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Study the relationship between rainfall erosivity and sediment yield in Shirin Darreh dam catchment, NE Iran

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Abstract:

The main goal of this study is to better understand the relationships between rainfall erosivity and sediment yield during 1982 to 2018 in the Shirin Darrehdam (*SDD*) basin (1750 km^2), North Khorasan Province, northeastern Iran. Rainfall erosivity was evaluated by the Fournier index (FI), Modified Fournier index (MFI), and rainfall erosivity (R factor), and specific sediment yield (SSY) was obtained based on the Fournier empirical model (FEM) using daily precipitation data from 3 and 2 gauging stations in the upstream and downstream of the dam, respectively. The relationship between rainfall erosivity, precipitation, and sediment yield was assessed by the coefficient of determination (R^2)and Pearson coefficient (r). The results showed that the upstream of the dam was more affected by rainfall and produced more sediments than the downstream. Strong correlations were observed between the sediment yield, precipitation, and rainfall erosivity indices ($R^2 \geq 0.5$ and the correlation was significant at the 0.01 level based on the r^2. The primary sources of sediment supply are the easily eroded sedimentary rocks such as the shale (Sanganeh Formation) and marl (Sarcheshmeh Formation) which cover the considerable area in the study basin.

Keywords: Shirin Darreh dam; Rainfall erosivity; Precipitation; Sediment yield; Shale

1. Introduction

Soil erosion is a severe environmental hazard affecting the quality of soil, land, and water resources upon which agricultural activities, human health, and stability of natural ecosystems depend for their sustenance(Wu et al., 2010; Bahrawi et al., 2021). One of the significant types of soil erosion is rainfall erosion, which results from the kinetic energy in raindrops striking the soil(Piacentini et al., 2018; Pugh and Stack, 2021; Jehangir Khan et al., 2021). The rainfall erosivity (R factor) was introduced by Wischmeier and Smith in the Universal Soil Loss Equation ($USLE$) and can be used to describe the effect of rainfall on soil erosion, especially sheet and rill types(Wischmeier and Smith, 1978). Some authors have recommended that a time series data of more than 20 years should be considered to estimate the R factor (Vente et al., 2011; GhasemShirazi et al., 2014; Silva et al., 2020). Unfortunately, data of such detailed temporal resolution are not readily available in many regions of the world. To solve this problem, some approaches were presented to drive the R factor that makes use of variables of easier access, like Fournier index (FI) and modified Fournier index (MFI)(Fournier, 1960; Arnoldus, 1980). To calculate the R factor, some empirical relationships were also suggested based on the MFI and mean annual precipitation(Arnoldus, 1977, 1980; Renard and Freimund, 1994; Yu and Rosewell, 1996). Specific sediment yield (SSY) is defined as the amount of sediment removed from a basin by different erosive factors during a specific period. Soil erosion and sediment yield are highly affected by several factors, including geology and geomorphology, hydrology, climate, runoff volume, vegetation cover, soil microbial activities, and anthropogenic modifications(Dutta, 2016; Orgiazzi and Panagos, 2018; Li et al., 2019; Xu et al., 2019b; Waila et al., 2020; Begy et al., 2021). There is often a strong correlation between rainfall and sediment yield that introduces the rainfall erosivity indices as readily available tools to estimate soil erosion(Vente et al., 2011; Otari and Dabiri, 2015; Xu et al., 2019a; Kolli et al., 2021).

The sediment discharge rate into the Shirin Darreh dam (*SDD*) reservoir, northeastern Iran, is high, and the reservoir has lost a considerable percentage of its initial capacity due to sediment retention. A few studies aimed at exploring the rainfall erosivity, documented results of the value of rainfall erosivity indices for the study area. Behzadfar et al. (2014)calculated the *MFI* based on daily rainfall data from 35 gauging stations in the North Khorasan Province and indicated that the several basins in the study area were low (46.36%) and medium (46.23%) erosion risk classes. Based on the *FI*, Qarehdaqi (2015) concluded that the main part of the North Khorasan Province was susceptible to erosion.Sdaeghi and Zabihi (2019)demonstrated that the *MFI* variations were consistent with the precipitation trend during 1987-2006. Although rainfall erosivity has been studied in the study basin, the relationship between this type of soil erosion and sediment yield has not been mentioned in detail yet. Due to more sensitivity of arid and semi-arid regions to changes in rainfall characteristics and fluctuations in sediment yield compared to the other climatic classesChen et al. (2012), Joghatayi et al. (2015), and Bahrawi et al. (2021), it was attempted to study the relationship between rainfall erosivity and sediment yield in the study area. The main objectives of this study are (1) to calculate and compare the rainfall erosivity indices (*FI*, *MFI*, and *R* factor) and *SSY* in the upstream and downstream of the *SDD*; and (2) to analyze the relationship between rainfall erosivity and sediment yield. In order to achieve these goals, the *FI*, *MFI*, and *R* factor were calculated based on daily rainfall data recorded at different sites the upstream and downstream of the dam for the period of 1982-2018, and the *SSY* was obtained according to the Fournier empirical model (*FEM*). Then, the effect of rainfall erosivity on sediment yield was evaluated based on the correlation coefficients.

1.1 Study area

The *SDD* basin is located about 65 km northwest of the Bojnord City, North Khorasan Province, Iran, and covers a total area of 1750 km^2 Fig. 1. The basin(longitude57°6′25″-57°58′35″ E;latitude37°41′31″-37°59′52″ N)is characterized by an arid and semi-arid climate with mean annual precipitation of 266 mm. The minimum rainfall occurs in summer, and most of the total annual precipitation is recorded from March to May. The significant type of land use are pastures with moderate to low density, dry farming, water farming and gardens, thin forests, grasslands and shrubs, river bed, and residential areas(Elahi, 2012). Rugged rock units, such as limestone (Tirgan Formation with Cretaceous age), form the higher topography, while marl and shale (Sarcheshmeh and Sanganeh Formations with Cretaceous age) cover the lowlands, so that the main part of the basin consists of shale and marl rocks, and limestone only exposed in the northeast of the basin(Mostakmeli, 2001). The main formations in the study basin are Tirgan limestone, Sarcheshmeh marl, Sanganeh shale, and Aitamir shale and sandstone with Cretaceous age. The youngest geological units include terraces, eolian deposits, and debris flows with Quaternary age Fig. 1. Theses formations cover 1, 24, 37, 30 and 8% of the study area, respectively.Therefore, the high erodibility of the Sarcheshmeh, Aitamir, and Sanganeh Formations, associated with their extended outcrops, are the essential factors that intensify the sediment yield during rainfall events. *SDD* (built-in 2005), northeast Iran, is classified as the biggest dam in North Khorasan Province. The dam formed a reservoir with a total capacity of 91 million cubic meters (Mm^3). The main purpose of dam construction on the Shirin Darreh River was to provide drinking water for Bojnord City, located about 65 km south-east of the dam and for agricultural and industrial purposes through the control of flood and runoff. The *SDD* suffers from a high rate of erosion and deposition in the upstream areas. Due to enormous volume of discharged and accumulated sediments, the capacity and lifetime of the dam have been decreased, and the reservoir lost 32% of its initial total capacity due to sedimentation during 2005-2019. Sedimentation continued, and the current total capacity is 61 Mm^3 (Emamgholizadeh et al., 2020).Sadra (2014) showed that the high erosion rate in the study basin is tightly related to the presence of erodible rocks, including marl and shale. High amounts of sand compared to silt and clay particles in sandy loam texture, which is the dominant type of soil texture in the study area, may be another reason for the high susceptibility of soils to erosion(Sadra, 2014). Moreover, vegetation and land use modifications, resulting in decreased pastures with high density and increased agricultural lands and construction areas, have intensified the erosion rate in upstream of the dam(Elahi, 2012). Therefore, natural factors along with anthropogenic effects have accelerated the soil erosion process in the study basin.

