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Evaluating Sediment Yield Response to Watershed Management Practices (WMP) by Employing the Concept of Sediment Connectivity

Hadi Nazaripouya [1], Mehdi Sepehri [2], Abbas Atapourfard [3], Bagher Ghermezcheshme [3], Celso Augusto Guimarães Santos [4], Mehdi Khoshbakht [5], Sarita Gajbhiye Meshram [6], Vikas Kumar Rana [7], Nguyen Thi Thuy Linh [8], Quoc Bao Pham [8] and Duong Tran Anh [9,10,*]

1 Watershed Research Department, Hamedan Agricultural and Natural Resources Research and Education Center, Agricultural Research, Education and Extension Organization (AREEO), Hamedan 65199-99811, Iran
2 Department of Watershed Management, Faculty of Natural Resources, Yazd University, Yazd 89168-69511, Iran
3 Hydrology and Water Resources Development Department, Soil Conservation and Watershed Management Institute, Agricultural Research, Education and Extension Organization (AREEO), Tehran 19395-1113, Iran
4 Department of Civil and Environmental Engineering, Federal University of Paraíba, João Pessoa 58051-900, Brazil
5 Department of Watershed Management, Faculty of Natural Resources, Isfahan University of Technology, Isfahan 84156-83111, Iran
6 Department for Management of Science and Technology Development, Ton Duc Thang University, Ho Chi Minh City 700000, Vietnam
7 Water Resources Engineering and Management Institute, Faculty of Technology & Engineering, The Maharaja Sayajirao University of Baroda, Vadodara 390002, India
8 Institute of Applied Technology, Thu Dau Mot University, Thu Dau Mot 75000, Vietnam
9 Laboratory of Environmental Sciences and Climate Change, Institute for Computational Science and Artificial Intelligence, Van Lang University, Ho Chi Minh City 700000, Vietnam
10 Faculty of Environment, Van Lang University, Ho Chi Minh City 700000, Vietnam
* Correspondence: duong.trananh@vlu.edu.vn

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Abstract: Watershed management practices (WMP) are widely used in catchments as a measure to reduce soil erosion and sediment-related problems. We used a paired catchment in the Gonbad region of Hamadan province, Iran, to evaluate sediment yield response to watershed management practices (WMP) by employing the concept of sediment connectivity (SC). To do this, the SC index as a representation of sediment yield was firstly simulated for the control catchment that there is no WMP. In the next step, the SC index was simulated for impacted catchment, including some WMP, i.e., seeding, pit-seeding, and exclosure. After assessing the accuracy of the produced SC maps using filed observations and erosion plots, the SC maps using quantile-quantile plot (Q-Q plot) were compared to achieve the role of WMP in reducing the rate of sediment yield. The Q-Q plot showed that there is a strong similarity between the SC of catchments, it can be concluded that the WMP has no significant impact on the reducing rate of the sediment yield in this study.

Keywords: soil erosion; sedimentation; best management practices; WMPs; biological method

1. Introduction

Soils as multi-functional materials provide critical ecosystem services to humans [1,2]. Environmental problems caused by soil erosion and sedimentation can be very costly. They can cause soil loss and land degradation (e.g., loss of nutrients and organic matter in the topsoil), which can harm the water quality of the river network [3,4], eutrophication [5,6], change in river morphology [7,8], reservoir storage [7,9], and flood risk [10,11] among other things. The study conducted by Pimentel and Burgess [12] demonstrated that the integration of inappropriate anthropogenic practices with heavy precipitation, steep slopes, and low/bare vegetation cover are some of the main drivers of soil erosion. Due to poor or lack of vegetation cover, as well as dry soils and heavy rains (especially in the western and southwestern regions), and other adverse conditions, the soil erosion issue has become a recurring challenge for decades, e.g., the annual soil erosion rate in Iran is 16.5 t/ha (2.7 billion tons of soil loss) [13,14].

To mitigate the negative issues related to soil erosion and sediment-related problems, watershed management practices (WMP) have been used as an effort to limit soil erosion and control non-point sources (NPS) of sediment and nutrients [15–18]. WMP are ever-evolving practices that involve structural (e.g., check dams, contour bridges) or non-structural (e.g., exclosure, afforestation) elements [19,20]. As a result, land use/cover and channel morphology in the watersheds have changed significantly. The effectiveness and feasibility of WMP need to be qualitatively and quantitatively assessed to determine how they effectively reduce soil erosion. In recent years, a new special consideration called connectivity has been used to evaluate the effectiveness of watershed management practices. Regarding the definition of connectivity, there is no consensus among researchers; thus, the concept has been defined in several ways [21–23]. Its most common definition can be described as the degree of linkage between the components of a geomorphic system [23,24].

