.01	82.30
Closed	1.93	0.68	0.68	4.10	8.43	4.40	99.70
Plantation	1.50	2.18	0.72	3.00	12.11	3.03	92.48
Farmland	0.71	1.38	0.54	1.81	8.70	2.55	10.93
Farming-pastoral	2.63	0.91	0.91	1.09	12.19	3.55	45.30

the problem of observation accuracy at low water flow. The parameter list and stage-discharge formulas of the weirs are shown in Table 2.

Artificial sampling was carried out from July to August in 2004–2019. According to the fluctuation of the water level during a rainfall event, the water samples were collected manually on the weirs at a certain time, and the sediment content was measured by laboratory filter drying. When taking water samples, the water level was observed with a water gauge, which was used to calibrate the measured data of the self-recording water gauge. The sediments were separated from the water samples and allowed to settle before drying in an oven.

2.4. Statistical analysis

In this study, rainfall events were divided by *K*-means clustering method. The runoff coefficient is a measure of the ability of a watershed to generate runoff (Zheng et al., 2021). The following formulas were used to calculate the runoff coefficient and soil erosion modulus (SEM):

$$RC = (R/P) \times 100\% \tag{1}$$

$$SEM = SL/A \tag{2}$$

where RC, R and P are the runoff coefficient of the watershed (%), surface runoff at the watershed outlet (mm), and precipitation (mm), respectively; SEM, SL and A are the soil erosion modulus of the watershed (t km^{-2}), sediment load at the watershed outlet (t), and watershed area (km^2), respectively.

We used Python software v.3.10.0 (Dua and Graff, 2019) to conduct the *K*-means clustering analysis for different rainfall regimes. A one-way ANOVA was applied to compare differences of the runoff coefficient and sediment yield among land-use types. The least significant difference (LSD) test was used to determine specific differences among various land uses. In all cases, differences were statistically significant at $p < 0.05$. All statistical analyses were carried out in the SPSS software with a version of 22.0.

3. Results

3.1. Rainfall characteristics

As shown in Fig. 2, the annual variation in precipitation in the watershed was large. The year with the most precipitation was 2014 (678.8 mm), while the year with the least precipitation was 2010 (333.2 mm). The hydrological year was determined using the Pearson-III frequency curve and annual precipitation data from Ji County Station for 1960–2019. Wet years were defined as those with precipitation greater than or equal to $P = 25$ % (544.7 mm), dry years were defined as those with precipitation less than or equal to $P = 75$ % (423.4 mm), and normal years were defined as those when precipitation occurs between wet and dry years (Li et al., 2020). In terms of rainfall for the experimental period from 2004 to 2019, the years 2004, 2008, 2009, 2010, 2012, 2015, and 2019 were dry years; the years 2011, 2013, 2014, and 2016 were wet years, and the years 2005, 2006, 2007, 2016, and 2018 were normal ones.

Based on the RA, RD, and I_{30}, the 180 rainfall events were grouped into four types (Table 3). The rainfall regime I (little precipitation, moderate duration of precipitation, and low intensity of precipitation) was the most common rainfall regime in the study area. The duration of precipitation in the rainfall regime II was the shortest of the four rainfall regimes and had an average amount and intensity of precipitation. The rainfall regime IV represented extreme rainstorms, with higher rainfall, shorter rainfall duration, and high rainfall intensity than that of the rainfall regime III.

During May 2004–October 2019, the rainfall regime I appeared 100 events, the total rainfall amount of this regime was 1723.3 mm, and the total rainfall duration of the regime was 1660.4 h. There were 55 observations of the rainfall regime II in all rainfall events,

Table 2
Parameter list and stage-discharge formulas of the weirs.

