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A Remote Sensing and GIS Approach for Prioritization of Wadi Shueib Mini-Watersheds (Central Jordan) Based on Morphometric and Soil Erosion Susceptibility Analysis

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Abstract

Recently watershed prioritization has become a pragmatic approach for watershed management and natural resources development. Wadi Shueib is a Jordan Rift valley and covers an area of 177.8 km^2. The upper catchment is of dry Mediterranean climate, whereas the lower part is arid. The drainage network is sub-dendritic pattern, with a trellis pattern developed due to the influence of W. Shueib structure. Fourteen mini-watersheds were delineated and designated as (MW 1 to MW 14) for prioritization purposes. Morphometric analysis, and soil erosion susceptibility analysis were conducted, and their values were calculated for each mini-watersheds. Based on value/relationship with erodibility, different prioritization ranks were ascribed following the computation of compound factors. Based on morphometric and soil erosion susceptibility analysis, and the resultant ranks, the mini-watersheds have been classified into four categories in relation to their priority for soil conservation measures: very high, high, moderate, and low. It is found that 64.3% of the 3rd order mini-watersheds are classified in the categories of very high and high priority. Based on soil erosion susceptibility analysis, three mini-watersheds are of very high priority and three are of high priority. The integration of morphometric and soil erosion susceptibility methods shows that mini-watersheds no.2 and no.3 are common mini-watersheds, and can be classified in the class of moderate and low priority respectively. By contrast, two mini-watersheds (no.8 and no.13) are categorized in the class of high priority based on morphometric analysis, and are classified in the category of very high priority based on soil erosion susceptibility analysis. Similarly, mini-watershed no.14 can be placed in the category of very high priority based on morphometric analysis, and ranks in the category of high priority based on soil erosion susceptibility analysis. With reference to the integration of the two methods of prioritization, it can be con-

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cluded that most of the mini-watersheds can be categorized in the classes moderate, high, and very high priority. Consequently, the entire W. Shueib watershed must be prioritized for soil and water conservation to ensure future sustainable agriculture and development of natural resources.

Keywords

Morphometry, Soil Erosion Susceptibility, Prioritization of Watersheds, Compound Factor, W. Shueib, Jordan

1. Introduction

Soil erosion is considered a major problem in the rainfed highlands of Jordan. Erosion of the top soil leads to continuous land degradation and decline of soil quality and productivity. Future sustainable agriculture is therefore seriously threatened by accelerated soil erosion. The most significant causes responsible for high soil erosion rates have been: rapid population growth (2.8% per year), historical and present misuse of the land, land cover changes since 1950s, traditional cultivation and cropping system practices, deforestation and overgrazing, poor conservation measures, and land fragmentation.

Several studies/reports on soil erosion and conservation were carried out on the highlands of Jordan during the 1960s. Soil erosion loss due to surface water catchments east of the Rift amounts to 1.328 million tons year^{-1}, which means, 0.14 cm of the top soil is eroded annually [1] [2]. Similarly, qualitative surveys on soil conservation are conducted in the southern highlands [3], Wadi Hasa [4], and northern Jordan with special reference to Wadi Ziqlab [5], and soil conservation surveys for Wadi Shueib and Wadi Kufrein [6]. The final results of these surveys are restricted to mapping of geomorphological soil erosion features, slope categories (%), detailed soil characteristics and distribution. A conventional land capability map illustrates land capability classes, and a map shows the location of proposed soil conservation structures only for Wadi Ziqlab. In light of the predominant high, very high, and extremely high soil erosion rates, specific geomorphic/terrain units, and mini-watersheds, should be prioritized for conservation practices [7]-[10]. Watersheds however, are considered fundamental geomorphic and hydrologic areal units for watershed management. It enables surface runoff to a defined channel, ravine, stream or river at a particular point [11]. Watersheds also constitute the surface area drained by one or several given water courses, and represent a fluvial erosional land component, where land and water resources interact in a perceivable form [12]. Moreover, the drainage basin has been considered an ideal unit for watershed management and sustainable development of natural resources. Watershed management in this context implies the process of formulating and executing a course of intervention in the watershed targeted to appropriate utilization of land, soil, forest, and water resources in a watershed. This process seeks optimum exploitation with minimum hazard to environmental resources including people who live across the watershed [12]-[14].