2. Methods

In analyzing the rainfall erosivity, daily precipitation data from three gauging stations in the *SDD* basin (upstream) and two stations outside the basin (downstream) over 36 years (1982-2018), recorded by the Regional Water Company of North Khorasan, were used(Table 1 and Table 2). At all these sites, the precipitation is measured daily by a standard rain gauge (Rahmawati et al., 2021). The rainfall erosivity was assessed based on the *FI*, *MFI* and *R* factor as below (Fournier, 1960; Arnoldus, 1980):

$$FI_t = \frac{p^2}{P} \tag{1}$$

$$MFI_t = \frac{\sum_{i=1}^{12} {p_i}^2}{P} \tag{2}$$

where p is the mean maximum monthly precipitation (mm), p_i is the precipitation (mm) for month i, P is the mean annual precipitation (mm), FI_t is the total Fournier index (mm), and MFI_t is the total modified Fournier index (mm). The annual Fournier index (FI_a) and annual modified Fournier index (MFI_a) were obtained by averaging the *FI*and *MFI* for each year of the study period. The *R* factor of erosive rainfall was calculated based on seven empirical equations presented in Table 3. Because of $MFI < 55$ mm for all the gauging stations, equation 6 was not included.

Table 1. Geographical characteristics of the gauging stations in the study area

Location to the dam	Station	Code No.	Longitude (E)	Latitude (N)	Elevation (m)	Drainage area (km^2)	Slope (%) (%)
	QalehBarbar	1	57°11′5″	37°45′5″	770	1525	4.32
Upstream	Qatlish	2	57°16′56″	37°48′38″	977	1355	3.92
	Ali Mohammad	3	57°37′5″	37°44′55″	1300	1421	3.10
Downstream	HassehGah	4	57°2′6″	37°40′2″	800	1818	4.40
	Aq Mazar	5	56°55′10″	37°41′43″	567	1320	2.10

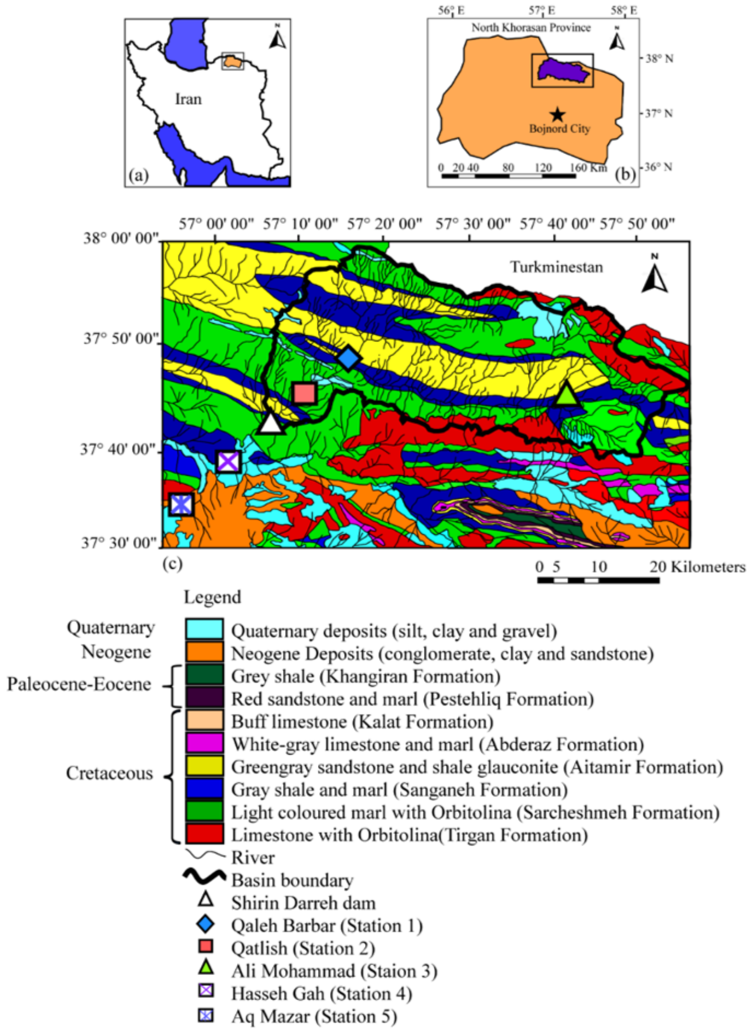

Figure 1. (a) North Khorasan Province and the study area on the map of Iran; (b) study area setting on map of North Korasan Province; (c) geological map (Modified from Afshar Harb (1994)with locations of the gauging stations in the study area.

It should be noted that in equations 3 to 7 , the R factor was obtained using two methods based on the MFI calculation procedure. In the first method, the MFI_t was used to calculate the Total R factor (R_t factor). The Annual R factor (R_a factor) was calculated based on the MFI_a values in the second method. The R factor is a function of P based on equations 8 and 9, which was also calculated using two methods. In the first method,P was considered in equations 8 and 9, and the $R_t$factor was obtained. In the second method, the R factor was calculated according to the precipitation for each year, and then the average of R factor was considered as the R_a factor.