Sub-watershed	Triangular groove		Rectangular weir		Stage-discharge formulas	R^2
	Width, m	Depth, m	Width, m	Height, m		
SW	1.0	0.5	4.0	2.0	$Q_{H \le 50} = 0.0172H^{2.5034}$ $Q_{H \ge 50} = 308 + 13.534(H - 50)^{1.5468}$	0.9994
PW	1.0	0.5	3.0	1.5	$Q_{H \le 50} = 0.0172H^{2.5034}$ $Q_{H \ge 50} = 308 + 10.798(H - 50)^{1.5181}$	0.9991
MW	0.6	0.3	3.0	1.5	$Q_{H \le 50} = 0.0172H^{2.5034}$ $Q_{H \ge 50} = 308 + 10.798(H - 50)^{1.5181}$	0.9991
CW	1.0	0.5	3.0	1.5	$Q_{H \le 50} = 0.0172H^{2.5034}$ $Q_{H \ge 50} = 308 + 10.798(H - 50)^{1.5181}$	0.9991
FW	0.6	0.6	3.0	1.5	$Q_{H \le 30} = 0.0172H^{2.5034}$ $Q_{H \ge 30} = 86 + 10.798(H - 30)^{1.5181}$	0.9991
FPW	0.6	0.3	4.0	1.5	$Q_{H \le 30} = 0.0172H^{2.5034}$ $Q_{H \ge 30} = 86 + 13.354(H - 30)^{1.5468}$	0.9994

Q—the runoff to the water level at a certain time, L/s; H—water depth of rectangular section, cm.

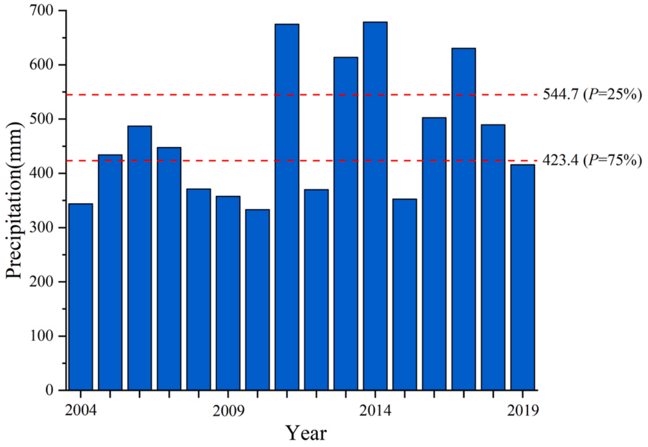

Fig. 2. Annual precipitation change in the Caijiachuan watershed from 2004 to 2019.

Table 3
Statistical feature of the rainfall regimes.

Rainfall regimes	Eigenvalue	Mean	V_{25}	V_{75}	Std. dev.	Sum	Frequency
I	RA (mm)	17.23	11.95	19.48	7.41	1732.30	100
	RD (h)	16.60	10.10	22.06	9.55	1660.37	
	I_{30} (mm h^{-1})	6.94	4.00	8.40	3.54		
II	RA (mm)	22.69	15.90	27.20	8.26	1248.10	55
	RD (h)	6.83	1.79	10.75	6.01	375.40	
	I_{30} (mm h^{-1})	25.73	18.90	31.00	10.06		
III	RA (mm)	63.41	50.60	69.60	15.74	1077.90	17
	RD (h)	38.55	26.00	46.00	21.68	655.37	
	I_{30} (mm h^{-1})	14.92	7.00	18.80	9.52		
IV	RA (mm)	85.96	69.48	96.70	17.51	687.70	8
	RD (h)	17.93	13.35	17.67	12.39	143.45	
	I_{30} (mm h^{-1})	51.38	38.25	53.15	22.80		

with a total of 1248.1 mm and 375.4 h. The rainfall regime III was observed 17 times, with a total duration of 655.4 h, and a total amount of 1077.0 mm. The total rainfall amount and duration of the rainfall regime IV was 687.7 mm and 143.5 h, respectively; however, it occurred only 8 times.

