

Original Articles

Using radiotracers and topographic metrics for sediment budgeting at pixel and hillslope scales: A case study from western Iran

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ABSTRACT

Topographic variables play important roles not only on soil erosion, but also on sediment redistribution inside the watersheds, both of which can be studied using radiotracer of ¹³⁷Cs. In this regard, the current research aims to establish a sediment budget using ecological indicators of topographic metrics and radiotracers and to examine the relationship between topographic metrics and the sediment budget components in two scales of pixel and hillslope. To achieve the study purposes, soil erosion and redistribution map was prepared based on ¹³⁷Cs method and work units' approach in the 102.14 ha control sub-watershed of Khamsan representative watershed, western Iran. Then, the 1-m digital elevation model was used to extract the topographic metrics. The sediment budget components including total erosion, total deposition, net erosion and sediment delivery ratio and topographic metrics including slope angle, slope length, profile curvature, plan curvature, stream power index, topographic wetness index and flow accumulation were calculated for 14 selected hillslopes. The results showed that land use dominates the rate of erosion and sedimentation of the watershed in the long term (60–70 years). Out of 526.87 t y⁻¹ of erosion occurred in the study sub-watershed, only 20.26 t y⁻¹ were redistributed within the watershed, and 506.61 t y⁻¹ were delivered to the watershed outlet and the specific net erosion was calculated at the rate of 5.05 (t/ha y⁻¹). The amount of erosion and sedimentation was noticeably affected by the reduction of the slope angle and changing rangelands to agriculture in the lower part of the slopes. At the pixel scale, the LS, slope angle and stream power index had significant positive correlations of 0.57, 0.60 (sig. < 0.01) and 0.39 (sig. < 0.05) with the rate of erosion and sedimentation, respectively. In the hillslope scale, with the decrease of the slope angle down the slopes, the intensity of erosion increased due to the land use change from rangeland to rainfed agriculture in the downslopes. Therefore, land use change to agriculture on lower slopes exacerbates soil erosion, emphasizing the need for targeted land management practices.

1. Introduction

Soil degradation and erosion is among the most important problems in arid and semi-arid regions around the world, especially in developing countries (Sadeghi et al., 2018). According to the preliminary statistics collected for the world, the annual erosion of surface soil from river basins amounts to 60 billion tons, of which 17 billion tons are dumped into the oceans (Wang et al., 2014). The global economic losses resulted from soil erosion estimated to be around \$8 billion, due to reduced soil fertility, decreased crop yields and increased water usage (Sartori et al., 2019). Reducing the negative impacts of soil erosion and applying the best strategies for soil conservation are considered necessary actions in

order to achieve sustainable development. These actions require deep understanding about the factors affecting soil erosion and redistribution. In this regard, studying and accurately measuring the variables affecting the rate of erosion and sedimentation is an inevitable necessity to achieve the goal of soil and water resources conservation (Rodrigo Comino et al., 2016). Soil redistribution due to erosion is considered as an undeniable factor in changing soil characteristics in various parts of the hillslopes as it was documented in previous studies (e.g., Fullen and Brandsma, 1995; Ritchie and Ritchie, 2007; Afshar et al., 2010; Du and Walling, 2011; Quigano et al., 2016; Xie et al., 2018; Sedighi et al., 2021; Ma et al., 2023). In other words, it can be said that soil erosion is a controlling and effective factor on soil characteristics through regulating

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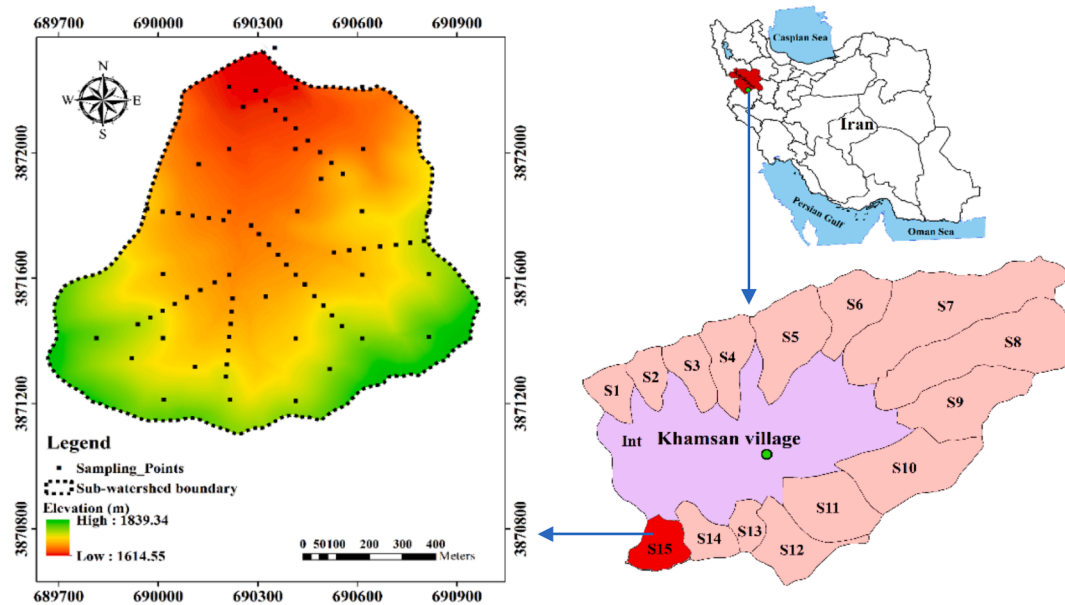


Fig. 1. Location of the study sub-watershed in Khamisan representative watershed, western Iran.

the movement of soil particles, minerals and organic matter on the surface and subsurface of the hillslopes. In addition, the effect of soil erosion and redistribution on many soil characteristics, especially soil texture and organic matter, leads to changes in soil erodibility, and this may affect the resistance of soil to erosion. For example, some authors documented an increase of soil resistance for soils characterized by a high clay content (Babur et al., 2021). In this regard, topography is an important factor regulating soil erosion (Di Stefano et al., 2000a; Rezaei and Gilkes, 2005; Liu et al., 2006) and topographic metrics have significant impacts on the rate of soil erosion and redistribution along the hillslopes (Jiang and Thelen, 2004; Sedighi et al., 2021). At the hillslope scale, sources and sinks are often connected through first order channels and their spatial distribution is rather controlled by topographic and lithologic factors (Yair and Lavee, 1985). At the pixel or patch scale, particular attention will be paid to the role of vegetation in creating spatial heterogeneity, and its implications for water and sediment redistribution (Puigdefábregas et al., 1999). While at the hillslope scale, topography mainly changes the spatial distribution of soil moisture and determines the transfer processes of water and sediment. In addition, the runoff coefficient and the sediment yield usually decrease with increase of area (Cerdan et al., 2004; Martinez et al., 2017), because of increasing the sinks and redistribution processes inside the hillslopes and watersheds. Topographic metrics include slope length and slope angle (LS factor), slope aspect, general, profile and plan curvatures, stream power index (SPI), topographic wetness index (TWI), flow accumulation, flow direction and surface roughness, are among the ecological indicators, most of which have a direct and indirect effect on the ecological aspects of the soil characteristics, land use, vegetation, sediment trapping, and sediment redistribution. For example, topographic metrics indicate the soil evolution, texture, infiltration, drainage, organic matter, moisture content and other physico-chemical characteristics of the soil (Jiang and Thelen, 2004; Li et al., 2018). In addition, slope angle and aspect are among the important factors that affect the change in the volume and velocity of runoff and soil erosion directly and indirectly (Tsui et al., 2004; Li et al., 2018). On the other hand, topographic wetness index usually has a high correlation with the redistribution of soil in watersheds and in fact it controls the redistribution of materials transported by water flow (Li et al., 2018). Erosion occurs at a higher rate on steeper hillslopes compared to the lower sections and the effects of slope angle on soil erosion and redistribution have been discussed by previous studies (e.g., Velasco et al., 2018; Kikuchi et al., 2020; Zhao et al., 2022).