Several watershed sediment models have been proposed [25] but it is worth highlighting that they have the following two main disadvantages: (1) they rely heavily on conceptualizing and lumping physical processes in their structure; (2) they often cannot represent many different active sediment sources and specific pathways from the erosion sites to the watershed outlet [26–29]. The connectivity concept is a solution to overcome model shortcomings associated with the spatial and temporal complexity of watershed properties, processes, and pathways [30–32]. In this study, it was applied the widely used method for quantifying sediment connectivity (SC), which was introduced by Borselli et al. [23].

This index is mainly a function of the impedance weighting factor (e.g., the RUSLE C-factor or Manning's n) and topography factors (slope and flow length). In previous studies that applied SC to investigate land-use change or any disturbance through a case study, they simply modified the impedance weighting factor while the other variables remained unchanged. To fill this gap, we have attempted to analyze changes in the SC due to watershed management practices by considering not just the impedance weighting factor but also the topography variables. The Gonbad watershed in Hamadan province, Iran, was used as a paired watershed to assess the effectiveness of the WMP. Using paired watersheds to analyze impacts before and after control is a good way to show how WMP adequately affects biophysical responses such as runoff and soil erosion.

2. Materials and Methods

2.1. Site Description

The Gonbad watershed, a paired catchment, represents an area of 4.47 km^2 located upstream of Gonbad village and 35 km from Hamadan city, with geographical coordinates of 48°41′ to 48°43′ east longitude and 34°41′ to 34°42′ (Figure 1). The average long-term annual rainfall in the region is 304.2 mm and according to the rainfall statistics of the meteorological station in the period from 2007 to 2016, the average rainfall is 234.8 mm with irregular distribution and is considered semi-arid rangeland with an average slope of 28%. The impacted and control sub-catchments in the catchment have areas of 1.45 km^2 and 1.43 km^2 and slopes of 34.8% and 33%, respectively. In this catchment, the data from the erosion plots have been measured in three points with three repetitions in each sub-catchment since 2011. In 2011, various biological practices such as seeding, pit-seeding, and enclosure were carried out in the impacted sub-catchment and changes in vegetation canopy were measured each year.

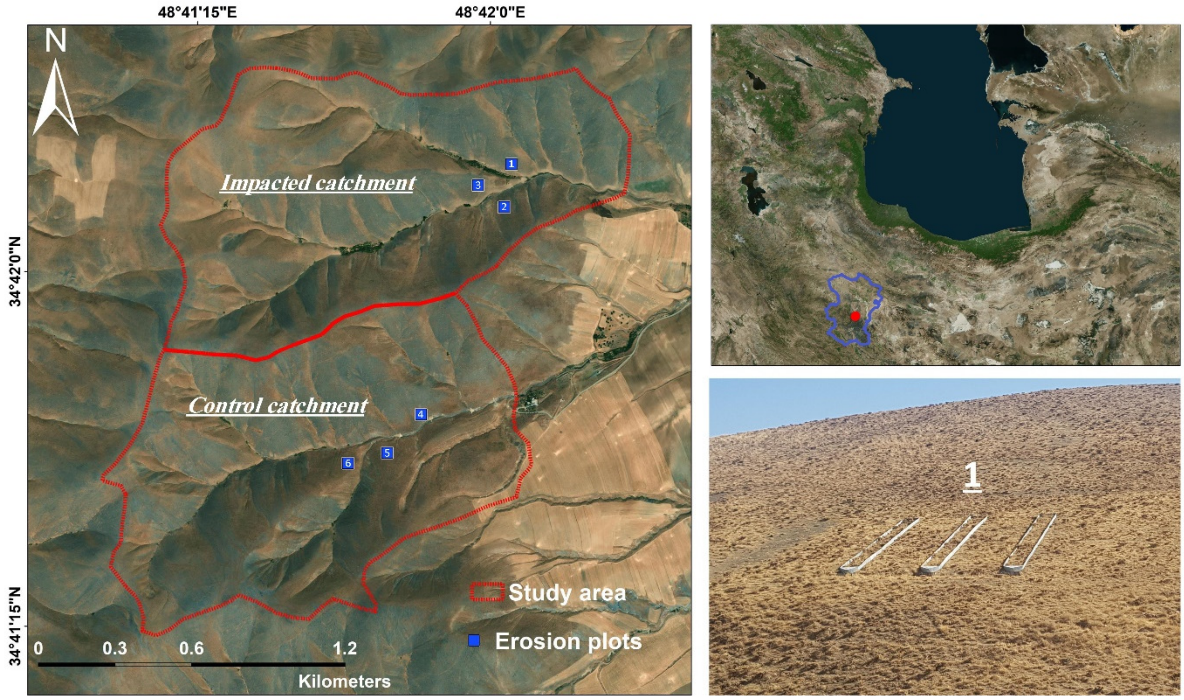

Figure 1. Location of the case study.