As is shown in Fig. 3(b), the total amounts of the four rainfall regimes were different in different years. Rainfall amount of the rainfall regime I was higher than in the rainfall regime II, except in 2005, 2006, 2007, 2014, and 2018, because the rainfall regime I was the most common rainfall event (Fig. 3(a)). Fig. 3(d) shows that I_{30} of the rainfall regime IV was lower than in the rainfall regime III, I and II. As shown in Fig. 3, on the whole, the distributions of the rainfall regimes showed high variations among different years. The rainfall regime II showed the most obvious interannual variations. For example, the rainfall amounts in 2010, 2017, and 2019 were 16.1, 14.9 and 12.4 mm, respectively, and the rainfall amounts in 2007, 2014 and 2018 were 157.2, 144.4 and 138.9 mm, respectively. Regarding the rainfall regime IV, all eight events appeared only in 2004, 2006, 2011, 2014, 2017, and 2019. No other years have seen such rainfall events.

3.2. Surface runoff and sediment yield in sub-watersheds with different land use/cover

According to Fig. 4, in 2004–2019, the mean runoff coefficient from May to October (the growing season) was ranked in the following order: FW (2.42 %) > FPW (2.38 %) > CW (1.11 %) > SW (1.08 %) > MW (0.73 %) > PW (0.43 %). The runoff coefficients during the growing season differed by years. For instance, the lowest and the highest values in the FW were 1.62 % in 2004 and 3.14 % in 2017, respectively. However, the lowest and highest values in the SW were 0.36 % in 2013 and 1.76 % in 2012, respectively. During the experimental years, the variation in the runoff coefficient in the FPW ($C_v = 65.57$ %) was the largest, followed by that in the SW ($C_v = 48.67$ %), and the smallest was in the PW ($C_v = 17.75$ %).

Fig. 5 shows the runoff coefficient in the hydrological years of the studied sub-watersheds. There were no significant variations of the runoff coefficient in the different hydrological years. Overall, the runoff coefficient of the FW was the highest, followed by the FPW, whereas the runoff coefficient of the PW was the lowest. It is worth mentioning that the runoff coefficient of the FW was significantly higher than that of the FPW ($P < 0.05$). The SEM of the SW was the lowest, followed by that in the CW, and the soil erosion modules of the FW and FPW were higher than those of the other sub-watersheds (Table 4).