The effect of slope forms (concave and convex) on the amount of erosion and sedimentation has also been investigated in the previous studies (Di Stefano et al., 2000b; Talebi et al., 2016). The general view is that in convex and uniform hillslopes, detachment and transport of eroded particles occur along the slope length, while in concave hillslopes, both erosion and sedimentation processes occur together.

Although Ayoubi et al. (2022) showed that land use change has less effect on the variability of soil characteristics and soil loss than the slope position, some other researchers have mentioned land use as the dominant factor in determining the amount of soil erosion and redistribution (e.g., Govers et al., 1996; Leh et al., 2013; Sedighi et al., 2021). In addition, changes in land use, especially from rangelands to rainfed agricultural lands in this region, during several decades, have led to a change in the topography of the hillslopes at the upstream edge of the agricultural lands, which can be well recognized using the 20-cm digital terrain model (DTM) prepared by drone photogrammetry.

Different methods such as field/laboratory measurements, empirical and statistical models can be used for measuring/estimating soil erosion and sediment yield components at various spatial scales. However, many of these methods cannot produce a distribution map of soil erosion, or the output distribution map of the model does not have acceptable accuracy and details to evaluate the effect of topographic features on soil redistribution. One of the most applicable methods for estimating the intensity of soil erosion and redistribution as well as preparing a distribution map is the use of radiotracers, especially ^{137}Cs and $^{210}\text{Pb}_{\text{ex}}$ (Alewell et al., 2016; Evrard et al., 2016; Masson et al., 2023), which can be used in watersheds at different spatial scales (Gruszowski et al., 2003; Maher et al., 2009; Porto et al., 2011). Meade and Trimble (1974) and Dietrich and Dunne (1978) were among the first researchers who presented an accurate sediment budget diagram for a watershed, also Walling et al. (2001) and Walling (2006) used this concept to understand soil redistribution at the surface of the watershed and on the way to transfer to the river. The sediment budget diagrams were then prepared and used by many researchers (e.g., Walling and Collins, 2008; Keesstra et al., 2009; Minella et al., 2014; Grimaldi et al., 2015; Porto et al., 2016; Rainato et al., 2017; Smetanová et al., 2017; Frings et al., 2018; Kondolf et al., 2018; Guo et al., 2021; Sedighi et al., 2021; Park et al., 2022; Ivanov et al., 2023) for various purposes. Sediment budget components include total erosion, total deposition, net erosion, and sediment delivery ratio. Among these components, total erosion, total deposition, and net erosion (t y^{-1}) can be expressed in a

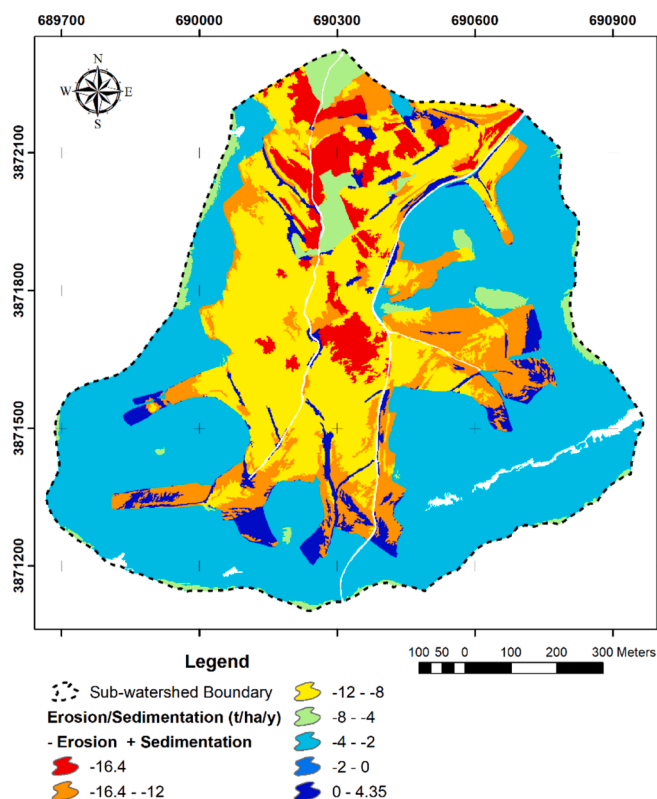


Fig. 2. Erosion/sedimentation map of the study area using work unit approach. (Note: negative numbers indicate erosion and positive numbers indicate sedimentation).

specific term by dividing by the watershed area ($t/ha\ y^{-1}$). These components reflect the individual and interaction effects of natural factors (i.e., climate, topography, lithology, etc.) and anthropogenic factors (i.e., construction, land use change etc.) on the occurrence of soil erosion and the sediment yield, transport and delivery processes. Since the sediment budget provide valuable information on the intensity of erosion and sediment redistribution and delivery in the hillslopes, and all this information is generally influenced by the ecological conditions such as soil and vegetation characteristics, therefore, radiotracers such as ^{137}Cs can be considered as an ecological indicator too.

The present research was conducted in the Khamsan watershed which is a representative watershed for a large high populated area in western Iran, where the Zagros Mountains creates specific landscapes with rainfed agriculture as the main effective land use change in this part of the country (Sedighi et al., 2021). In addition, availability of the detailed data especially the land use/cover map and digital elevation model with a spatial accuracy of one meter and also the results of previous ^{137}Cs measurements and researches were the important significances of this watershed for the present research.

The main subject of the present research is to use of topographic measurements and radiotracers as ecological indicators to investigate the relationship between topographic metrics and sediment budget components in both pixel and hillslope scales. Addressing these issues will lead to a better understanding of sediment sources and sedimentation patterns and a more detailed analysis of the sediment connectivity index and sediment transport paths. Finally, by considering these

details, it is possible to design and implement soil conservation measures based on sustainable development indices, and especially to obtain more preparedness to face climate change and unknown future conditions. In addition, considering the mutual effect of topography and soil erosion/redistribution, the use of DEM with high spatial accuracy compared with soil erosion/redistribution map in a proportional scale, reduces the error and increases the accuracy of the analysis.

2. Materials and methods

2.1. Study area

The study area was the control sub-watershed located in the extreme southwest of the Khamsan representative-paired watershed in Kurdistan province, western Iran. The area and average slope and elevation of the study sub-watershed were 102.14 ha, 26.4 % and 1707 m above sea level, respectively. No soil and water conservation and sediment control measures have been carried out in this sub-watershed. The average annual air temperature and precipitation of the study area are 12.5 °C and 428 mm, respectively (Sedighi et al., 2021) which has led to semi-arid climate in this region. Fig. 1 shows the location of the study area in Khamsan representative watershed, western Iran.