2.2. Description of the Index of Connectivity (SC)

The SC was formulated by Borselli et al. [23] and was investigated to understand the role of WMP on the spatial pattern of sediment yield (Equation (1)). This index allows one to quantify the probability of transferring sediments or flows from hill slope areas to a certain feature such as a reach, basin outlet, or target area [23,33,34]. The index is defined by a range of values $(-\infty, \infty)$, with higher values reflecting greater sediment connectivity and vice versa. At each pixel of the case study, the SC values are calculated considering the ratio of the potential for downward routing of runoff and sediment and the characteristics of the flow path length that a particle travels to arrive at the designated target or sink.

$$SC = \log_{10}\left(\frac{D_{up}}{D_{dn}}\right) = \log_{10}\left(\frac{\overline{w}\overline{s}\sqrt{A}}{\sum_i \frac{d_i}{w_i s_i}}\right) \tag{1}$$

where D_{up} is the upslope component, which demonstrates the potential of the upslope of a pixel in the downward routing of sediment/runoff, and D_{dn} represents the flow length of the pixel that has to travel to the nearest sink or target. $\overline{w}$, $\overline{s}$ and A indicate the characteristics of the upslope area, including average weighting factor (dimensionless), average slope (m/m), and upslope area (m^2), respectively. The variable d_i is the flow length along the ith pixel according to the steepest downslope direction (m), s_i and w_i are the slope and a weighting factor of ith pixel, respectively.

According to the above-mentioned descriptions, it can be found that SC is constructed using recognized variables of sediment connectivity such as slope, upslope area, and flow length path, which are known as static variables and remain variable, i.e., the weighting factor represents the dynamic variable [33]. The weighting factor is the proxy of impedance to runoff and sediment fluxes due to land cover and topographic properties. This variable can be used as a bridge connecting land use cover information and landscape disturbances to the analysis of SC [23]. Borselli et al. [23] used the C-factor based on RUSLE models to parameterize the impedance to sediment fluxes. C-factor is one of the main variables for simulating the role of different land cover and land-use changes on SC, but applying this variable to sediment connectivity has the following two main disadvantages: (1) it overestimates sediment connectivity in bare land areas and (2) this variable refers only to the cover so that in vegetated areas, it does not consider the role of surface roughness [33,35,36]. Manning's n-roughness coefficient can be used as an alternative to represent the resistance to flow and sediment, where the variability of the n-value within different anthropic or natural surface characteristics can be notable [30,33,37].

Based on Cowan's original approach [38] a modified Manning's n for each land cover class was derived according to the scale of values, which was refined later by Arcement and Schneider [39]. Each Manning's coefficient is given by the sum of the values assigned to the following parameters assessed in the field: a base value for the floodplain's bare soil (n_b), degree of surface irregularity (n_1), the effect of obstructions (n_3), and amount of vegetation (n_4). The overall coefficients (n), assigned to each land cover class, were calculated as follows:

$$n_{a,b,c,d} = (n_b + n_1 + n_2 + n_3 + n_4)m \quad (2)$$

where m is a correction factor for the meandering and n_2 is a value for variations in shape and size of the flood-plain cross-section, which in the case of floodplains or hill slopes are conventionally set as 1 or 0, respectively [39].

Another important variable in SC is related to this spatial pattern and depends on the vegetation pattern, topography, and any land disturbance [40–42]. In previous works, regarding the evaluation of the role of land-use change, topography, and WMP on sediment connectivity, the main attention of the authors was turned to the changing of the weighting factor. Therefore, to quantify the rate of sediment connectivity, it is necessary to consider the vegetation pattern, topography, and land disturbances as intra-weighting for flow length. To do this, the di is calculated as follows:

$$d_i = f(n_{a,b,c,d}) \quad (3)$$

where f is the function index.