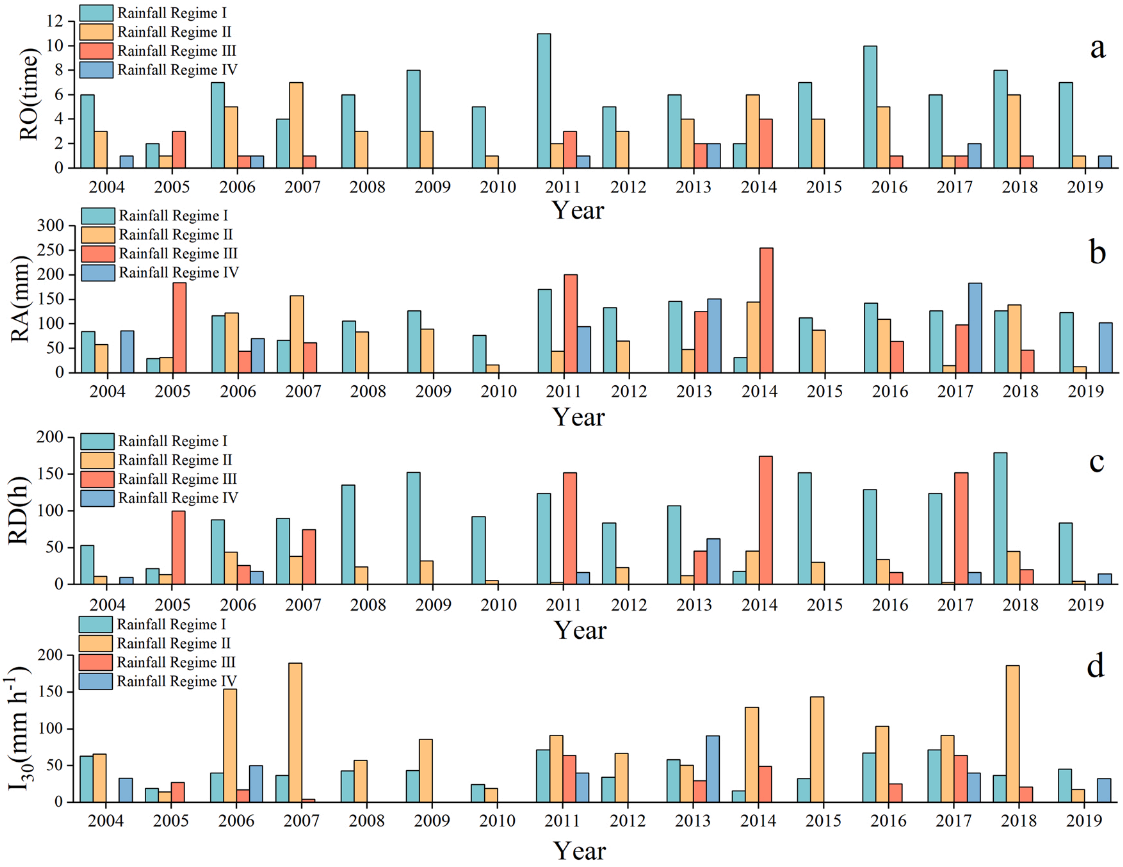

Fig. 3. Characteristics of the four rainfall regimes from 2004 to 2019. *Note:* RO, rainfall occurrence (time); RA, rainfall amount (mm); RD, rainfall duration (h); I_{30}, the maximum 30-min rainfall intensity (mm/min). In some years, there were no data for the rainfall regime III or rainfall regime IV, because this kind of rainfall did not occur during these years.

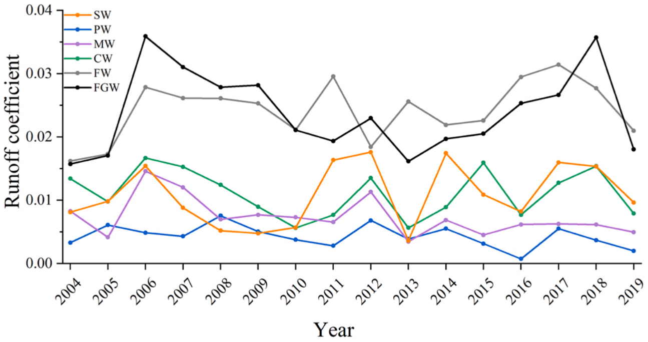

Fig. 4. The runoff coefficient from May to October under different land uses during 2004–2019.

3.3. Surface runoff and sediment yield under different rainfall regimes

The runoff coefficient under each rainfall regime was different (Fig. 6). The runoff coefficient of the rainfall regime I was notably lower than under other rainfall regimes. In the FPW and PW, the runoff coefficient of the rainfall regime IV was highest. Comparing the runoff coefficient of different rainfall regimes, the SW had the smallest difference.

As shown in Fig. 7, there were clear differences in the runoff coefficient of the studied sub-watersheds with different land-use types in hydrological years. In addition to the FW and FPW, there were no significant differences in other land-use types. Overall, the runoff coefficient of the rainfall regime IV was highest.

Under the rainfall regime I, the SEM among all six sub-watershed was very small, even close to zero (Table 4). The SEM of the

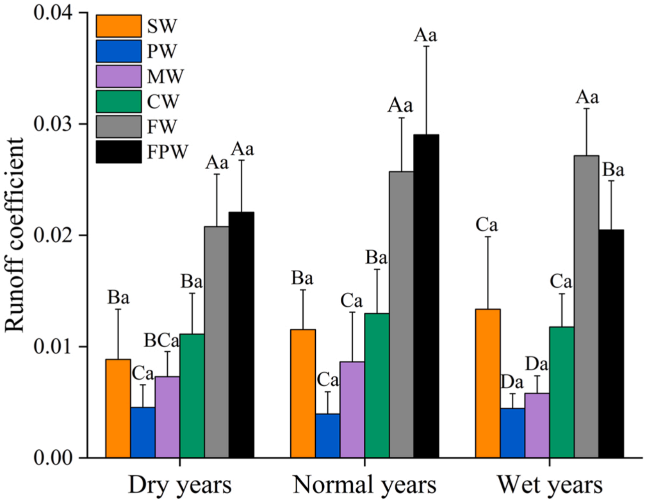

Fig. 5. The runoff coefficient in hydrological years of the studied sub-watersheds. *Note*: Capital letters indicate significant differences between the studied land-use sub-watersheds in the same hydrological years, and lowercase letters indicate significant differences between different hydrological years in the land-use sub-watersheds.