2.2. Additional soil sampling for ^{137}Cs inventory in the reference area

The ^{137}Cs inventory in the reference area was done as the first step and an essential parameter for the quantitative assessment of soil redistribution (Mabit et al., 2013). Two old cemeteries of Mouchesh and Ghorogh villages were selected as reference points in previous studies

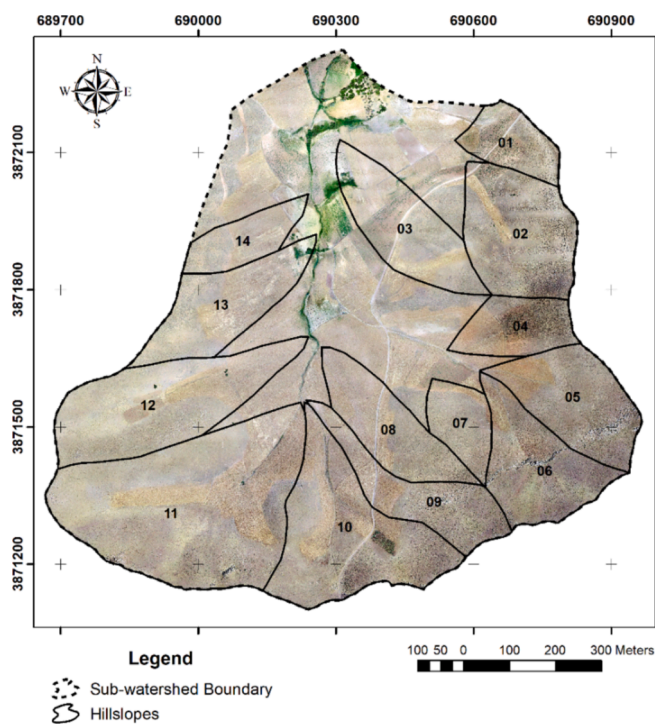


Fig. 3. Hillslopes selected in the control sub-watershed to investigate the relationship between topographic metrics and sediment budget components.

Table 1
Sediment budget results of the study area using work unit approach.

Total Erosion (t y^{-1})	Specific Total Erosion (t/ha y^{-1})	Total Deposition (t y^{-1})	Specific Total Deposition (t/ha y^{-1})	Net Erosion (t y^{-1})	Specific Net Erosion (t/ha y^{-1})	SDR
526.87	5.25	20.26	0.20	506.61	5.05	0.96

Table 2
The results of calculating the average topographic metrics in the 14 selected hillslopes in the study sub-watershed.

Slope Number	Area (ha)	Aspect	Slope angle (degree)	Slope length (L factor)	LS Factor	Flow Accumulation	Plan Curvature	Profile Curvature	SPI	TWI
1	2.2694	275.394	20.912	0.926	2.494	103.127	0.0015	-0.0010	0.098	3.979
2	6.0306	231.974	33.802	1.149	4.515	185.046	-0.0007	0.0001	0.347	4.011
3	4.8586	277.123	21.082	0.955	2.473	232.998	0.0012	-0.0004	0.111	3.845
4	2.8124	255.017	24.245	1.187	3.177	145.172	0.0002	0.0006	0.212	4.354
5	4.8102	296.564	38.959	1.087	5.460	219.164	-0.0003	-0.0001	0.342	3.580
6	4.9299	207.993	44.908	1.026	6.079	213.077	-0.0002	0.0015	0.405	3.373
7	2.1546	241.021	38.238	1.189	5.477	100.327	0.0025	-0.0021	0.413	3.963
8	4.1505	291.924	25.407	1.062	3.307	233.683	0.0013	-0.0011	0.194	3.863
9	3.9251	304.137	35.983	1.053	4.783	258.395	0.0013	0.0004	0.310	3.588
10	8.4369	198.452	33.582	1.035	4.484	302.189	-0.0005	0.0001	0.271	3.601
11	14.7385	114.458	34.490	1.155	4.684	327.724	0.0002	-0.0002	0.341	3.902
12	7.9542	67.641	32.658	1.121	4.329	326.320	0.0000	0.0000	0.302	3.826
13	4.8195	75.612	21.208	0.948	2.444	237.236	0.0007	-0.0007	0.110	3.752
14	2.3254	66.999	21.468	0.902	2.453	122.602	0.0018	-0.0002	0.123	3.777

Table 3
The results of sediment budget components in the 14 selected hillslopes.

Slope Number	Area (ha)	Total Erosion (t y ⁻¹)	Specific Total Erosion (t/ha y ⁻¹)	Total Deposition (t y ⁻¹)	Specific Total Deposition (t/ha y ⁻¹)	Net Erosion (t y ⁻¹)	Specific Net Erosion (t/ha y ⁻¹)	SDR
1	2.2694	-17.038	-7.508	0.134	0.059	-16.903	-7.448	0.992
2	6.0306	-10.843	-1.798	0.253	0.042	-10.590	-1.756	0.977
3	4.8586	-35.368	-7.279	1.017	0.209	-34.351	-7.070	0.971
4	2.8124	-21.150	-7.520	1.188	0.422	-19.962	-7.098	0.944
5	4.8102	-10.075	-2.095	1.354	0.281	-8.721	-1.813	0.866
6	4.9299	-4.605	-0.934	0.733	0.149	-3.872	-0.785	0.841
7	2.1546	-2.732	-1.268	0.212	0.099	-2.520	-1.170	0.922
8	4.1505	-24.457	-5.892	0.478	0.115	-23.979	-5.777	0.980
9	3.9251	-14.255	-3.632	0.477	0.122	-13.778	-3.510	0.967
10	8.4369	-28.281	-3.352	4.271	0.506	-24.010	-2.846	0.849
11	14.7385	-43.721	-2.966	4.156	0.282	-39.565	-2.684	0.905
12	7.9542	-24.373	-3.064	1.416	0.178	-22.957	-2.886	0.942
13	4.8195	-30.531	-6.335	0.145	0.030	-30.386	-6.305	0.995
14	2.3254	-14.400	-6.192	0.309	0.133	-14.091	-6.059	0.979

Table 4
The disturbed and undisturbed soil area coverage (%) in the selected hillslopes.

Hillslope	Disturbed soil area (%)	Undisturbed soil area (%)	Hillslope	Disturbed soil area (%)	Undisturbed soil area (%)
1	56.53	43.47	8	54.00	46.00
2	12.45	87.55	9	35.57	64.43
3	62.46	37.54	10	36.37	63.63
4	57.66	42.34	11	29.17	70.83
5	17.92	82.08	12	30.67	69.33
6	8.76	91.24	13	55.62	44.38
7	13.51	86.49	14	62.22	37.78

(Sedighi et al., 2021) and the incremental sampling was done at different depths of 0–3, 3–6, 6–10, 10–15, 15–20, and 20–25 cm in 10 points. Two new bulk samples were added to the reference site and the coefficient of variation was recalculated as < 20 %, which showed the reference inventory acceptable.

2.3. Soil sampling in the study area

Google Earth software was used to determine the location of soil sampling points (Li et al., 2018). In the present study, 31 sampling points in a 200-meter grid were used with a systematic-random method (Walling et al., 2014) and also 48 points on six transects were taken to investigate the effect of slope curvature (Fig. 1). Bulk sampling was done using a 25-cm high and 8.5-cm diameter corer (Sedighi et al., 2021).