2.3. Watershed Management Practices

Watershed management practices (WMP) can be used as a useful strategy to reduce non-point pollution resulting from watersheds [43–46]. They have been widely used to achieve sediment removal requirements on a watershed scale [4,45,47]. The benefits of WMP are the function of some particularities, including the geographic situation of the case study, type of WMP, intensity and stationary land use, age of watershed management practices after impalement, and post-management operations for monitoring WMP [27,48–50]. In a study conducted by Giri and Nejadhashemi [51], they concluded that the effectiveness of WMP hinges on their type and spatial placement, timing, and evaluation of their performance after construction [52]. In recent years, various methods have been used to evaluate the performance of watershed management practices before and after their implementation. Some of these studies are based on field measurements that need extensive and long-term monitoring. In this way, the major studies available are based on empirical models. In this study, the SC was used for this purpose. In this regard, in the current study, the role of watershed management practices on sediment yield was simulated. After watershed management practices were put into place in the paired catchment, the amount of sediment that would be produced was looked at in Figure 2.

2.4. WMP Configuration, Implementation, and Assessment

To evaluate the efficiency of WMP regarding sediment yield reduction, it is necessary to evaluate the accuracy of the calculated SC for the desired paired watershed. To do this, the output of SC was compared with sediment yield, which was measured at the plot scale. The monitoring design is shown in Figure 1. Nine closed sediment plots were installed on three different slopes. The slope gradient of plots for impacted/controlled watersheds varied from 23% to 43.4%. Moreover, the aspects of these plots are N-S-SE. The sediment from each plot was collected in a storage tank, where it was measured. After calculating the SC and its accuracy assessment, the Q-Q plot, whose aim is to find out if two sets of data come from the same distribution, was used to compare the SC of control and impacted watersheds and evaluate the role of WMP on the sediment yield rate.

All WMP evaluated in the impacted catchment were simulated by straightforward parameter changes, which were used in the control catchment. Only non-structural practices (i.e., exclosure, seeding, and pit-seeding) were used in the impacted catchment of the current study. From the comparison between SC of the mentioned catchments, the role of watershed management practices on the sediment yield rate can be obtained. The effects of the mentioned WMP, which reduce the amount of sediment yield, were simulated by changing the variables of Equation (2). Rangeland exclosure is one of the most effective techniques for restoring degraded rangelands by modifying species' composition, abundance, and diversity [53–55]. The effects of rangeland exclosure were simulated by changing n_4, whereas the effects of seeding and pit-seeding were represented by changing n_4.