Table 4

Characteristics of rainfalls and sediments in the studied small sub-watersheds under various types of land use.

Data	Rainfall regime	RA, mm	RD, h	I_{30} mm h^{-1}	Soil erosion modulus (t km^2) SW	PW	MW	CW	FW	FPW
2004/7/29	II	10.0	1.7	20.4	0.020	0.690	0.550	0.342	1.911	1.568
2005/7/31	I	11.0	1.5	10.0	0.003	0.006	0.013	0.005	0.009	0.007
2005/8/7	I	18.5	6.5	8.2	0.001	0.003	0.001	0.003	0.002	0.004
2006/7/22	I	22.0	12.3	4.8	0.004	0.019	0.015	0.003	0.028	0.061
2006/7/31	II	22.5	1.8	25.6	0.419	4.600	0.660	1.505	1.893	3.577
2006/8/2	I	10.8	5.2	3.6	0.002	0.003	0.001	0.002	0.006	0.009
2006/8/3	IV	70.0	17.9	60.0	4.473	117.250	25.072	19.878	134.587	160.188
2007/7/27	II	26.8	6.5	32.0	1.944	7.124	0.835	2.459	13.452	9.825
2009/7/20	II	36.1	10.4	32.0	1.352	3.251	0.436	1.752	8.710	6.210
2009/7/26	II	26.8	6.5	23.4	0.634	1.263	0.022	0.835	3.366	2.358
2009/8/21	I	12.0	9.0	4.0	0.001	0.004	0.001	0.002	0.012	0.008
2009/8/25	II	31.0	4.8	31.6	1.432	1.883	0.563	1.324	4.537	3.269
2010/8/10	II	16.1	1.7	19.0	0.025	0.022	0.010	0.018	0.037	0.033
2016/7/18	III	65.1	14.8	26.2	0.684	4.333	0.263	1.192	7.532	5.193
2016/7/23	I	16.8	4.9	11.0	0.293	0.852	0.094	0.391	1.206	1.144
2016/7/31	II	15.7	1.7	19.8	0.363	2.321	0.108	0.113	4.931	2.248
2017/7/17	IV	62.3	3.7	54.6	2.583	23.186	11.945	17.374	42.698	65.347
2018/8/7	II	19.8	1.2	29.6	0.691	3.953	0.143	0.382	5.321	4.133
2018/8/9	II	12.5	1.8	18.4	0.390	1.851	0.112	0.203	6.549	3.170

rainfall regime IV was as much as tenfold that of the rainfall regime II. Among all six sub-watersheds, the SEM of the SW was lowest.

4. Discussion

4.1. Effects of land use on surface runoff and soil loss

In this study, surface runoff and sediment yield varied significantly relying on the type of sub-watershed land use (Fig. 4). There is ample evidence in the literature that revegetation can actually reduce surface runoff and sediment yield (Wei et al., 2009; Liang et al., 2020). The vegetation canopy can effectively intercept rainfall (Dunkerley, 2000; Zhang et al., 2016), thus weakening rainfall energy and reducing soil erosion. Roots also improve soil resistance to erosion and enhance the soil moisture infiltration rate (Yu et al., 2016; Wang et al., 2021). Furthermore, litter layer can exert major effects in relation to decreasing the surface runoff and sediment yield (Chen et al., 2018; Cui et al., 2022). The surface runoff and soil loss of the FW and FPW were higher than other sub-watersheds. The forest coverage of the FW and FPW is 10.93 % and 45.30 %, respectively. However, the forest coverage of the other sub-watersheds is above 80 %. Thus, vegetation coverage might be a very significant impact factor controlling runoff generation and soil loss (Zuazo and Pleguezuelo, 2008; Feng et al., 2016). It follows that reasonably increasing the vegetation coverage is an active strategy to control