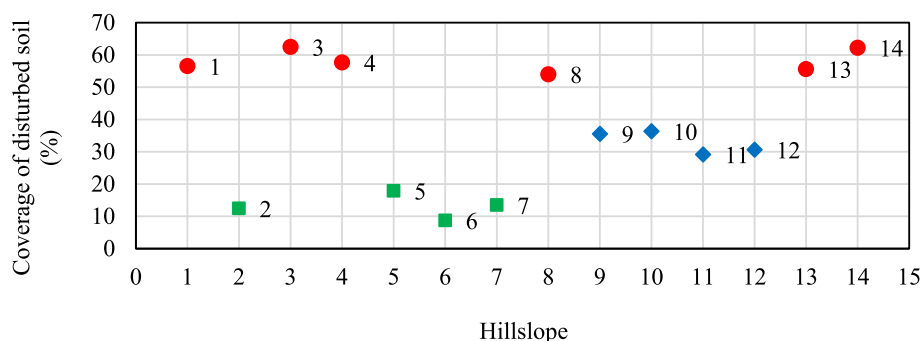


Fig. 4. Grouping the selected hillslopes based on the coverage of the disturbed soil.

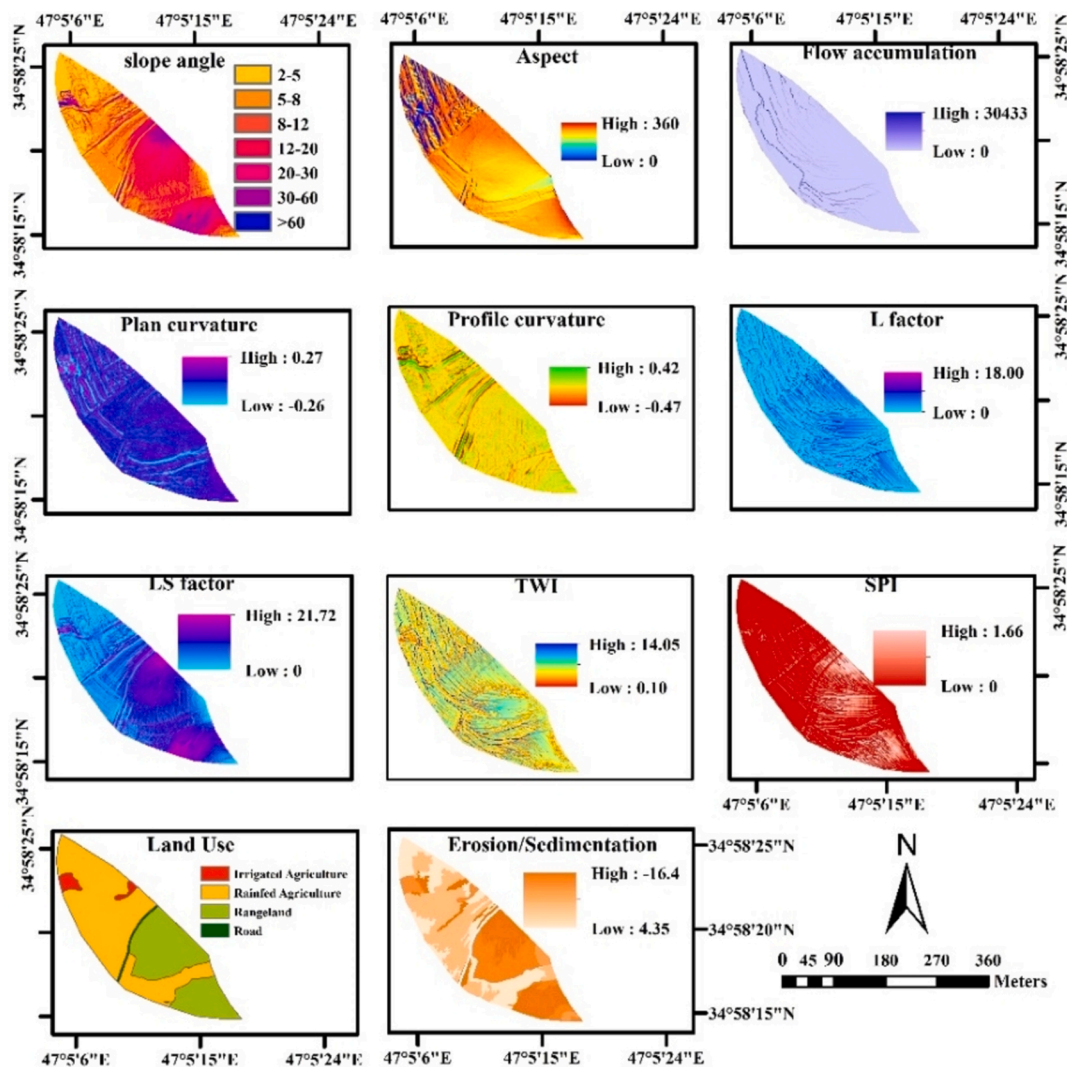


Fig. 5. Topographic metrics and erosion/sedimentation map for the hillslope number 3 (representative for the hillslopes with > 54 % coverage of the disturbed soil).

2.4. Sample preparation and measurement of ¹³⁷Cs inventory

Each sample was dried in an aluminum container for 24 h at a temperature of 105 degrees Celsius. Then the sample was weighed and passed through a 63 μm sieve (Chiu et al., 2011) and the amount of 293 gr of soil was poured into a special container and the ¹³⁷Cs activity (Bq kg⁻¹) was measured using the gamma spectrometer method (Collins et al., 1997). Then, the ¹³⁷Cs activity was converted to the ¹³⁷Cs inventory using equation (1) (Walling et al., 2003).

$$CPI = \sum C_i B_i D_i 10^3 \quad (1)$$

where, CPI is the ¹³⁷Cs inventory (Bq/m⁻²(-)), C_i is the ¹³⁷Cs activity (Bq kg⁻¹), D_i is the thickness or depth of the sampling layer (0.25 m) and B_i is the bulk density of the soil (gr cm⁻³).

2.5. Calculation of erosion/sedimentation using conversion models

To convert ¹³⁷Cs inventory to the amount of erosion/sedimentation, the mass balance model II was used for agricultural lands, and the diffusion and migration model was used for rangelands (Walling et al., 2007). Considering the time of plough operations before the autumn rainfalls in the study area, the depth of autumn rainfall on the total annual rainfall was calculated as 0.335 and considered as the proportion coefficient factor (Sedighi et al., 2021). In this study, the relaxation

depth was equal to 8.0 cm and the coefficient of migration rate (V) and diffusion coefficient (D) were calculated from equations (2) and (3) (Walling et al., 2007) as 0.45 and 24.27, respectively.

$$V = \frac{W_p}{t - 1963} \quad (2)$$

$$D = \frac{(N_p - W_p)^2}{2(t - 1963)} \quad (3)$$

where t is the year of sampling, W_p is the mass depth (kg m⁻²) of the layer with the maximum concentration of ¹³⁷Cs and N_p is the mass depth (kg m⁻²) of the layer where the concentration of ¹³⁷Cs decreases to 1/e of the maximum value in the soil surface. Finally, equations (4) and (5) (Walling et al., 2014) were used to determine the stable condition boundaries.

Boundary between stable condition and erosion = Mean - 95 % confidence interval (4).

Boundary between stable condition and deposition = Mean + 95 % confidence interval (5).

where Mean and 95 % confidence interval are the average ¹³⁷Cs inventory and the 95 % level of confidence between the ¹³⁷Cs concentrations in the reference points by accepting an error of 10 %.