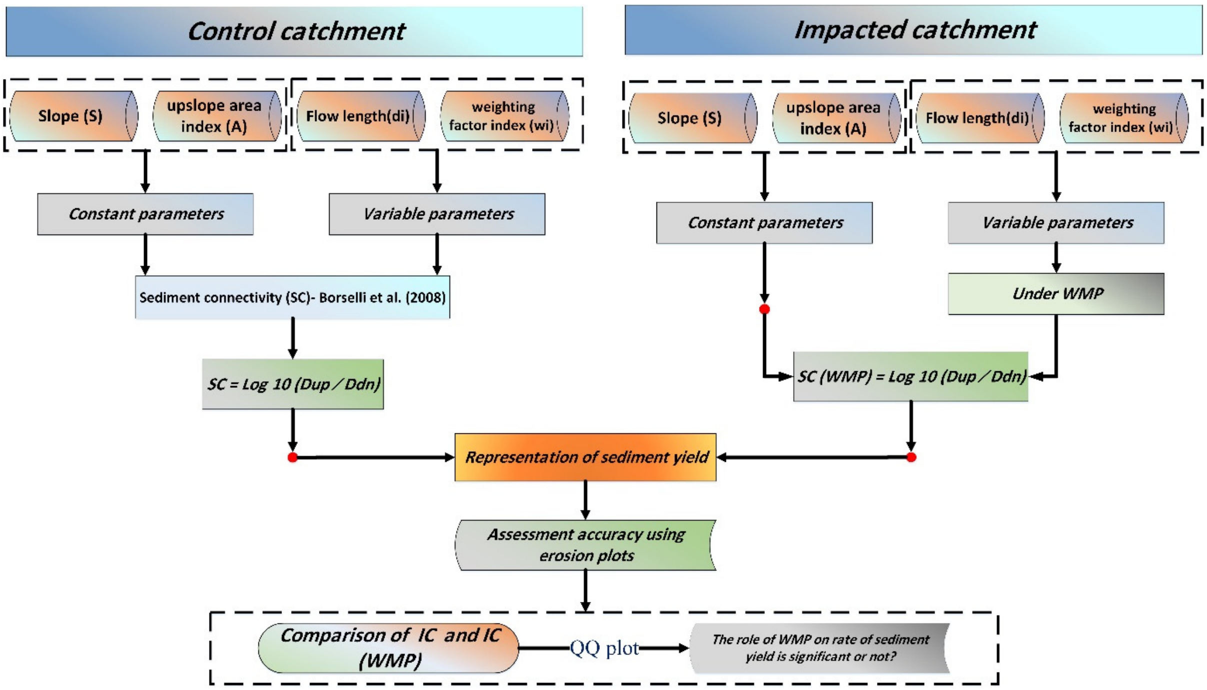

Figure 2. Flowchart of the proposed methodology [23].

3. Results

Results from our analysis of SC patterns within the catchment were strongly determined by the impedance weighting factor. Therefore, since there were no WMP in the control catchment, only the variables of the floodplain's bare soil (n_b), degree of surface irregularity (n_1), and the amount of vegetation (n_4) were considered for the calculation of the impedance weighting factor. Regarding the remaining variables of SC, i.e., slope and upslope contributing area, they were calculated based on the high-resolution digital elevation model by resolution of 2×2 m. The statistical features of the calculated map of SC for the control catchment showed a mean value of -3.85 (0.68 standard deviations) at the catchment scale with a range of values of 6.18. As could be expected, most connected areas of sediment are related to northern hill slopes (surface slopes in the northern hemisphere). In contrast, the lowest values were observed in southern hillslopes and valleys (the valleys are mainly devoted to the establishment of gardens) (Figure 3). Hillslopes are the key landscape features responsible for the water availability on land. Valley bottoms are wetter than hilltops, and surface slopes are warmer and drier than shaded ones [56–58]. Due to this hydrologic organization, there are systematic differences in soil and vegetation between valleys and hilltops and between sunny and shady slopes. Therefore, these patterns are fundamental to understanding the structures and functions of water and terrestrial ecosystems [59–61]. The process of modeling SC in an impacted catchment is similar to that in a control catchment, with the difference that this catchment is under exclosure, pit-seeding, and seeding practices. It is expected that with these practices, some of the parameters would be changed. As for control catchments, the distribution of sediment connectivity in impacted catchments follows a normal distribution with a mean value of −3.94 (0.61 standard deviations) at the catchment scale and a range of values of 7.39. Table 1 summarizes the main statistics of SC in the impacted and control catchments. As in the control catchment, most areas that are not connected are on the northern and southern hillslopes in this watershed.

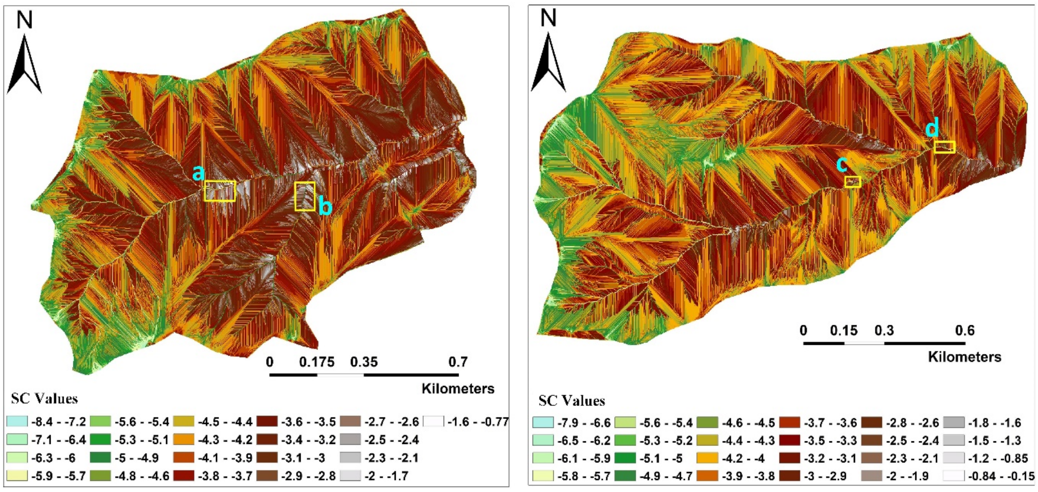

Figure 3. Map and histogram of SC values.

Table 1. Statistical description of the sub-watersheds.