Prioritization of sub-watersheds for soil and water conservation is conducted recently in several areas. Such studies confirm the role of geographic information system (GIS), remote sensing (RS), and morphometric analysis as efficient tools in ranking different sub-watersheds according to the order in which they have to be taken for treatment and for soil conservation measures [15]. At an early stage of morphometric analysis application in prioritization of sub-watersheds, Biswas *et al*. [12] employ ten morphometric parameters: three of them are basin geometric parameters such as area (km^2), perimeter (km), and basin length (km); four linear parameters (bifurcation ratio, drainage density (km/km^2), stream frequency (no/km^2), and texture ratio). Similarly, Pandey *et al*. [16] utilize six morphometric parameters: two linear (drainage) parameters (bifurcation ratio, drainage density (km/km^2); two shape parameters (circularity ratio, elongation ration); and two relief (steepness) parameters (ruggedness number, and relief ratio). Later, elaboration on morphometric application with respect to prioritization of watersheds is carried out by several researchers [17]-[22]. Ten linear and shape morphometric parameters in relation to erodibility have been adopted: five linear parameters(bifurcation ratio, drainage density (km/km^2), texture ration, length of overland flow, and stream frequency (km/km^2), texture ration, length of overland flow, and stream frequency (km/km^2); and five shape parameters (compactness coefficient, circularity ratio, elongation ratio, shape factor, and form factor). Such parameters are aimed to identify prioritized sub-watersheds for conservation on more consistent bases.

Watersheds are prioritized using different factors such as: morphometry, land use/land cover, estimated soil erosion loss (*i.e.* USLE or RUSLE models), Sediment Yield Index (SYI) model, or a combination of these methods. Recently, several studies on prioritization have been accomplished in relation to sub-watersheds using morphometric analysis, sediment yield index (SYI), and sediment product rate (SPR) [12] [15] [17]. Other studies employed morphometric analysis and land use/land cover parameters [19] [20]. By contrast, one investigation utilized morphometric indices and soil loss estimation based on the USLE model [18] in Bago River Basin, Myanmar. Chaudhary and Sharma [23], and Patel *et al*. [21] conducted prioritization studies based only on morphometric analysis. Abdul Rahaman *et al*. [24] adopted the Fuzzy Analytical Hierarchy process in combination with morphometric analysis to carry out a prioritization study in Tamil Nadu, India. However, the prioritization concept is found to be very helpful for understanding the morphology and fluvial characteristics of individual watersheds, and for designing efficient water harvesting structures across a watershed [21].

Remote sensing and GIS techniques are the most powerful tools for watershed development, management, and prioritization of sub-watersheds for soil and water conservation. The quantitative analysis of drainage basins is also considered a basic technique for watershed characterization and geomorphometric analysis of drainage basins and stream networks. Morphometic analysis can be implemented by measuring basic, linear and shape parameters of drainage networks and contributing ground slopes [12] [20] [21]. Computation of morphometric parameters can be carried out using an appropriate DEM, GIS software, and formulas developed for this purpose. The objective of the present study is to prioritize fourteen 3rd order mini-watersheds based on morphometric analysis and soil erosion susceptibility methods using remote sensing and GIS. Priority maps for mini-watersheds can be generated based on one or two methods, then, a third priority map can be developed by integrating the results achieved from the two methods of prioritization. These results provide significant information which can assist decision makers in formulating more effective soil and water conservation plans for the W. Shueib watershed in the future.

2. The Study Area

The Wadi Shueib watershed (Central Jordan) lies between the latitudes 31˚50' to 32˚02'N, and longitude 35˚35' to 35˚50'E (**Figure 1**), and covers an area of 177.8 km^2. The maximum basin length is 23.48 km, and the basin relief (B_h) is 1347 m.

2.1. Geology and Geomorphology

Four lithological units are exposed across the watershed. The lower Cretaceous Kurnub sandstone is dominated