The sediment yield was calculated as below (Fournier, 1969):

$$\log SSY_t = 2.65 \log \frac{p^2}{P} + 0.46 \log H(\tan S) - 1.5 \qquad (10)$$

where SSY_t is the total specific suspended sediment yield (ton $year^{-1} km^{-2}$), p is the mean maximum monthly precipitation (mm), P is the mean annual precipitation (mm), H is the mean elevation (m), and S is the mean slope (degree) in a basin. The annual specific suspended sediment yield

Table 2. Statistical characteristics of rainfall (mm) in the study area during 1983-2018

	Upstream									Downstream					
Station	1			2			3			4			5		
	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean
Oct.	0.0	37.0	13.5	0.0	42.5	11.0	0.0	41.5	13.3	0.0	38.0	13.2	0.0	37.5	10.4
Nov.	0.0	73.5	31.3	0.0	48.0	20.6	0.0	78.0	27.6	0.0	67.5	26.6	0.0	57.0	20.4
Dec.	8.5	93.0	32.9	0.0	54.5	23.7	2.0	89.5	31.1	0.0	74.5	32.7	0.5	59.0	25.4
Jan.	0.0	65.0	26.2	0.0	53.5	19.3	0.0	102.0	34.9	0.0	86.0	33.0	2.0	53.5	24.0
Feb.	4.5	95.5	42.8	6.5	77.0	26.8	8.0	95.0	49.4	13.0	119.0	47.6	6.5	86.0	37.1
Mar.	9.0	105.0	45.8	10.5	69.5	31.6	17.5	105.5	49.8	11.5	110.0	49.5	11.5	75.5	36.1
Apr.	2.0	123.5	42.0	0.0	82.5	30.6	10.5	130.5	48.5	15.5	103.5	46.8	2.0	95.5	36.6
May.	0.0	142.0	40.0	0.0	77.5	27.4	0.0	144.0	45.5	0.0	103.0	36.0	0.0	75.5	24.4
Jun.	0.0	94.0	17.5	0.0	52.5	14.8	0.0	63.0	19.4	0.0	50.0	14.1	0.0	52.5	9.5
Jul.	0.0	93.5	12.8	0.0	35.5	10.2	0.0	45.0	9.9	0.0	43.0	11.1	0.0	38.3	9.2
Aug.	0.0	88.0	9.7	0.0	52.0	10.3	0.0	85.5	10.3	0.0	72.5	10.4	0.0	51.0	9.4
Sep.	0.0	105.5	9.8	0.0	48.0	7.6	0.0	75.5	10.0	0.0	45.2	7.4	0.0	39.0	5.9
Mean	-	-	27.0	-	-	19.4	-	-	29.1	-	-	27.3	-	-	20.7
Annual	99.5	563.0	324.2	132.0	392.0	233.7	181.0	582.0	349.7	188.0	594.0	328.6	101.0	402.0	248.5

Table 3. Statistical characteristics of rainfall (mm) in the study area during 1983-2018

Type of regression	Eq. No.	Equations		Reference
	3	$R = 0.302MFI^{1.93}$	(3)	(Arnoldus, 1977)
	4	$R = 1.735 \times 10^{((1.5 \log MFI)-0.08188)}$	(4)	(Arnoldus, 1980)
Eq.based on	5	$R = 0.7397MFI^{1.847}MFI55mm$	(5)	(Renard and Freimund, 1994)
the MFI	6	$R = 95.77-6.081MFI+0.477MFI^2 MFI \geq 55mm$	(6)	
	7	$R = 3.82+MFI^{1.41}$	(7)	(Yu and Rosewell, 1996)
Eq.based	8	$R = 38.46+3.48P$	(8)	(Lo et al., 1985)
on the P	9	$R = 0.0483P^{1.61}$	(9)	(Renard and Freimund, 1994)

(SSY_a) for each year was also calculated by the maximum monthly precipitation in a year (instead of the p), and the sum of precipitation in a year (instead of the P) for each gauging station. When the indices (FI, MFI, R factor, and SSY) were calculated at total and annual scales for each gauging station, the estimated average (EA) was used to compare them in the upstream and downstream of the dam:

$$EA = \frac{\sum_{i=1}^{5} X_i A_i}{A} \tag{11}$$

where EA is the estimated average of an index in upstream or downstream, x_i is the index value for station i, A_i is the area covered by station i (km^2), and the A is the total area (km^2) covered by all the gauging stations in upstream or downstream.

3. Results

3.1 Rainfall erosivity indices and sediment yield

The FI and MFI calculation results for the study area are presented in Table 4 and Figure 2. In the upstream of the SDD, the maximum FI_t, FI_a, MFI_t, and MFI_a were calculated for station 3 (equal to 18.37, 19.60, 37.57, and 50.29 mm, respectively). In contrast, their minimum values were obtained for station 2 equal to 10.63, 11.2, 22.95 and 31.87 mm, respectively. In the downstream, station 4 showed higher values for all the FI_s than station 5. Based on the EA, the downward sequence of the indices for the upstream was as MFI_a (42.77), MFI_t (31.53), FI_a (15.8), and FI_t (15.01), respectively (Figure 2). Similarly, it was arranged as MFI_a (40.71), MFI_t (30.55), FI_a (15.63), and FI_t (14.92) for the downstream. According to Table 4, the stations 2 and 3 in the upstream were included in the minimum and maximum R factor, respectively, based on equations. 3 to 9. In the downstream, the higher values of the R factor were calculated for station 4 compared to station 5. The EA was higher for the R factor in upstream than in downstream, which in some cases, the difference between them was significant (e.g., R_a factor based on equation 5) (Figure 2).In the upstream of the dam, the maximum SSYt and SSY_a were obtained for stations 3 (362.62 ton km^{-2} yr^{-1}) and 1 (584.99 tonyear^{-1}km^{-2}), respectively (Table 4). In the downstream, the values of these two parameters for station 4 (328.89 and 478.83 ton year^{-1}km^{-2}, respectively) were higher than for station 5 (132.73 and 227.64 tonyear^{-1}km^{-2}, respectively). On the other hand, the EA for the SSY_t and SSY_a upstream had relatively significant differences compared to downstream (3.31 and 67.11 tonyear^{-1}km^{-2}, respectively) (Figure 2).