	Statistical Properties				
	Min	**Max**	**Average**	**STD**	**Range Difference**
Impact catchment	−7.19	−0.15	−3.94	0.61	7.04
Control catchment	−8.4	−1.7	−3.85	0.68	6.7

Regarding the assessment accuracy of calculated SC maps for both catchments, it can be said that the average SC of the plots coincides with the sediment yields measured in the plots (Table 2). Figure 4 confirms a close spatial relationship between the SC map and field observations.

Table 2. Comparison of SC values with erosion plot data.

	No. Plot	**Coordinate System (x/y)**	**Data (Rainfall (mm))**	**Rate of Sediment (ton/ha)**	**Average Sediment Rate (ton/ha)**	**Data (Rainfall (mm))**	**Rate of Sedi-ment (ton/ha)**	**Average Sediment Rate (ton/ha)**	**SC Values (Equation (1))**
Control catchment	1	48° 42′ 4/5″ and 34° 42′ 15/1″	15 April 2015 (42 mm)	0.00544	0.00622	20 April 2016 (56.6)	0.00029	0.00746	−3.74
				0.00804			0.00809		
				0.00519			0.01400		
	2	48° 42′ 3″ and 34° 42′ 9.7″		0.00671	0.00890		0.00902	0.00718	−2.86
				0.00739			0.00572		
				0.01260			0.00681		
	3	48° 41′ 59/4″ and 34° 42′ 12/4″		0.01640	0.00926		0.01210	0.00773	−3.38
				0.00490			0.00840		
				0.00840			0.00210		

Table 2. *Cont.*

	No. Plot	Coordinate System (x/y)	Data (Rainfall (mm))	Rate of Sediment (ton/ha)	Average Sediment Rate (ton/ha)	Data (Rainfall (mm))	Rate of Sediment (ton/ha)	Average Sediment Rate (ton/ha)	SC Values (Equation (1))
Impacted catchment	4	48° 41′ 51/6″ and 34° 41′ 43″	15 April 2015 (42 mm)	0.00159	0.00306	20 April 2016 (56.6)	0.00039	0.00532	−4.50
				0.00292			0.00817		
				0.00466			0.00739		
	5	48° 41′ 46/2″ and 34° 41′38/3″		0.00501	0.00365		0.00379	0.00542	−3.85
				0.00495			0.00513		
				0.00099			0.00735		
	6	48° 41′ 40/1″ and 34° 41′ 36/8″		0.00385	0.00572		0.01070	0.00707	−3.89
				0.00490			0.00840		
				0.00840			0.00210		