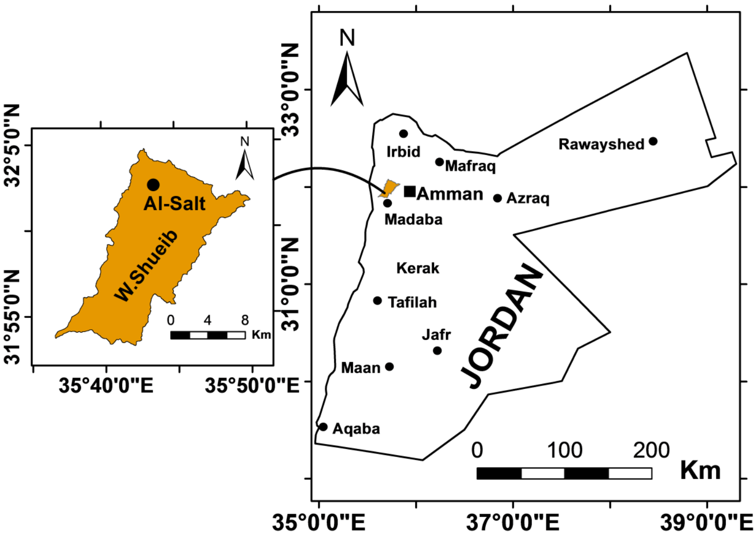

Figure 1. The study area.

by silty and clayey sandstone in the upper part, whereas varicoloured shaley sandstone characterizes the lower part [25]. The Kurnub sandstone is overlain by two lithological units of Upper Cretaceous age: the nodular limestone unit (the marly-clay unit) which is predominantly marls and clays interbedded with marly limestones, limestones, nodular limestone, and dolomites. The echinoidal limestone unit, or the marly-limestone unit consists of limestones, dolomitic limestones, marl, sandy limestones, marly limestones, and chert nodules. This unit is exposed at the crest of landslide complexes and rock bluffs. The fourth lithological unit is comprised of the Eocene-Senonian dolomites which are exposed in the upper part of the watershed. Chalky marls, chalk, limestone, shales, clays and phosphatic beds (much of their thickness are silicified) are also present in the catchment. Wadi Shueib is part of a major compressional belt termed locally “Wadi Shueib Structure” [26] [27]. It extends from Shuneh town (at the Ghor) and runs along the eastern flank of Wadi Shueib in a NNE direction to pinch out south of Jerash City at the Zerqa River. The structure consists of several highly folded synclines and anticlines partially overturned to the west. In several localities, the structure is heavily deformed by a set of faults and joints of different trends. When these joints are combined with bedding status they probably contribute to the most unstable conditions. The Wadi Shueib longitudinal profile displays prominent irregularities, which probably represent some form of rejuvenation points associated with the formation of the Jordan Rift. The average slope of the longitudinal profile is 2.76˚. The northeastern reaches of the catchment between 800 and 1000 m (a.s.l), and the interfluve ridges are characterized by broad level areas and gentle slopes, which possibly represent the remnants of Miocene-Pliocene erosion surface [28] [29]. The remainder of the watershed is characterized by steep convex slopes in the upper reaches, and deeply incised gorges in the lower section. Sharp breaks exists on the Wadi cross profiles as a result of lithological variation and rejuvenation activity [30]. The presence of old landslide complexes, and active landslides reveals the role of: (1) tectonic activity and uplifting of the scarp shoulder during the Miocene and Pleistocene tectonics; (2) progressive river incision and rejuvenation activity as a result of recurrent lowering of the base level (the Jordan Rift), and; (3) seasonal flooding and repetitive heavy rainstorms, and remarkable deformation of slopes. Thus, the watershed is highly susceptible to soil erosion and landsliding [28] [31]-[33].

2.2. Climate

Wadi Shueib is classified as “dry Mediterranean” in the upper catchment and arid in the lower part (the Ghor close to the Dead Sea). Mean annual rainfall ranges from 639 mm at Al-Salt city (796 m a.s.l) to 180 mm at Shunneh town (-230 m b.s.l). Most of the catchment highland areas have 20 to 50 rainy days/year, while the lower parts of the watershed have 10 to 30 rainy days/year. The amount of rainfall on any rainy day varies from 0.1 mm to maximum of 150 mm [6]. Several days can receive precipitation ranging between 20 - 80 mm. This indicates that rainfall storms of high intense daily rainfalls are common in Wadi Shueib, thus, the watershed is considered of high susceptibility to soil erosion and landsliding. Such conditions emphasize the need for prioritization of mini-watersheds for soil and water conservation. Rainfall is concentrated in winter during the cold season from October to March.