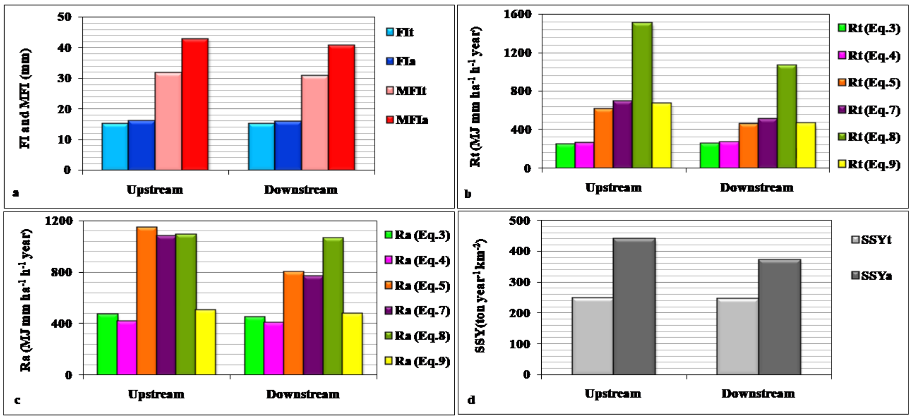

Figure 2. Comparison of estimated average for rainfall erosivity indices in upstream and downstream of the dam; (a) total and annual Fournier index, total and annual modified Fournier index; (b) total rainfall erosivity; (c) annual rainfall erosivity; (d) total and annual specific sediment yield.

Table 4. Calculation results of the rainfall erosivity and sediment yield in the study area

Index	Station		Upstream 1	2	3	EA[e]	Downstream 4	5	EA
	FI_t		15.78	10.63	18.37	15.01	16.81	13.55	14.92
FI[a]		Min	4.76	4.58	3.21		6.26	5.01	
	FI_a	Max	26.28	24.90	22.58	15.80	31.38	28.72	15.63
		Mean	16.55	11.21	19.60		17.49	14.28	
	MFI_t		33.55	22.95	37.57	31.53	35.72	26.81	30.55
MFI[b]		Min	18.36	15.64	22.44		26.88	14.00	
	MFI_a	Max	81.76	47.78	80.06	42.77	73.29	64.53	40.71
		Mean	45.47	31.87	50.29		46.94	36.2	
	R_t		265.94	127.79	330.80	243.84	300.15	172.43	246.42
R factor[c]		Min	83.07	60.98	122.36		173.38	49.20	
(Eq.3)	R_a	Max	1483.33	526.10	1424.35	473.57	1201.25	939.56	451.97
		Mean	534.85	253.96	617.22		539.03	332.07	
	R_t		279.32	158.03	330.96	258.16	306.86	199.46	261.68
R factor		Min	113.07	88.93	152.78		200.31	75.26	
(Eq.4)	R_a	Max	1062.31	474.66	1029.33	421.12	901.69	744.94	410.47
		Mean	462.57	264.52	525.98		473.77	323.29	
	R_t		486.16	241.10	599.09	611.66	545.85	321.16	451.33
R factor		Min	159.66	118.77	231.28		322.83	96.72	
(Eq.5)	R_a	Max	2518.45	933.96	2422.54	1147.32	2058.11	1626.86	802.48
		Mean	940.40	463.17	1082.76	951.26	597.59	951.26	
	R_t		541.29	316.89	634.86	687.37	591.32	394.43	508.49
R factor		Min	231.34	184.58	306.99		396.00	157.79	
(Eq.8)	R_a	Max	1997.70	1402.62	2063.82	1096.92	2105.58	1437.42	1064.77
		Mean	1166.51	852.29	1255.52		1182.04	903.28	
	R_t		532.41	314.75	601.58	667.06	544.22	347.10	461.30
R factor		Min	79.51	125.33	208.35		221.48	81.45	
(Eq.9)	R_a	Max	1294.98	722.99	1366.07	508.52	1411.70	752.92	480.55
	SSY_t		281.94	94.96	362.62	249.68	328.89	132.73	246.37
Specific		Min	11.78	10.22	48.56		24.07	9.52	
sediment	SSY_a	Max	6536.00	906.39	3622.50	440.27	1720.80	972.78	373.16
yield[d]		Mean	584.99	165.97	546.54		478.83	227.64	

[a]Fournier Index (mm)
[b]ModifiedFournier Index (mm)
[c]Rainfall erosivity (MJ mm ha^{-1} h^{-1} year)
[d]in ton $year^{-1}$ km^{-2}
eEstimated average

3.2 Correlation between rainfall erosivity and sediment yield

The results of the calculation of the coefficient of determination (R^2) between rainfall erosivity indices, sediment yield, and precipitation are presented in Figure 3. As seen, all the rainfall erosivity indices were strongly and positively correlated with the precipitation (except for the FI_a (Figure 3.a))($R^2 \geq 0.50$). The strongest correlation between all the rainfall erosivity indices and precipitation was obtained for stations 1 and 3 in upstream, and the weakest correlation was calculated for station 2. In the downstream, station 4 showed a stronger correlation than station 5 for all the rainfall erosivity indices. Overall, the strongest correlation between rainfall erosivity indices and precipitation was obtained for the stations in upstream of the dam. The relation between mean annual precipitation and *SSY* was presented in Figure 3.h. The SSY_t and SSY_a were strongly correlated with the precipitation, and the R^2 for both of them was more than 0.9. Based on the Pearson correlation coefficient (r)(Table 5, the correlation between precipitation, rainfall erosivity indices and sediment yield was significant for all the upstream stations (except for the FI_a in station 2). In the downstream, correlation between the mentioned parameters was not significant in station 4 (SSY_a) and station 5 (FI_a and SSY_a). Totally, according to the r results, the correlation between the precipitation and rainfall erosivity indices and sediment yield was more significant in upstream of the *SDD* than in downstream.

4. Discussion

Considering Table 2, it is revealed that the maximum mean annual precipitation was equal to 349.7 and 328.6 mm, respectively, for stations 3 and 4, where the maximum of the FI_s were obtained in upstream and downstream of the dam. Furthermore, the minimum values of these indices in the upstream and downstream were calculated for stations 2 and 5, with the minimum mean annual precipitation of 233.7 and 248.5 mm, respectively. Similarly, based on all the equations, the R factor had the maximum and minimum values for the stations with the highest and lowest mean annual precipitation, respectively, in the upstream and downstream of the *SDD* (Table 2). It suggests a strong correlation between rainfall and rainfall erosivity. When raindrops hit the soil surface, they can dislodge soil particles and create small craters. Furthermore, the raindrop force break down soil aggregates and loosen the soil, making it