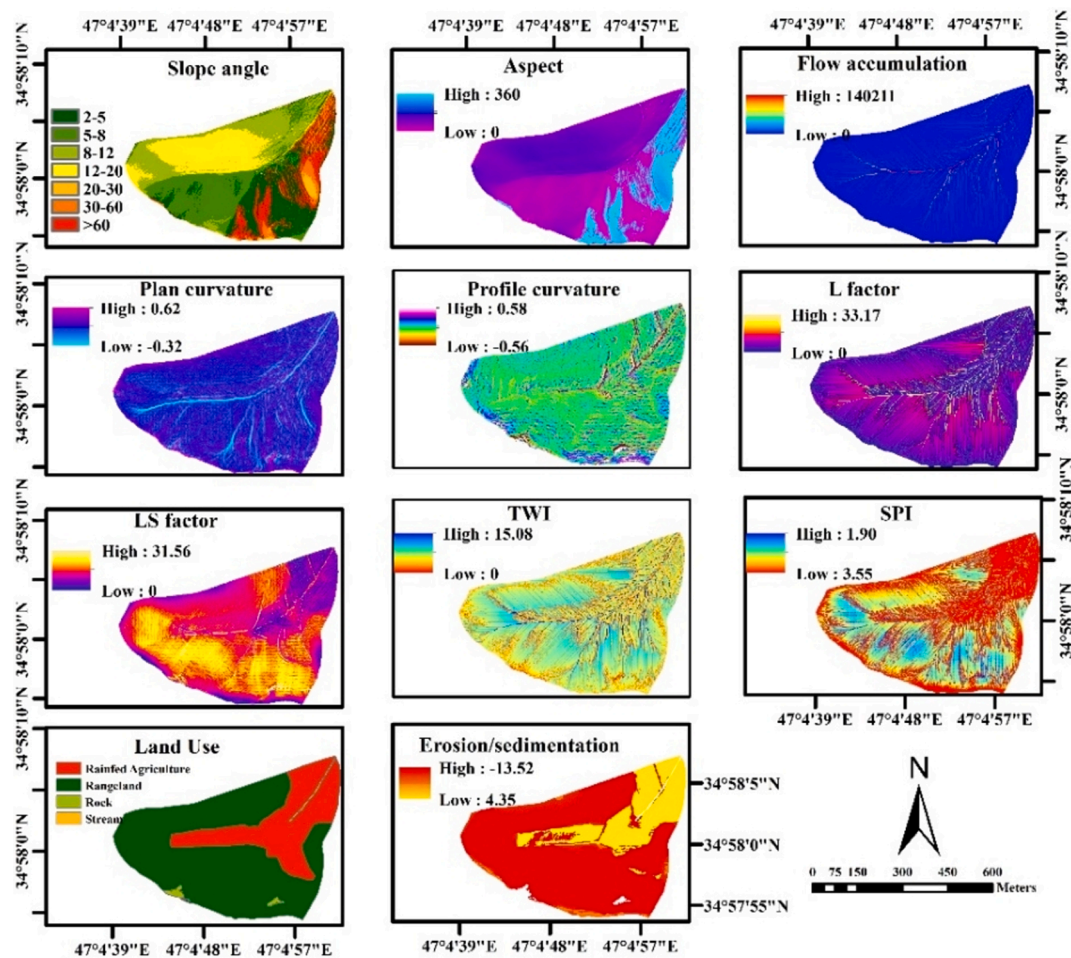


Fig. 6. Topographic metrics and erosion/sedimentation map for the hillslope number 11 (representative for the hillslopes with 29–37% coverage of the disturbed soil).

2.6. Preparation of erosion/sedimentation maps and sediment budgeting

The distribution map of erosion/sedimentation was prepared using the work unit method (Sedighi et al., 2021) by overlapping two land use maps and the map of slope classes. The erosion/sedimentation map was divided into three erosion, stable and sedimentation conditions and the min, max, area, average and standard deviation were calculated for each of the three areas.

In this research, 14 hillslopes were selected based on the variety of the area, slope angle and slope direction in the control sub-watershed. Then, the sediment budget components (i.e. total or gross erosion, total sedimentation, net erosion and sediment delivery ratio) were calculated. The sediment delivery ratio was calculated as the ratio of net erosion to total erosion or specific net erosion to total specific erosion. At each point, the decrease and increase of ^{137}Cs activity outside the range of Mean \pm 95 % confidence interval compared to the reference area, respectively, indicates the dominance of the erosion processes or the sedimentation processes in the last 65 years.

2.7. Extraction of topographic metrics and maps

To extract the topographic metrics of the study sub-watershed, a digital elevation model (Glenn et al., 2006) with a spatial accuracy of one meter prepared by a photogrammetric drone was used. The topographic metrics including slope angle (degrees), slope aspect (azimuth angle from zero to 360 degrees), profile and plan curvatures, slope length (L), topographic factor (LS), stream power index (SPI),

topographic wetness index (TWI) and flow accumulation were prepared using ArcGIS software version 10.8 (Afshar et al., 2010; Li et al., 2018).

2.8. Data analysis

Due to the high accuracy of the spatial data (DEM = 1 m) and also the use of ^{137}Cs in the calculation of erosion and sedimentation, it has been tried to analyze the relationships in both slope and pixel scales. All the data were entered into the R software and the normality of the data was checked using the Kolmogorov Smirnov test (Steinskog et al., 2007). Then, the correlations and relationships between the topographic metrics and the sediment budget components were investigated at the hillslope scale using the Pearson correlation coefficient (Masroor et al., 2021) and ANOVA. In addition, the relationships between topographic metrics and soil erosion/redistribution at the pixel scale (raster maps) were investigated using Pearson correlation coefficient in R software.

3. Results and Discussion

3.1. Sediment budget analysis

The erosion/sedimentation map prepared using the work unit approach for the study sub-watershed is shown in Fig. 2, and Sediment budget components are shown in Table 1.

According to Table 1, out of 526.87 t y^{-1} of erosion occurred in the study sub-watershed, only 20.26 t y^{-1} were redistributed within the watershed, and 506.61 t y^{-1} were delivered to the watershed outlet.