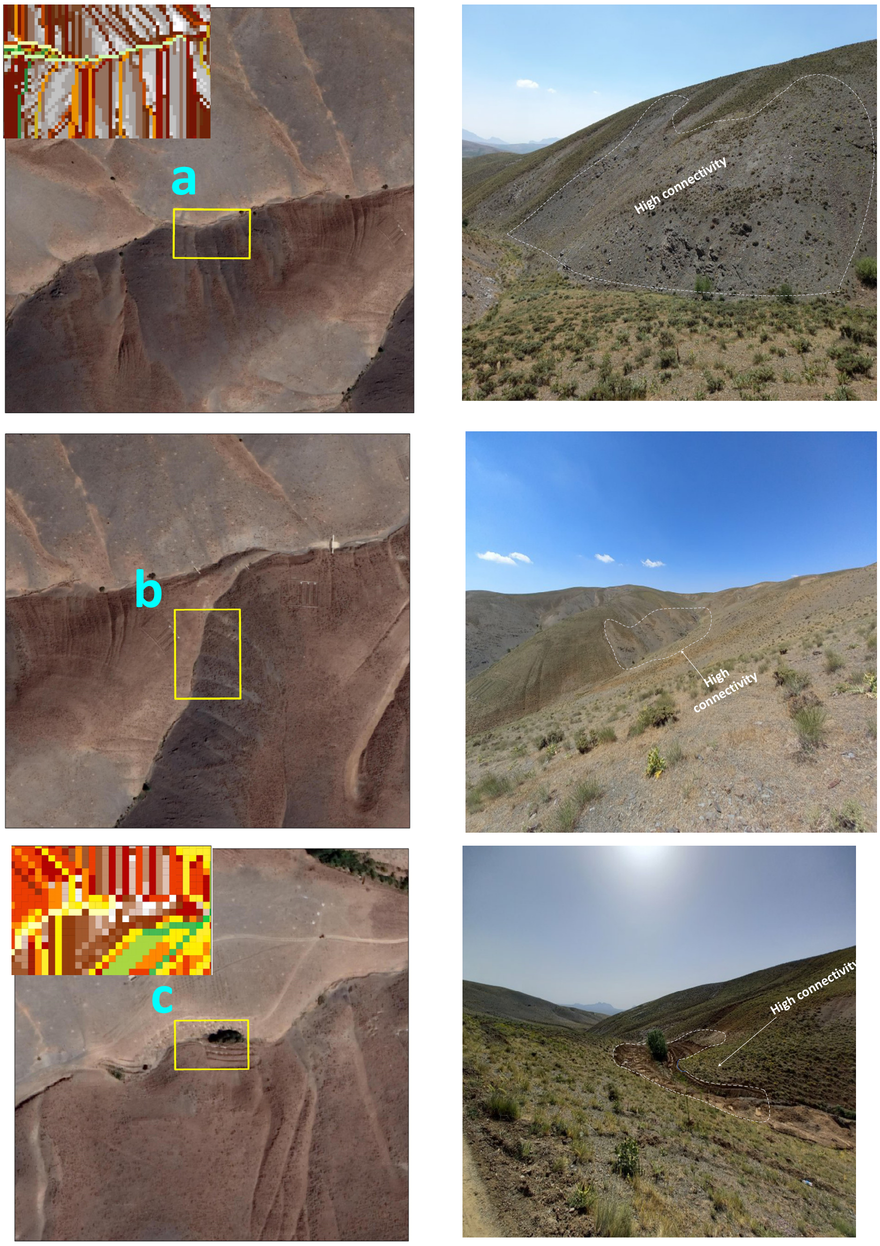

Figure 4. *Cont.*

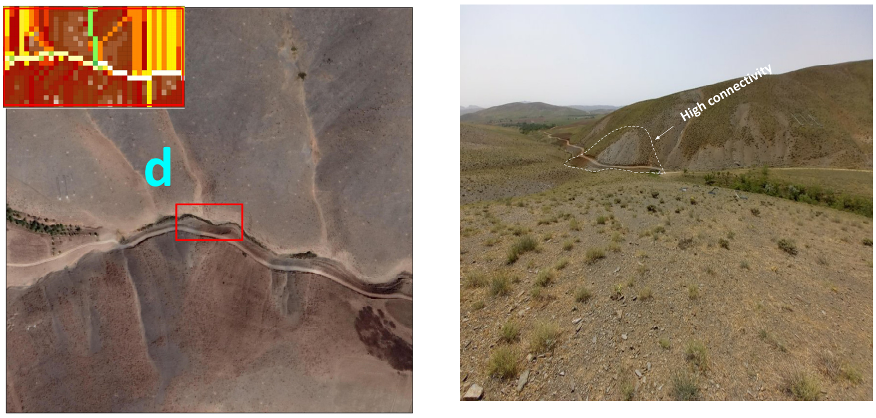

Figure 4. Spatial relation between SC map and field observations (the letters of a, b, c and d refer to previous figure).

4. Discussion

After the assessment of the accuracy of calculated SC for impacted and control catchments, we used the quantile-quantile plot (Q-Q plot) (Black line) to compare their statistical distribution of SC and consequently to provide an overview of the spatial distribution of SC, which indicates the role of WMP on SC (Figure 5).

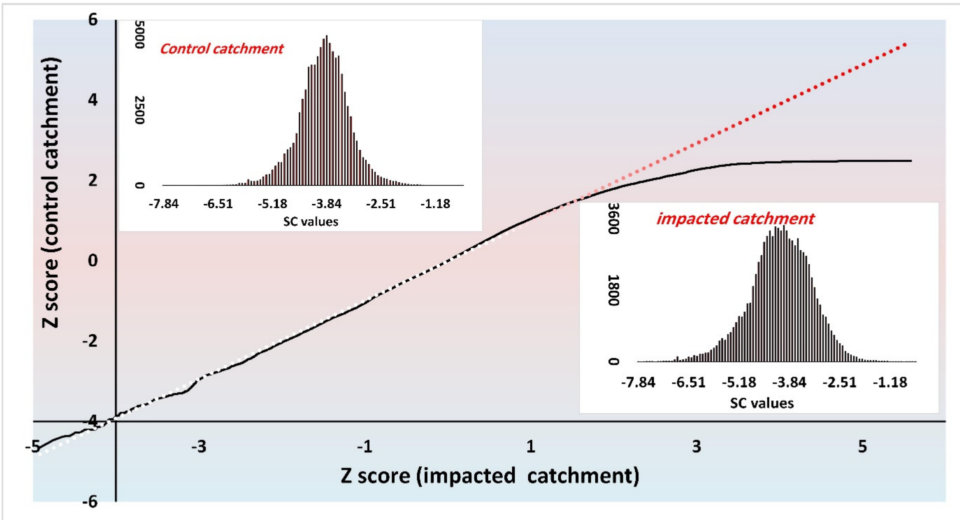

Figure 5. Q-Q plot comparing the distribution of the SC between impacted and control catchments.