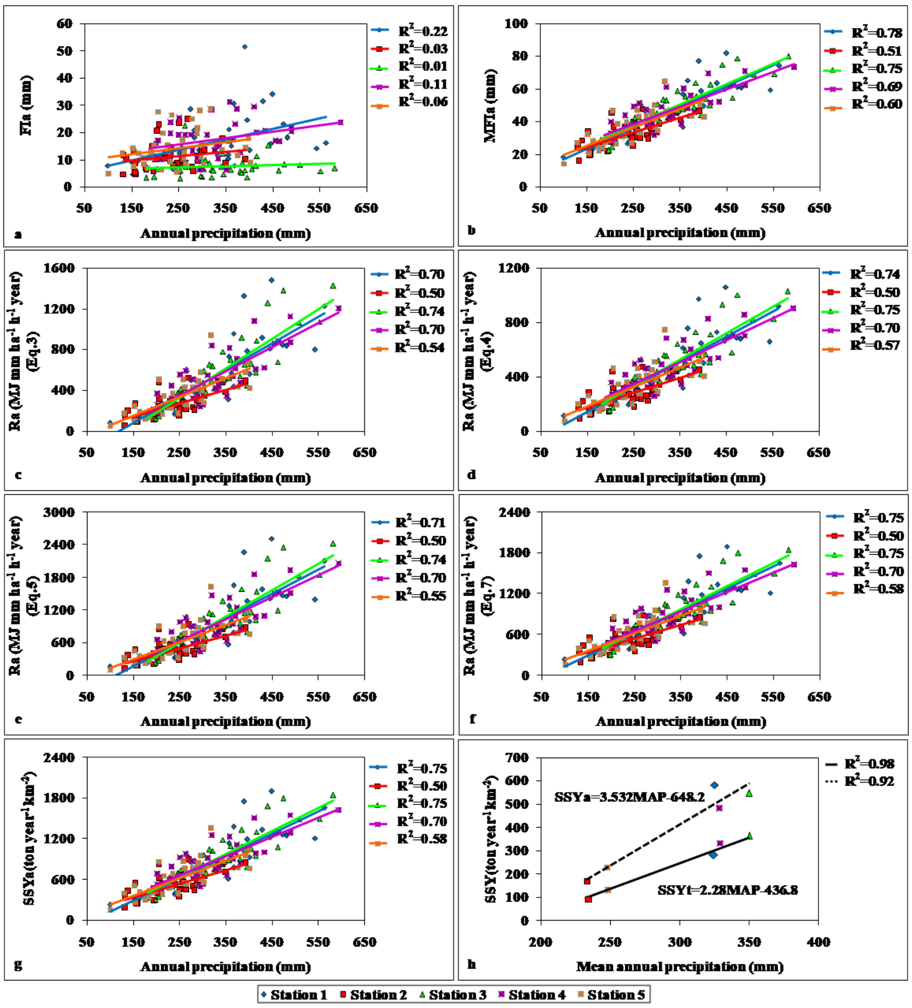

Figure 3. Coefficient of determination values between rainfall erosivity indices and sediment yield, and precipitation and sediment yield .

Table 5. r values between precipitation and rainfall erosivity indices and sediment yield

	Station	Upstream		Downstream		
Index		1	2	3	4	5
FI_a	r	0.477**	0.181	0.500**	0.342*	0.259
	Sig.	0.003	0.289	0.002	0.041	0.126
MFI_a	r	0.877**	0.719**	0.870**	0.836**	0.779**
	Sig.	0.000	0.000	0.000	0.000	0.000
$R_a$factor(Eq.3)	r	0.839**	0.703**	0.861**	0.841**	0.739**
	Sig.	0.000	0.000	0.000	0.000	0.000
$R_a$factor(Eq.5)	r	0.844**	0.705**	0.862**	0.841**	0.743**
	Sig.	0.000	0.000	0.000	0.000	0.000
$R_a$factor(Eq.7)	r	0.869**	0.714**	0.869**	0.840**	0.764**
	Sig.	0.000	0.000	0.000	0.000	0.000
SSY_a	r	0.470**	0.312**	0.304**	0.303	0.196
	Sig.	0.002	0.004	0.007	0.073	0.253

**Correlation is significant at the 0.01 level (2-tailed).
*Correlation is significant at the 0.05 level (2-tailed).

more susceptible to erosion ((Sakhraoui and Hasbaia, 2023; Zhao et al., 2023). Therefore, due to the higher values of the mean annual precipitation during 1983-2018, rainfall in upstream of the dam was more erosive than in downstream that results in more sediment yield. This is in good agreement with the results of Piacentini et al. (2018) in the NE Abruzzo Hills Area in Central Italy, and Silva et al. (2020) in the Epitácio Pessoa reservoir catchment, Paraíba, Brazil, who found that the rainfall erosivity was strongly correlated with precipitation variations.The slope gradient has a crucial role in the extent and intensity of rainfall erosion through several ways such as increased runoff, enhanced sheet erosion, rill and gully formation, reduced infiltration, increased sediment transport, and reduced soil stability. Elevation is another parameter can control rainfall erosivity by changing the precipitation patterns and intensity, direct relationship with slope gradient, and influence on soil characteristics and vegetation cover(Chen et al., 2022; Ahamd et al., 2024). Because of the important role of slope gradient and elevation on rainfall erosion, in the *FEM* (equation 10), the *SSY* has a direct relationship with these two parameters of a basin, as well as the precipitation of the wettest month of a year to annual precipitation ratio. Therefore, the higher slope and elevation, the more sediment is predicted to yield in a basin. As seen in Figure 4.a, the steeper slopes are mostly observed in the upstream areas. Furthermore, the elevation classes in upstream of the *SDD* are between 600 and mare than 2400 m, while the elevation only ranges between 600 and 1800 m for downstream areas (Figure 4.b). In dam upstream, the *EA* for slope gradient and elevation is 3.79% and 1010.32 m, and it is about 3.43% and 701.98 m for downstream. Moreover, the *EA* for p to P ratio in the *FEM* was calculated 0.23 and 0.22 for the upstream and downstream, respectively, resulting in more sediment yield in upstream than in downstream, despite the negligible differences between these two ratios. Totally, the upstream of the dam is more susceptible to rainfall erosion than downstream because of the impacts of geographical factors (slope gradient and elevation (Fig. 4) and climatic parameters (precipitation). This result ties well with previous research wherein Wu et al. (2018) and Deng et al. (2019) observed that as the slope gradually increased, more sediment leached from the surface and flowed downward. Considering the effect of precipitation on sediment yield, Babur et al. (2020) found a direct relationship between precipitation and sediment yield in a mountainous watershed of India and Pakistan They predicted an upward trend for sediment production during 2011-2100 and adverse effects on Mangla dam in Pakistan. The elevation is also directly related to sediment yield so that sediments in highlands are rapidly eroded and transferred to the lowlands of a basin. This result corresponds with the findings in Eroglu et al. (2010) study of the Hatila Valley, Turkey. Also,Nearing et al. (2015)concluded that annual rainfall erosivity increased by 25% when elevation varied between 1234 and 1644m in southeastern Arizona during 1960-2012. Therefore, when comparing our results to those of previous studies, it is revealed that the higher slope, elevation, and precipitation rate in upstream of the dam results in more sediment yield than in downstream based on the *FEM* equation. According to Figure 3 and Table 5,rainfall erosivity and *SSY* were strongly correlated with the precipitation. These results are compatible with the study conducted by Vente et al. (2011) and Farajzadeh et al. (2017) in NW Mediterranean geoecosystems (Spain), and basins in central Iran and Khazar basin (Iran). A similar approach indicated that the correlation coefficient between sediment yield and maximum 60-minute rainfall intensity (I_{60}) was 0.6, and a high volume of sediments was produced when the number of rainfall peaks and their continuity increased for Miyun Dam Basin, China ((Xu et al., 2019a)). Therefore, one of the governing factors of sedimentary materials production in the study area is rainfall erosivity, which significantly affects the sediment yield based on annual and total scales. Based on the Erosion Potential Model (*EPM*),