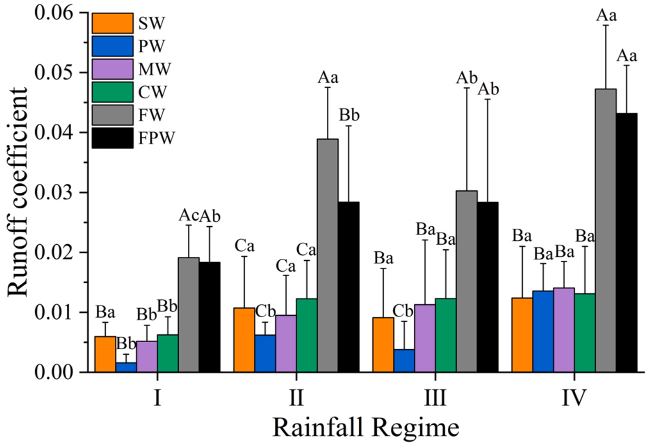

Fig. 6. The runoff coefficient of the studied sub-watersheds under different rainfall regimes. *Note*: Capital letters indicate significant difference between the land-use sub-watersheds in the same rainfall regimes, and lowercase letters indicate significant difference between different rainfall regimes in the same land-use sub-watersheds.

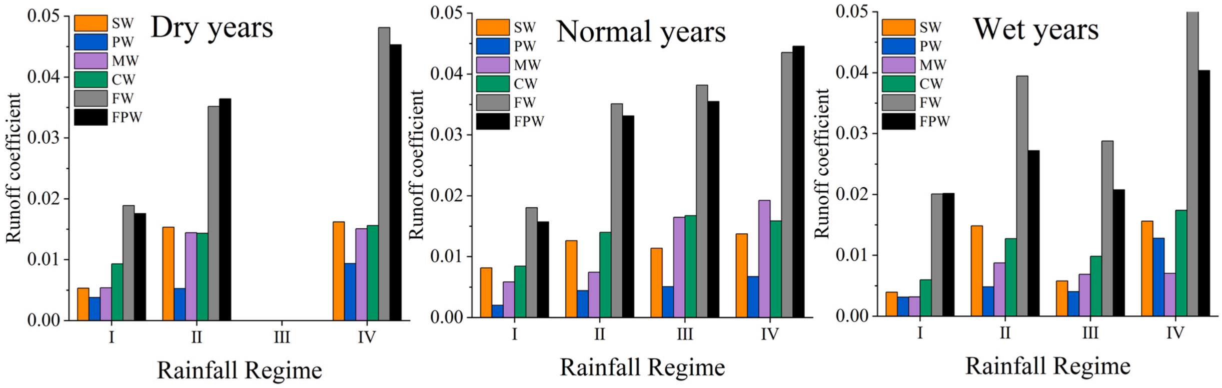

Fig. 7. The runoff coefficient of the studied sub-watersheds under different rainfall regimes and in different hydrological years. *Note*: There are no data for the rainfall regime III in dry years because this kind of rainfall did not occur.

serious soil erosion. For instance, the annual sediment flux was decreased to approximately 0.2 billion tons, which was largely due to the implementation of the “Grain for Green” project; vegetation coverage within the Loess Plateau increased from 31.9 % in 1999 to 59.6 % in 2013 (Chen et al., 2015). According to an analysis of 59 watersheds over the Loess Plateau, annual runoff coefficients and SEM decreased with increased vegetation coverage (Zhang et al., 2022).