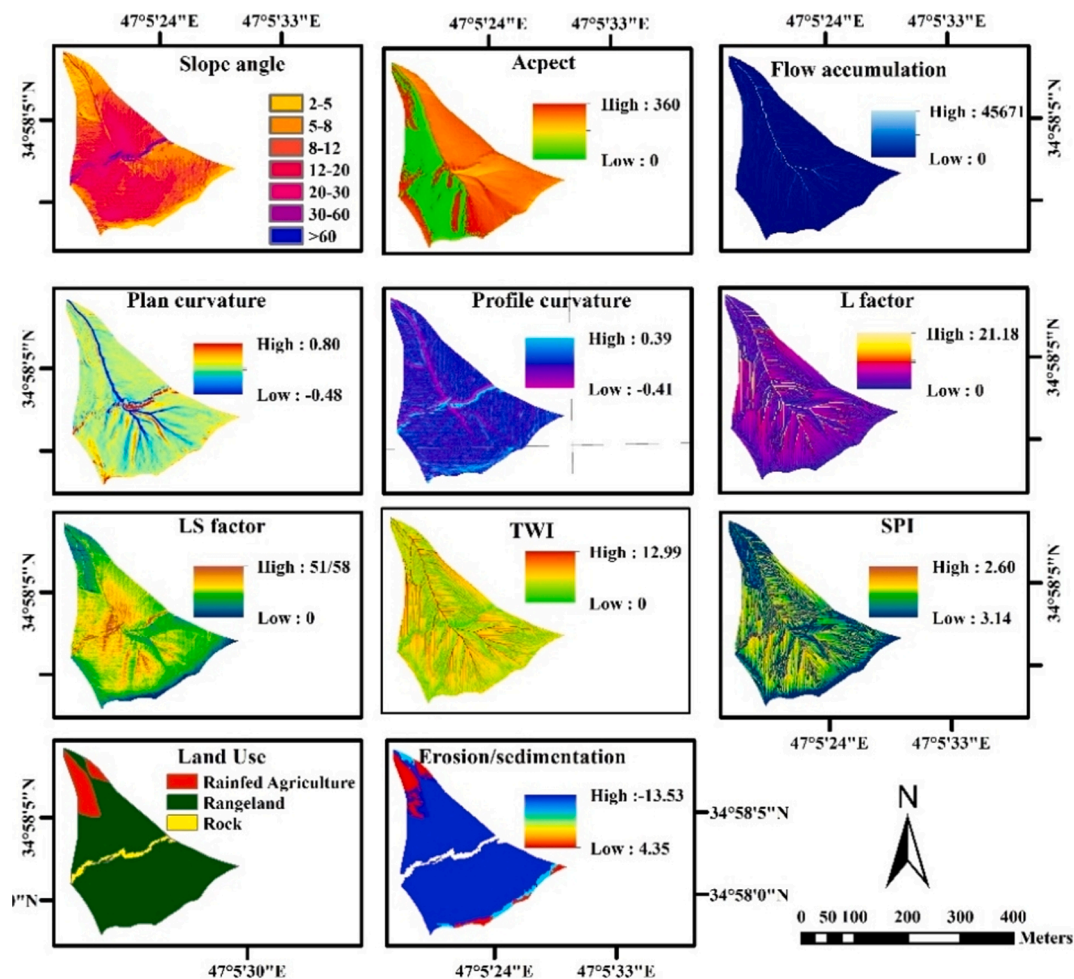


Fig. 7. Topographic metrics and erosion/sedimentation map for the hillslope number 6 (representative for the hillslopes with < 18 % coverage of the disturbed soil).

Therefore, specific net erosion was calculated by dividing the net erosion by the area of the watershed at the rate of $5.05 \text{ (t/ha y}^{-1}\text{)}$. Finally, the sediment delivery ratio resulting from the division of specific net erosion by specific total erosion was 0.96 %. This ratio indicates that about 96 % of the erosion that occurred in the watershed can reach to the watershed outlet. In other words, not only the intensity of soil erosion has increased due to changes in land use and soil disturbance, but also the intensity of sediment transport to the outlet of the hillslopes and watershed has increased. These results should be considered by managers and decision makers in the field of soil conservation and erosion control in the study area and similar areas in western Iran.

As a general view, the erosion rate is increasing with decreasing the slope gradient down the hillslopes which is related to land use. These results are in agreement with the results of Sedighi et al. (2021) in this watershed who revealed that the highest net erosion rate is related with medium slope (< 20 %). The results strongly indicate the role of land use and the interactions between land use and slope gradient (Sedighi et al., 2022). In the upstream, where rangeland is the main land use, the redistribution rate was higher than the downstream of the hillslopes due to the higher soil surface roughness in the rangeland compared to agricultural lands. These results are consistent with the results of many previous studies (e.g., Vermang et al., 2015; Meshkat et al., 2019; Sun et al., 2021; Bahddou et al., 2023) who stated that the soil surface roughness is the most important factor in the rate of erosion and sedimentation.

3.2. Hillslope classification

Fourteen hillslopes were selected in the study sub-watershed as shown in Fig. 3. In Table 2 the mean value of the topographic metrics for the corresponding hillslopes are also reported.

The sediment budget components for 14 selected hillslopes are presented in Table 3.

According to Table 3, the specific net erosion rate ranged between 0.79 and $7.45 \text{ (t/ha y}^{-1}\text{)}$ and the sediment delivery ratio obtained between 0.84 and 1.00 for the 14 selected hillslopes. Such high annual sediment delivery ratios are probably due to the use of rainfed agricultural lands and plowing in the direction of the slope gradient in large areas of the selected hillslopes, as it was emphasized by some previous studies (e.g., Sedighi et al., 2021,2022; Samanta et al., 2023).

Considering that 14 selected hillslopes were selected in different parts of the sub-watershed with different conditions (Fig. 3), they were grouped according to the percentage of disturbed soil to investigate the impact of topographic metrics on the sediment budget components at the hillslope scale (Table 4). The hillslopes with < 18 % coverage of the disturbed soil including hillslopes 2, 5, 6, 7, the hillslopes with 29–37 % coverage of disturbed soil including hillslopes 9,10, 11, 12 and the hillslopes with > 54 % coverage of disturbed soil area, mostly consist of rainfed and irrigated agricultural lands, including hillslopes 1, 3, 4, 8, 13 and 14, are shown in (Fig. 4).