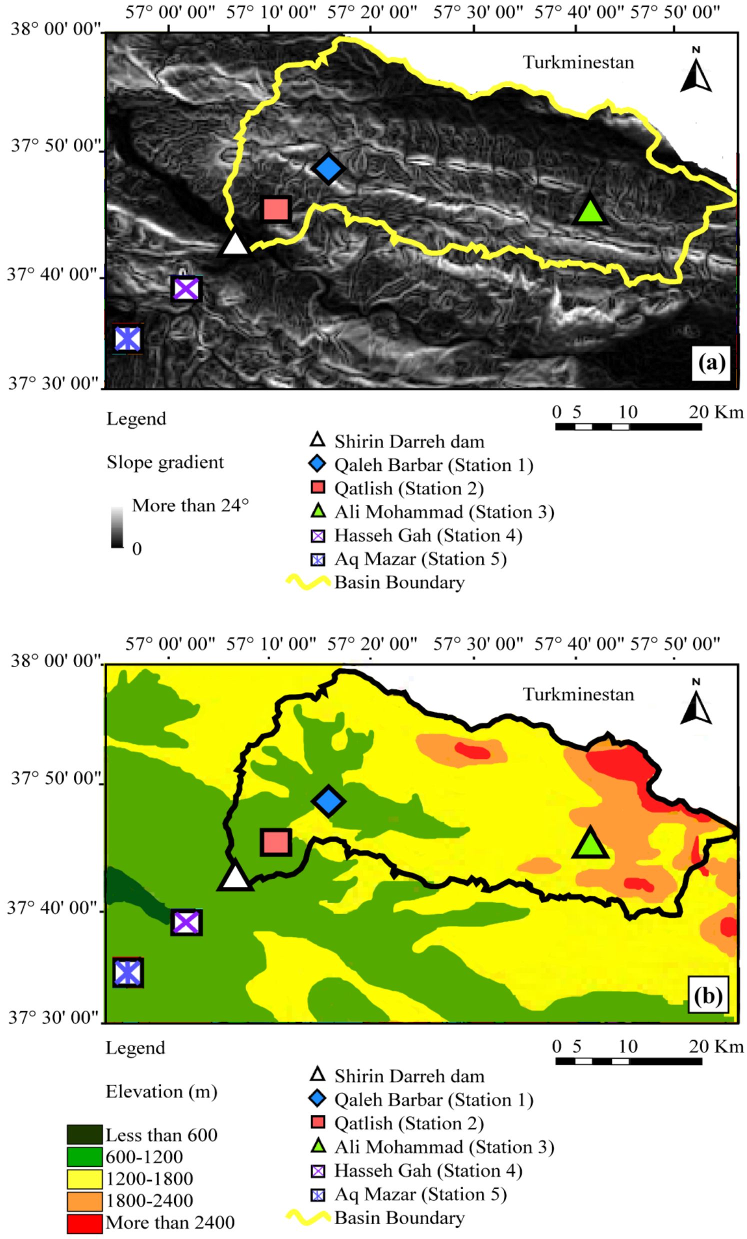

Figure 4. (a) Slope gradient, and (b) elevation variation in the study area.

the *SSY* in upstream of the dam was about 480 tonkm^{-2} year−1, during 1968-2014 (46 years) (Regional Water Company of North Khorasan 2015). Assuming this sediment yield rate remains constant over time and deposited bulk density of about 1.35 ton m^{-3},it suggests a sediment inflow rate of about 30 million tons or 22 Mm^3 during the study period (1983-2018). In the present study, the *EA* of the *SSY* originating from the rainfall erosivity was obtained 249.68 and 440.27 tonyear^{-1}km^{-2} at total and annual scales, respectively, in the upstream of the dam (Table 4). If the area is the simple average of the area covered by each station in upstream of the dam (1433 km^2), 13 and 23 million tons (equal to 9 and 17 Mm^3, respectively) of sediments trapped in the reservoir totally and annually, respectively, due to rainfall impact over 1983-2018. Therefore, rainfall erosion can produce 41 and 77% of the total volume of sediments (22 Mm^3) discharging into the reservoir totally and annually. If the estimated *SSY* in the present study remains constant over time, the sediments produced by rainfall erosion will be enough to fill the reservoir in the next 307 and 158 years, at annually and totally scales, respectively. Although it takes a long time for the reservoir to be completely filled with sediments from rainfall events, constant sediment yield rates over time are not possible. It is well accepted that the main factors, including changes in climatic patterns and anthropogenic impacts on vegetation cover and land use, can highly increase the rate of sediment yield. Moreover, the present study obtained the higher precipitation rate, rainfall erosivity indices, and sediment yield for the study sites upstream of the dam. Consequently, the sediments originating from rainfall erosivity upstream are expected to fill the reservoir in a shorter period.