Furthermore, anthropogenic disturbances had a significant impact on the FW and FPW. Corn was widely farmed in these sub-watersheds: seeding occurred in the late April, and machine harvesting was conducted in early October. Unlike vegetation, bare soil surfaces are exposed to rainfall, resulting in increased water surface runoff and sediment yield (El Kateb et al., 2013). However, there is a direct link among grazing, plant coverage, and soil erosion (Palacio et al., 2014). According to a study in semiarid woodlands in eastern Australia (Vandandorj et al., 2017), livestock grazing had a direct overwhelming effect on the rate of infiltration. Soils have been compacted or hardened at shallow depths as a result of farmland management, as well as reduced soil infiltration capacity (Zhou et al., 2010; Sirimarco et al., 2018),increased runoff response (Zhao et al., 2010), and increased resistance to root penetration.

It is worth mentioning that in some old plantations, trees grow to only approximately 30–50 % of the normal height, and are colloquially referred to as "little old man trees". Similar phenomena have occurred in other areas of the Loess Plateau (Chen et al., 2015; Jia et al., 2017). In semi-arid and semi-humid locations, the severe loss of deep soil water due to artificial forest restoration and long-term precipitation shortages promote soil drying and ecological deterioration (Chen et al., 2008). The PW had the lowest runoff coefficient (Figs. 4 and 5). The most likely explanation was run-on infiltration (Liu et al., 2012), because plantations consume more water and soil water deficit was very serious, compared with secondary forest. Sediment yields were scarce in the SW and CW, especially after severe storms. The analysis found that the SW and CW were determined to be in the advanced stage of community succession, with a rich species composition, stable community, and high resistance stability (Guariguata and Ostertag, 2001).

4.2. Responses of surface runoff and soil losses to different rainfall regimes

In the Caijiachuan watershed, although the rainfall amount of the rainfall regime I was smaller than that of the other rainfall regimes, it was the most frequent rainfall event. Meanwhile, under the rainfall regime I, almost no erosion events recorded in the six sub-watersheds. Most of the low-intensity rainfall would be trapped by vegetation canopy and litter. Comparatively, the rainfall regime III accounts for about a third of the total rainfall events and had a little erosive effect on the soil. The rainfall regime IV was extreme rainfall event that occurred just eight times during 16 years. In comparison with the other rainfall regimes, the rainfall regime IV resulted in much greater surface runoff and soil loss, indicating that the regime IV was the most destructive rainfall type. In the semiarid loess hilly region, surface runoff and sediment yield were mainly caused by rainfall with short rainfall duration and high rainfall intensity (Wei et al., 2007). In other parts of China, such as the karst region in Southwest China, rain showers with very high rainfall and intensity more easily caused soil loss (Peng and Wang, 2012). Hence, the rainfall regime IV was most sensitive to surface runoff and sediment yield to rainfall regimes, followed by II, III, and I.

The surface runoff and soil erosion in hilly and gully regions were not simply related to a rainfall eigenvalue. The surface runoff and soil erosion of the PW, MW, FW, and FPW were higher than those during rainfall storms without antecedent rainfall when rainfall events with large antecedent rainfall depth. For instance, the SEM of the PW, MW, FW, and FPW was 117.250, 98.457, 134.587, and 160.188 t km^{-2}, respectively. It is possible that antecedent rainfalls increased the prior antecedent soil moisture before the storms, thus reduced the water buffering capacity of the soil (Gao et al., 2019).

There was no obvious variance in the runoff coefficient in different hydrological years. The infiltration of excess surface runoff is thought to be the primary runoff generation mechanism on the Loess Plateau. Compared to plot-scale studies, the rainfall regime had little effect on surface runoff and soil erosion. For one thing, the surface conditions (e.g., topography, geomorphology, altitude, slope, and soils) of a watershed are complicated. For another thing, forests possess the ability to preserve water, and their soils have a high osmotic capacity and a high storage capacity. The water flow regulation fuction of watersheds represents their ability to control minimizes flood peaks by modulating direct runoff through soil water infiltration and percolation through the soil profile (Tarigan et al., 2018).