In this figure, the z-score of the control catchment and the z-score of the impacted catchment have been evenly aligned on the first and middle of the reference line (dot point line), which are related to low and middle values of SC, highlighting that the spatial distribution of the calculated SC for the two catchments are from a common distribution. Therefore, it can be argued that there is a strong similarity between the catchments. The similarity in SC distribution reflects that the accomplished biological practices did not play a significant role in reducing the SC rate (i.e., the sediment yield rate). Two main reasons can be used as an explanation for this similarity. The first reason is related to the geographical location of the desired paired-wise watershed. In pair-wise watersheds, only the impacted watershed is under exclosure. Still, in the current study, the desired paired watershed is very far from the human communities and most of the residents of the surrounding rural areas (especially young people) due to lifestyle changes, natural factors, welfare and cultural factors, economic factors, and security factors mainly concentrated near urban areas, such as Hamadan and Malayer city. Therefore, the control watershed, as the impacted watershed, experiences conditions such as exclosure due to these factors.

The control watershed is grazed by livestock from some rural communities in some cases. Still, this type of grazing is a conservation grazing controlled by the General Department of Natural Resources of Hamadan Province. Conservation grazing increases the biodiversity of natural or semi-natural grasslands, heathlands, wood pastures, wetlands, and many other habitats. Consequently, this phenomenon reduces the effect of some natural hazard events such as flooding, erosion, and sediment yield. The second reason is related to post-control actions through the impacted watershed. As mentioned in Section 2.1, the impacted watershed is under seeding, pit-seeding, and exclosure. According to Iran's technical regulations of rangeland management (https://www.bhrc.ac.ir/Portals/8/PropertyAgent/1567/Files/1784/Code422.pdf, accessed on 22 May 2008), in arid and semiarid regions, much of the success of biological practices depends on the annual rainfall, which must be nearly 200 mm; thus, in years of severe drought, rangeland irrigation should be performed manually. In recent years, Hamedan province has experienced an unprecedented drought compared to some years ago (https://www.isna.ir/service/province/hamedan, accessed on 22 May 2008). As a result, the relevant authorities should have irrigated the cultivated plants in the study area. As they did not, all of the plants withered.

The divergence at the upper end of the reference line, which is related to lower values of SC, will happen when the impacted and control watersheds are different from each other. Since the impacted and control watersheds have nearly similar morphometric and soil features; therefore, this divergence mainly is due to the effect of the role of performed WMP in the case study.

Llena et al. [33] investigated SC as a raster-based method to indicate the change in sediment dynamics as a result of terracing, which is mostly used in WMPs in mountain environments. The results of this study showed that terracing by increasing flat areas will reduce the rate of sediment connectivity, but in special places, these practices maybe will be associated with topographic convergence, which may increase the rate of SC.

Zhao et al. [59] in a novel research, paid to optimize WMPs to reduce sediment loads induced forest roads, entering their case study. To do this, the authors analyzed the spatial relationship between forest roads and streams, presented the spatial distribution of sediment connectivity by integrating the forest roads into the calculation of the SC, determined how sediment connectivity would respond to additional WMPs through simulating scenarios, and used these data to optimize the WMPs so they would intercept the greatest sediment loads.

5. Conclusions

Soil erosion and sediment yield are one of the most important challenges in the implementation of development projects. WMP can be used as a measure to reduce adverse consequences of soil erosion and sediment-related problems. In the current study, a meta-analysis of WMP based on the SC index was conducted in the Gonbad watershed as a paired catchment. The comparison of SC of impacted and control catchments shows that performed WMP in impacted catchments did not play a significant role in reducing the SC rate (i.e., the sediment yield rate).

WMP across the world is known as the most appropriate approach to ensure the preservation, conservation, and sustainability of all land-based resources and for improving the living conditions of the people in watersheds. Thus, in this study, we concluded that in order to successfully reach the WMP apart from the social-economic issues, kind, age, and optimal site selection of WMP, it is dependent on other reasons, such as land use intensity/stationary and post-management operations for monitoring WMP.

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