5. Conclusions

In this study, the FI, MFI, R factor, and sediment yield were calculated based on empirical methods in upstream and downstream of the Shirin Darrehdam basin over 36 years. The FI, MFI, and R factors revealed that upstream areas suffer from more rainfall erosivity than downstream. Based on the FEM, the SSY in the upstream of the dam (with the EA of SSY_t4and SSY_a equal to 249.68 and 440.27 ton year^{-1} km^{-2}, respectively) was more than in the downstream (with the EA of SSY_t and SSY_a equal to 246.37 and 373.16 ton year^{-1} km^{-2}, respectively), and strongly correlated with P and rainfall erosivity indices at annual and total scales. One of the most critical factors accelerating the erosion in upstream of the dam can be related to exposures of marl, shale, and sandstone, which are low resistant to raindrop's energy and produce fine-grained sediments discharging into the reservoir. Fluctuations in precipitation, long dry periods, and frequent flood events, which are most evident in arid and semi-arid regions, can be the other factors involved in rainfall erosivity. In order to compare the rainfall erosivity more accurately, it is suggested to provide comprehensive data on lithology, vegetation density, soil texture, mean annual and monthly runoff, drainage density, hydrologic network, agricultural practices, topography, and geomorphology in upstream and downstream of the dam. Investigations on spatiotemporal variability of precipitation and rainfall erosivity are also recommended globally, mainly in arid and semi-arid regions, where the effects of rainfall events on erosion process are highly evident.

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Authors Contributions
All authors have contributed equally to prepare the paper.

Availability of Data and Materials
The data that support the findings of this study are available from the corresponding author upon reasonable request.

Conflict of Interests
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.

References

Afshar Harb A. (1994) Geology of Iran: Geology of Koppeh-Dagh. *Geological Survey of Iran (in Persian)*

Ahamd N.S., Mustafa F., Yusoff S. (2024) Spatial prediction of soil erosion risk using knowledge-driven method in Malaysia's steepland agricultural forested valley, Environment, Development and Sustainability. *Geological Survey of Iran (in Persian)* 23:78–95. https://doi.org/10.1007/s10668-023-03251-8

Arnoldus H. M. J. (1977) Assessing Soil Degradation. *Food and Agriculture Organization (FAO)*

——— (1980) Assessment of Erosion. *Wiley*

Babur M., Shrestha S., Bhatta B., Datta A., Ullah H. (2020) Integrated assessment of extreme climate and land-use change impact on sediment yield in a mountainous transboundary watershed of India and Pakistan. *Journal of Mountain Science* 17:624–640. https://doi.org/10.1007/s11629-019-5547-z

Bahrawi J., Alqarawy A., Chabbani A., Elfeki A., Elhag M. (2021) Spatiotemporal analysis of the annual rainfall in the Kingdom of Saudi Arabia: predictions to 2030 with different confidence levels. *Theoretical and Applied Climatology* 25:105–115. https://doi.org/10.1007/s00704-021-03778-8

Begy R. C., Savin C. F., Klemen S., Veres D. (2021) Investigation of the effect of anthropogenic land use on the Panazii lake (Romania) catchment area using Cs-137 and Pb-210 radionuclides. *PLoS ONE* 16:215–230. https://doi.org/10.1371/journal.pone.0251603

Behzadfar M., Hasanzadeh H., Saberi M. (2014) Study the Fournier erosivity index in North Khorasan. *5th National Conference on Watershed Management Sciences and Engineering of Iran, Department of Natural Resources, Gorgan University of Agricultural Sciences and Natural Resources, Iran (in Persian),* no. 3, 277–298.

Chen H., Xu CY., Guo S. (2012) Comparison and evaluation of multiple GCMs, statistical downscaling and hydrological models in the study of climate change impacts on runoff. *Journal of Hydrology* 434-435:36–45. https://doi.org/10.1016/j.hydrol.2012.02.040

Chen T., Shu J., Han L., Tian G., Yang G., Lv J. (2022) Modeling the effects of topography and slope gradient of an artificially formed slope on runoff. *sediment yield, water and soil loss of sandy soil, CATENA* 212:106060. https://doi.org/10.1016/j.catena.2022.106060

Deng L., Zhang L., Fan X., Sun T., Fei K., Ni L. (2019) Effects of rainfall intensity and slope gradient on runoff and sediment yield from hillslopes with weathered granite. *Environmental Science and Pollution Research* 26:32559–32573. https://doi.org/10.1007/s11356-019-06486-z

Dutta S. (2016) Soil erosion, sediment yield and sedimentation of reservoir: a review. *Modeling of Earth System Environments* 2:58–69. https://doi.org/10.1007/s40808-016-0182-y

Elahi F. (2012) The role of upstream land use on surface water quality in the Shirin Darreh Dam watershed. *Dissertation, Gorgan University of Agricultural Sciences and Natural Resources (in Persian)*

Emamgholizadeh S., Khademi N., Hosseini S. H. (2020) Prediction of input sediment to the Shirin-Darreh dam reservoir using HEC-RAS numerical model. *Journal of Watershed Management Research. (in Persian)* 11 (208-22): 11–19.

Eroglu H., Cakır G., Sivrikaya F., Akay E. (2010) Using high resolution images and elevation data in classifying erosion risks of bare soil areas in the Hatila Valley Natural Protected Area , Turkey. 24:699–704. https://doi.org/10.1007/s00477-009-0356-5

Farajzadeh M., Hodaei A. A., Mollashahi M., RajabiRostam Abadi N. (2017) The analysis and comparison of the suspended sediment in the Caspian sea and central Iran drainage basins. *Hydrogeomorphology : (in Prsian).* 4:59–81.

Fournier F. (1960) Climat et erosion; la relation entre l'erosion du solparl'eau et les precipitations atmosperiques. *Presses universi-taires de Frances. (in French)*

——— (1969) Transport solideeffectues par les course d'eau. *Bulletin of International Association of Scientific Hydrology.(in French)* 39:7–49.

GhasemShirazi B., Bakhshandeh L., Yazdi A. (2014) Paleoecology of Upper Cretaceous Sediments in Central Iran, Kerman (Bondar- e Bido Section) Based on Ostracods. *Marine Science* 4 (2): 49–57. https://doi.org/10.5923/j.ms.20140402.04

Jehangir Khan S.and Mehmood M. M.and Ghazi, Yazdi A., Naseem A. A., Serwar U., Zaheer A., Ullah H. (2021) Sedimentological and provenance analysis of the Cretaceous Moro formation Rakhi Gorge, Eastern Sulaiman Range, Pakistan. *Iranian Journal of Earth Sciences* 13 (4): 252–266. https://doi.org/10.30495/ijes.2021.1917721.1564

Joghatayi H., Dabiri R., Moslempour M. E., Otari M., Sharifiyan Attar R. (2015) Groundwater quality assessment using the Groundwater Quality Index and GIS in Joghatay plain, NE Iran. *Human & Environment* 13 (4): 17–25.