4.3. Implications and limitations

With the establishment of the "Grain-for-Green" project in the late 1990s, large-scale ecological restoration has been conducted in the Loess Plateau, and the implementation of artificial ecological forest areas has occurred at a relatively large scale. However, due to the unreasonable expansion of some artificial ecological forests, a series of severe issues appeared, such as single stand structure, excessive plant density, and poor biodiversity (Liu et al., 2018). The planted artificial vegetation may develop a “dried soil layer”, obstructing the normal growth and succession of vegetation (Fu et al., 2017). As a result, the long-term viability of plant regeneration has been hampered, and diminished the benefits of soil and water conservation (Wang et al., 2011a, 2011b; Chen et al., 2018). According to the recent reports, the Loess Plateau’s current artificial vegetation coverage was near the region’s water carrying capacity threshold (Q. Feng et al., 2016; X. Feng et al., 2016). To alleviate the adverse effects on the water supply, and to promote the conservation of the water and soil of artificial vegetation in the study region, in addition to traditional timber-oriented forest management, thinning is an important forest management activity (Tian et al., 2021). The focus of the expansion of vegetation cover on the Loess Plateau has switched to address extreme rainfall. Thus, natural vegetation succession might be a good technique for ecological restoration efforts in hilly and gully areas. On the Loess Plateau, such forest trees might promote long-term soil conservation without jeopardizing future water demand.

However, there are some limitations in this work, which can help to guide future research. (1) Due to the sediment was sampled manually and some rainfall events occurred at night, the amount of sediment data was relatively small. Although the sample size is small, the events are representative, because they include different rainfall amount, rainfall intensity, and rainfall duration. Therefore, a sediment concentration meter is required at each weir to measure sediment. (2) In addition to land use/cover, other sub-watershed characteristics (soils, geology, and topography) affect runoff and sediment output. These factors require more detailed study.

5. Conclusion

In this study, based on RA, RD, and I_{30}, 180 rainfall events from 2004 to 2019 in one of the small watershed of the Loess Plateau were classified into four rainfall regimes by the K-means clustering method. The average runoff coefficient among the studied six sub-watersheds varied as follows: FW (2.42 %) > FPW (2.38 %) > CW (1.11 %) > SW (1.08 %) > MW (0.73 %) > PW (0.43 %). However, the SEM of the natural restoration sub-watersheds (the SW and CW) was lowest. Generally, surface runoff and sediment yield under the rainfall regime IV (large rainfall amount and intensity) were highest, while those under the rainfall regime I (low rainfall amount and intensity, high frequency) were lowest. The runoff coefficient and sediment yield of the rainfall regime I (little precipitation, moderate duration of precipitation, low intensity of precipitation) were least; in the rainfall regime IV (high precipitation, short duration of precipitation, high intensity of precipitation), they were largest. The CW had the lowest average sediment yield, while the FPW showed the highest one. In addition to the FW and FPW, the influence of hydrological years on surface runoff of this sub-watershed was not significant due to forest regulation operations. Natural restoration measures (such as secondary forest measures and closing hillsides to facilitate afforestation) are the optimal choice to control soil erosion for sustainable (sub-)watershed management in the future.

Others in this field or different fields may use the findings presented in this work to inspire some future research. Most of the studies on surface runoff and sediment yield were focused on the runoff plot scale, while there have been no studies at the watershed scale..

Thus, it is necessary to increase the long-term observations of hydrological processes in the watershed. In addition, it is necessary to compare the runoff dynamics of watercourses at different spatial scales, in particular, in nested watersheds; this will show how the watershed scale processes and their distribution reflect changes in water flows and propagate downstream.

CRediT authorship contribution statement

Jiongchang Zhao: Methodology, Formal analysis, Investigation, Writing – original draft. **Jianjun Zhang:** Conceptualization, Methodology, Funding acquisition, Supervision, Writing – review & editing. **Yawei Hu:** Data curation, Investigation, Software. **Yang Li:** Data curation, Investigation, Software. **Peng Tang:** Data curation, Investigation, Software. **Artyom V. Gusarov:** Methodology, Writing-review & editing. **Yang Yu:** Conceptualization, Methodology, Funding acquisition, Supervision, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

Data will be made available on request.

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