3.3. Topographic metrics and erosion/sedimentation analysis

After grouping the hillslopes, three hillslopes of 3, 11 and 6 were

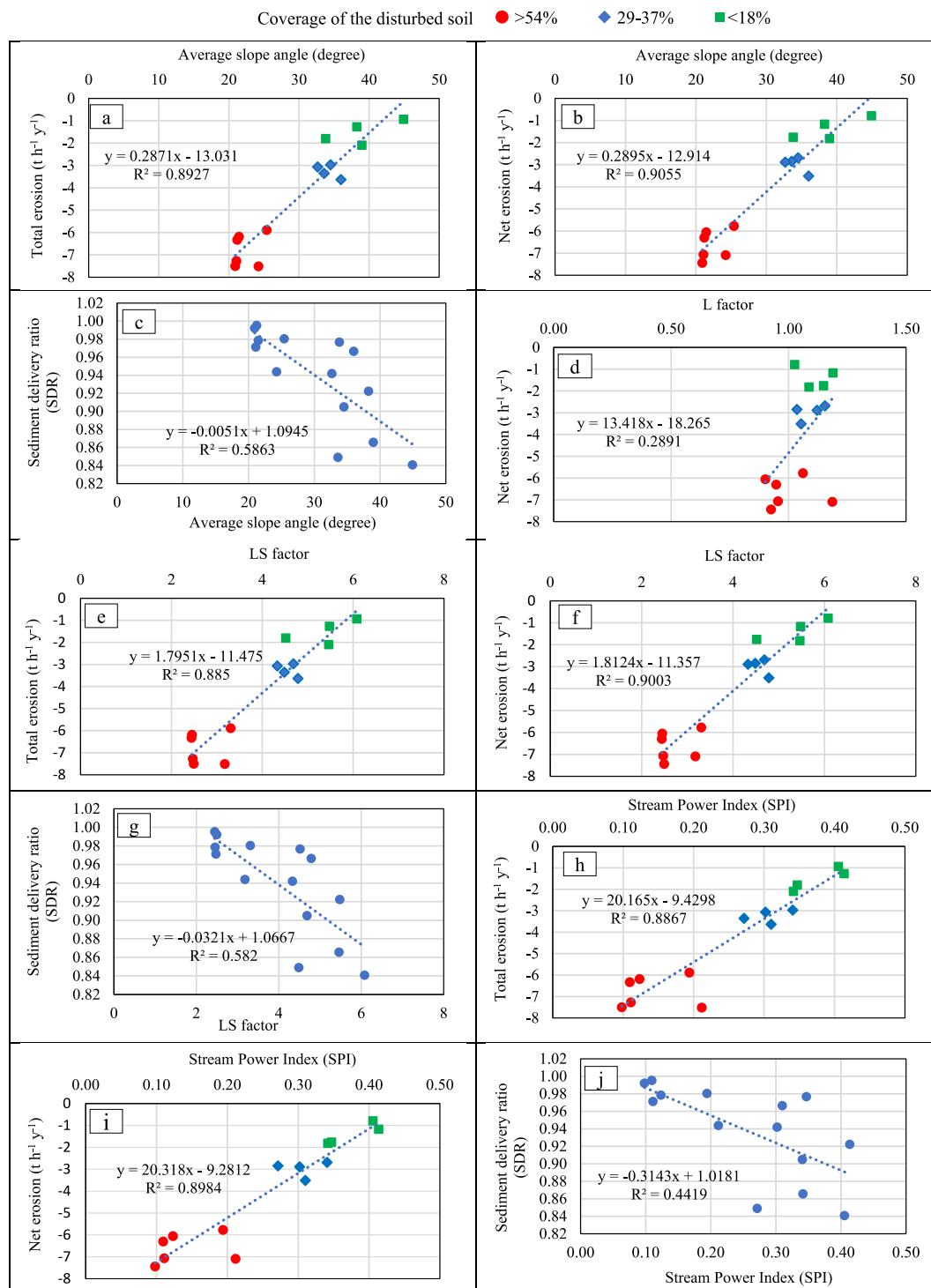


Fig. 8. The discussable relationships between topographic metrics and the sediment budget components.

selected as the representatives for three groups based on the variety of land use and slope angle and distributed maps of the studied variables including topographic metrics and erosion/sedimentation map are shown in Figs. 5-7, for the hillslopes with > 54 %, 29-37 % and < 18 % coverage of the disturbed soil, respectively.

According to the grouping of the hillslopes, the results of the discussable relationships between topographic metrics and the sediment budget components are presented in Fig. 8.

3.4. Statistical analysis

In the next step, the Shapiro-Wilk test was used to check the normality of the data of the 14 investigated hillslopes. The results indicate that all the topographic metrics as well as sediment budget components of the studied hillslopes were normally distributed (sig. < 0.05), and therefore, Pearson coefficient was used to check the correlation between the topographic metrics and sediment budget components in the hillslope scale (Table 5).

According to Fig. 8-a and (8-b), total and net erosion (t/ha y⁻¹) were

Table 5
The Pearson correlation coefficient between topographic metrics and sediment budget components at the hillslope scale.

Budget components	Total Erosion (t/ha y ⁻¹)	Total Deposition (t/ha y ⁻¹)	Net Erosion (t/ha y ⁻¹)	SDR
Aspect	0.021	0.072	0.017	-0.055
Slope angle	-0.945**	0.132	-0.952**	-0.765**
Slope length (L factor)	-0.521	0.296	-0.538*	-0.321
LS factor	-0.940**	0.156	-0.949**	-0.762**
Flow accumulation	-0.254	0.347	-0.274	-0.318
Plan curvature	0.355	-0.500	0.383	0.485
Profile curvature	-0.146	0.393	-0.168	-0.470
Stream power index (SPI)	-0.943**	0.116	-0.949**	-0.664**
Topographic wetness index (TWI)	0.469	0.046	0.465	0.514

* and ** indicate significant correlation at 95% and 99% confidence levels, respectively.

Note: All signs of total and net erosion columns were reversed due to the negative sign of erosion.

decreased with increasing the slope gradient. On the hillslope scale, the correlation test showed negative and significant relationships (sig. < 0.01) between slope angle and total and net erosion (t/ha y⁻¹) at the level of -0.95 and -0.95, respectively. In most hillslopes, the movement of eroded soil particles down the slopes is facilitated, but according to the obtained results, the specific total and net erosion (t/ha y⁻¹) decreased with increasing the slope gradient. The only acceptable reason is the hillslope effect of the land use, in which as a result of the reduction of the slope gradient, the rangelands has been changed to agricultural lands. In other word, although the slope gradient is lower in the downslopes, the erosion is higher because of the soil disturbance and plowing in the direction of the slopes in rainfed agricultural lands. With increasing the soil tillage practices, the degradation rate of the soil is increased and the roughness of the soil surface is reduced. As a result, a large amount of soil particles is available to be detached and transported by the surface runoff which leads to increase the amount of sediment delivered to the bottom of the hillslopes. The results of some previous studies (e.g., Zhao et al., 2022; Sedighi et al., 2021; Govers et al., 1996) also indicated that the land use factor can be a hillslope factor that may change the logical effects of the other variables, especially slope gradient on erosion. Sedighi et al. (2021) showed that the highest intensity of net erosion was related to sub-watersheds with an average slope gradient of < 20 %, which can be interpreted only by the role of land use and its interaction with the slope gradient. The results of the present study are contrary to the results of many previous studies (e.g., Zhao et al., 2022; Kikuchi et al., 2020; Velasco et al., 2018;), who showed that the rate of erosion in the upper steep parts of the hillslopes is higher than in the lower slope gradients. The main reason for this inconsistency is the very important change in land use and land

Table 6
Correlation between soil erosion/redistribution and topographic metrics at pixel scale.

Topographic metrics	Erosion/Sedimentation	Aspect	Flow accumulation	L factor	LS factor	Plan curvature	Profile curvature	Slope angle	SPI	TWI
Erosion/Sedimentation	1.000									
Aspect	0.056	1.000								
Flow accumulation	0.022	0.000	1.000							
L factor	0.001	0.000	0.773**	1.000						
LS factor	-0.572**	-0.004	0.057	0.186	1.000					
Plan curvature	-0.009	-0.001	-0.081	-0.208	-0.136	1.000				
Profile curvature	-0.010	-0.004	-0.040	-0.090	-0.069	0.569**	1.000			
Slope angle	-0.599**	-0.011	-0.050	-0.034	0.907**	0.011	-0.001	1.000		
SPI	-0.387*	-0.030	0.031	0.305	0.669**	-0.132	-0.059	0.566**	1.000	
TWI	0.036	-0.003	0.227	0.669**	0.092	-0.213	-0.107	-0.128	0.524**	1.000

* and ** indicate significant correlation at 95% and 99% confidence levels, respectively.

Note: All signs in the first column were reversed due to the negative sign of erosion.

management (conversion of rangeland to rainfed agriculture with plowing in the direction of the main slope gradient), which can overshadow the effect of other factors, even the slope gradient.

In addition, according to Fig. 8-c, the sediment delivery ratio of the hillslopes with a lower slope gradient is much higher than the steeper hillslopes. But again, the inconsistency of the relationship between the sediment delivery ratio and the slope gradient according to the laws governing erosion, shows that the main and important factor influencing these results is the land use of the studied hillslopes. The rainfed agriculture located in the lower parts of the investigated hillslopes because of lower slope angle, while in the upper steep parts of the hillslopes, it was not possible to change the land use of rangeland to rainfed agriculture, and for this reason, the intensity of soil erosion and the sediment transport and delivery in these parts of the hillslopes are lower, which is consistent with the findings of Sedighi et al. (2021) and Zhao et al. (2022).