Kolli M.K., Opp C., Groll M. (2021) Estimation of soil erosion and sediment yield concentration across the Kolleru lake catchment using GIS. *Environmental Earth Sciences* 80 (4): 352–369. https://doi.org/10.1007/s12665-021-09443-7

Li Z., Xu X., Zhu J., Xu C., Wang K. (2019) Effects of lithology and geomorphology on sediment yield in karst mountainous catchments. *Geomorphology* 343 (4): 119–128. https://doi.org/10.1016/j.geomorph.2019.07.001

Lo A., El-Swaify S. A., Dangler E. W., Shinshiro L. (1985) Soil Erosion and Conservation. *Soil Conservation Society of America*

Mostakmeli A. (2001) Sedimentology of Shirin Darreh Dam catchment (north-north west of Bojnord town) with special regard on erosion problem. *Dissertation, Shahid Beheshti University (in Persian).*

Nearing M.A., Unkrich C. L., Goodrich D. C., Nichols M. H., Keefer T.O. (2015) Temporal and elevation trends in rainfall erosivity on a 149 km^2 watershed in a semi-arid region of the American Southwest. *International Soil and Water Conservation Research* 3:77–85. https://doi.org/10.1016/j.iswcr.2015.06.008

Orgiazzi A., Panagos P. (2018) Soil biodiversity and soil erosion: it is time to get married, adding an earthworm factor to soil erosion modeling. *Global Ecology and Biogeography* 27:1155–1168. https://doi.org/10.1111/geb.12782

Otari M., Dabiri R. (2015) Geochemical and environmental assessment of heavy metals in soils and sediments of Forumad Chromite mine, NE of Iran. *Journal of Mining and Environmental* 6 (2): 251–261. https://doi.org/10.1111/geb.12782

Piacentini T., Galli A., Marsala V., Miccadei E. (2018) Analysis of soil erosion induced by heavy rainfall: a case study from the NE Abruzzo Hills Area in Central Italy. *Water* 10:1314. https://doi.org/10.3390/w10101314

Pugh K., Stack M. M. (2021) Rain erosion maps for wind turbines based on geographical locations: a case study in Ireland and Britain. *Journal of Bio- and Tribo-Corrosion* 7:126–139. https://doi.org/10.1007/s40735-021-00472-0

Qarehdaqi H. (2015) Investigation of potential impacts of climate changes on rainfall erosivity index (case study: North-East of Iran). *Dissertation, University of Tehran (in Persian).*

Rahmawati N., Rahayu K., Yuliasari S. (2021) Performance of daily satellite-based rainfall in groundwater basin of Merapi aquifer system, Yogyakarta). *Theoretical and Applied Climatology* 146:173–90. https://doi.org/10.1007/s00704-021-03731-9

Renard K.G., Freimund J. R. (1994) Using monthly precipitation data to estimate the R-factor in the revised USLE. *Journal of Hydrology* 157:287–306.

Sadra B. (2014) Quantity and quality investigation of water resources and sediment in Shirin Darreh Dam catchment area (North Khorasan Province). *Dissertation, Ferdowsi University of Mashhad (in Persian)* 157:287–306.

Sakhraoui F., Hasbaia M. (2023) Evaluation of the sensitivity of the RUSLE erosion model on rainfall erosivity: a case study of the Ksob watershed in central Algeria. *Water Supply* 23 (8): 3262–3284. https://doi.org/10.2166/ws.2023.182

Sdaeghi S. H. R., Zabihi M. (2019) Trend analysis of modified Fournier erosivity and standardized precipitation indices variations in North Khorasan Province, Iran. *Watershed Engineering and Management.(in Persian)* 10:506–515. https://doi.org/10.2166/ws.2023.182

Silva R.M. da, Santos C. A. G., Costa Silva J. F. C. B. da, Silva A. M., Neto R. M. B. (2020) Spatial distribution and estimation of rainfall trends and erosivity in the Epitácio Pessoa reservoir catchment, Paraíba, Brazil. *Natural Hazards* 102:829–849. https://doi.org/10.1007/s11069-020-03926-9

Vente J. de, Verduyn R., Verstraeten G., Vanmaercke M., Poesen J. (2011) Factors controlling sediment yield at the catchment scale in NW Mediterranean geoecosystems. *Journal of Soils and Sediments* 11 (8): 690–707. https://doi.org/10.1007/s11368-011-0346-3

Waila S., Singh S., Babbar R. (2020) Runoff induced soil erosion and its impact on the quality of water for Upper-Patiala-Ki-Rao Catchment lying on Shivalik Hills. *Journal of Geological Society of India* 95:385–392. https://doi.org/10.1007/s12594-020-1447-7

Wischmeier W. H., Smith D. D. (1978) Predicting rainfall erosion losses: a guide to conservation planning. *United States Department of Agriculture (USDA)* 95:385–392.

Wu L., Peng M., Qiao S., Ma X. (2018) Effects of rainfall intensity and slope gradient on runoff and sediment yield characteristics of bare loess soil. *Environmental Science and Pollution Research* 25:3480–3487. https://doi.org/10.1007/s11356-017-0713-8

Wu Y., Yang L., Buyuksonmez F., Beighley RE., Gu Z., Grey M. (2010) Evaluation of soil erosion and sediment control products for release of heavy metals. *Environmental Engineering Science* 27:905–914. https://doi.org/10.1089/ees.2010.0149

Xu J, Zhang J., Li M., Wang F. (2019a) Effect of rain peak morphology on runoff and sediment yield in Miyun Water Source Reserve in China. *Water* 11:2429. https://doi.org/10.3390/w11122429

Xu S., Zhao Q., Liu Y., Ding S., Qin M. (2019b) Effect of rain peak morphology on runoff and sediment yield in Miyun Water Source Reserve in ChinSensitivity and applicability of landscape leakiness index in determining soil and water conservation function of a subtropical riparian vegetation buffer. *Environmental Engineering Science* 36:1–10. https://doi.org/10.1089/ees.2018.0061

Yu B., Rosewell C. J. (1996) Technical Notes: A robust estimate of the R-factor for the Universal Soil Loss Equation. *Transaction of American Society of Agricultural Engineering* 39:559–561. https://doi.org/10.1089/ees.2018.0061

Zhao L., Zhang Z., Dong F., Fu Y., Hou L., Liu Y. J.and Wang (2023) Research on the features of rainfall regime and its influence on surface runoff and soil erosion in the small watershed, the lower Yellow River. *Water* 15 (14): 2651. https://doi.org/10.3390/w15142651