According to Fig. 8-d, the Net erosion (t/ha y⁻¹) decreased with increasing the slope length (L factor). According to Table 5, there is a significant negative correlation of 0.54 (sig. < 0.05) between the slope length and Net erosion (t/ha y⁻¹) too. With the increasing the slope length, despite the possibility of increasing the depth and velocity of surface runoff, the possibility of redistribution of eroded soils also increases, and as a result, the negative relationship between the slope length and net erosion is not far from expected in the special conditions of the studied hillslopes. Besides that, the plan and profile curvatures of the hillslopes, which are generally compound (convex in the upper parts and concave in the lower parts), can be considered as an effective factor in these results. Increasing the slope length has led to the runoff reaching the lower parts of the hillslopes with lower slope angle and reducing the sediment transport capacity and increasing sedimentation and as a result has reduced net erosion (t/ha y⁻¹). It can also be said that the roughness of the soil surface is higher in the upper undisturbed rangeland soils, and therefore the trapping and redistribution of the sediment is more than the rainfed agricultural lands. In the lower parts of the hillslopes, the roughness has been reduced by agricultural activities and the sediment transport has been facilitated, especially in the furrows caused by plowing. The significant role of the surface roughness on runoff characteristics and/or sediment transport has been emphasized in previous studies (e.g., Meshkat et al., 2019; Mombini et al., 2021). Generally, with increasing the surface roughness, the influence of the profile curvature overcomes the effects of the plan of the hillslope.

Fig. 8-e, (8-f) and (8-g) showed that the total and net soil erosion (t/ha y⁻¹) and even sediment delivery ratio decreased with increasing LS factor, generally. Pearson's correlation coefficient also showed that there are significant negative relationships of -0.94, -0.95 and -0.76 (sig. < 0.01) between the LS factor, in one side, and total and net soil erosion rates and the sediment delivery ratio, in other side, respectively. These results are not acceptable according to the laws governing the process of erosion and sediment transport, and the only reason that can justify the results is the dominant effect of rainfed agriculture in the

lower parts of the hillslopes which causes the negative relationships between the slope angle and even LS factor with soil erosion.

The grouping of the investigated hillslopes based on the disturbed soil area (Fig. 4) shows that the hillslopes with more disturbed soils (more land use change from rangeland to rainfed agriculture) have less slope angle. Due to soil degradation and plowing in downslopes, they have far more erosion than steeper upslopes where the main land use is still rangeland (Sedighi et al., 2022; Zhao et al., 2022).

According to Fig. 8-h, (8-i) and (8-j) the total erosion, net erosion ($t/ha\ y^{-1}$) and sediment delivery ratio decreased with increasing the stream power index (SPI). The correlation coefficients between the stream power index with the total erosion, net erosion ($t/ha\ y^{-1}$) and sediment delivery ratio were -0.94 , -0.95 and -0.66 (sig. < 0.01), respectively. According to the rules of total erosion, net erosion and sediment delivery ratio, increasing the stream power causes more detachment of soil particles and more erosion transport. Because the stream power index increases with increasing the slope angle, the justification of the results of this section is exactly the same with the relationship between slope angle and erosion. Despite accepting the effectiveness of stream power index on soil erosion (Conforti et al., 2011), the results of the present study showed that the land use can be the dominant effective factor on the soil erosion processes and delivery in hillslopes (Sedighi et al., 2021).

The correlations between soil erosion/redistribution and topographic metrics at pixel scale were also investigated and shown in Table 6.

According to Table 6, the correlation between topographic metrics and erosion/sedimentation at the pixel scale showed that there is a negative correlation of 0.57 (sig. < 0.01) between LS factor and erosion/sedimentation. The hillslope shape (concave and convex) together with the length and slope of the hillslopes upstream and downstream, make the deposition points down the slopes where the slope length increasing just before reaching to the slope break down due to rainfed agriculture. These results are not in agreement with Ahmad et al. (2024) who stated that soil loss in the upstream has a high positive correlation with LS factor. In addition, at the pixel scale, the relationship between erosion/sedimentation with slope angle and stream power index obtained negative correlations of 0.60 (sig. < 0.01) and 0.39 (sig. < 0.05), respectively. There are many reasons to justify the direct and indirect effects of slope angle on soil erosion and sediment transport processes. The slope angle can change many variables including the impact angle and kinetic energy of raindrops at the soil surface, soil temperature and moisture, vegetation, soil splash and runoff processes (Zhao et al., 2022). In other words, especially with the decrease of the slope angle down the slopes, the intensity of erosion increased due to the land use change from rangeland to rainfed agriculture in the bottom of the hillslopes. Other topographic metrics, such as aspect, TWI, profile curvature, etc., did not show a significant positive correlation with soil erosion and redistribution at the pixel scale.

Due to the difference in topography, geology, soil, climate, vegetation and the impact of human activities, especially land use changes in different watersheds, the analysis of the relationship between topographic features and erosion and sediment redistribution processes will also be different. In this regard, the approach presented in our study can be used to more accurately understand the relationships between topographic metrics and sediment budget components in other watersheds. This issue is especially important when land use has been widely changed and knowledge of the impact of these changes is very necessary to apply correct management decisions as well as educational goals.

4. Conclusion

The present study investigates the relationship between topographic metrics and sediment budget components at two hillslope and pixel scales. A 1-m digital elevation model and soil erosion/sedimentation map prepared by using ^{137}Cs method were used to extract topographic

metrics and sediment budget components, respectively. The main limitation of this research was the number of soil sampling points for ^{137}Cs inventory. Although 79 sampling points were considered for a small sub-watershed, the larger number of soil sampling points can also consider the effect of minor changes in topographic metrics in soil redistribution. Statistical errors in the preparation of the distribution map of erosion/sedimentation have also been another source of error. However, a digital elevation model was prepared with a spatial accuracy of one meter, which is one of the strengths of the current research. According to the results:

- Land use change to rainfed agriculture in downslopes is one of the most important and effective indicators in erosion/sedimentation in the last 60 years. Plowing in the direction of the slope gradient is a key factor to accelerate soil erosion and sediment transport in these lands. In addition, not only the soil disturbance is the result of rainfed agriculture, but also the deficit of vegetation cover in the autumn and early spring with erosive rainfalls will cause the accelerated erosion and sediment yield.
- The interaction between land use and slope angle dominates the differences between runoff and soil erosion processes in up- and downslopes. The slope gradient acts as a key limitation that prevents the change of land use from rangeland to rainfed agriculture.
- Soil erosion in downslopes with lower slope angle was higher than the upslopes due to more soil disturbance and plowing which leads to detach and transport more soil particles in the flow paths. In other words, high slope gradient in the rangelands with undisturbed soil had less runoff and erosion than a low slope gradient but with the use of rainfed agricultural lands and plowed in the direction of the slope gradient.
- The most important conservational message of the present study is to avoid land use change or at least defining a specific slope angle threshold for changing rangelands to rainfed agricultural lands.
- At the hillslope scale, the significant relationships between sediment budget components and topographic metrics were dominated by grouping the hillslopes based on the land use and soil disturbance coverage.
- The effect of land use on the rate of erosion/sedimentation is much greater than the topographic metrics, but itself depends on the slope angle and this metric is the main factor indirectly.
- According to the results, considering two pixel and hillslope scales for sediment budgeting studies is essential to understand the interaction effects of topography and land use on hillslope processes.

CRediT authorship contribution statement

Reza Zarei: Writing – original draft, Visualization, Validation, Software, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Abdulvahed Khaledi Darvishan:** Writing – review & editing, Validation, Supervision, Software, Project administration, Methodology, Investigation, Formal analysis, Conceptualization. **Paolo Porto:** Writing – review & editing, Validation, Supervision, Methodology, Investigation, Formal analysis, Conceptualization. **Mohammad Reza Zare:** Software, Formal analysis, Data curation.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Reza Zarei reports financial support was provided by Tarbiat Modares University. If there are other authors, they 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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