2.3. Soils

Atkinson *et al*. [6] distinguish six soil types in Wadi Shueib. The most widely distributed is the terra rossa. This type has a high internal variability, ranging from cultivated phases, often quite thin to mature terra rossa profile under woodland. Texture is predominatly heavy, ranging from 50 to 70 per cent clay, and silt content varies from 20 to 60 per cent. Sand content is consistently low. Sandstone soil developed on the Kurnub sandstone. Where cultivated, it shows more compacted sub-soils and more distinctive ploughed horizons than their uncultivated counterpart, but of sandy loam texture. The siliceous and cherty rock faces give rise to Brown stony soil, especially on the eastern part of the watershed. Such soil is characterized by very heavy stone content, and the texture ranges from clay loams to silty clays. Alluvial and bench soils are exposed along the Wadi bottom, and more commonly, on structural and rejuvenated terraces along the valley side slopes. In areas of calcareous rocks, with rolling and gentle sloping topography, continuous soil wash and accelerated erosion has led to the accumulation of soil materials in depressional areas to make infill soils which provide good arable land, being cropped for cerals or field crops. Slope soil can be divided into red brown and yellow brown soils. Slope soils are derived largely from terra rossa and brown soil materials, and thus resemble them in properties of texture, structure and color.

3. Materials and Methodology

Topographic maps with scale 1:50000 (20 m contour interval) of Wadi Shueib were obtained from the Royal Jordanian National Geographic Centre (Amman). The topo sheets were then scanned and georeferenced using Arc GIS 10.1 software, then converted to WGS-1984, zone 36˚N projection system. Contours and drainage were digitized from the registered topo sheets, and the catchments were divided into fourteen 3rd order mini-watersheds, and assigned as (MW1-MW14) (**Figure 2**). The drainage network of W. Shueib, and the mini-watersheds were generated using ASTER DEM (30 m resolution), and digitized using Arc GIS 10.1. Stream order was assigned following the stream ordering system developed by Strahler [34] [35]. The W. Shueib watershed was found to be of the 5th order. Basic, linear, and shape morphometric parameters for the entire W. Shueib watershed and the drainage networks related to each the fourteen mini-watersheds were measured and calculated using GIS software, and the mathematical equations elaborated by Horton [36], Strahler [34] [35], Schumm [37], Miller [38], and Nooka Ratnam *et al*. [17] (**Table 1**).

The quantitative approach developed by van Zuidam and van Zuidam-Cancelado [39] [40] for a soil erosion susceptibility survey (**Figure 3**) was employed to compile a map illustrating soil erosion susceptibility classes for the entire W. Shueib, and then digitized using Arc GIS 10.1. Morphometric analysis of linear and shape parameters, and soil erosion susceptibility parameters were employed separately for prioritization of the mini-watersheds, and a priority map was produced based on each method. Then, a third priority map was generated by integrating the results obtained from both methods (the two maps) in order to assess the correlation if any between the two generated maps, and to explore the common priority that may found between the mini-watersheds.

4. Results and Discussions

4.1. Morphometric Analysis

Quantitative analysis of W. Shueib and the fourteen mini-watersheds was performed to assess the characteristics and properties of the drainage networks. Twenty-five morphometric parameters which represent basic, linear, areal, shape and relief aspects of W. Shueib were considered for analysis to characterize the entire watershed (**Table 2**). Whereas, five basic parameters, five linear parameters, and five shape parameters were computed for the mini-watersheds to prioritize them for soil conservation. The dominated drainage pattern is the trellis type, which is indicative of structural control on drainage, where the mean bifurcation ratio (R_{bm}) for the entire watershed is 4.6 (**Table 2**). Stream ordering for the main watershed and the mini-watersheds has been ranked

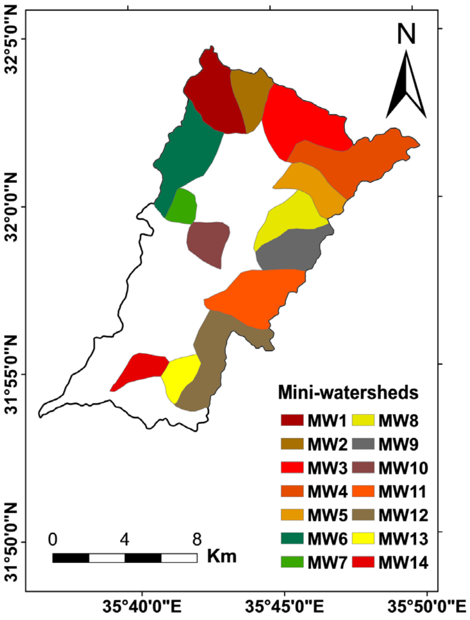

Figure 2. 3rd order mini-watersheds.

Table 1. Computation of basic, linear and shape morphometric parameters.

Morphometric Parameters	Formula	References
Basic Parameters		
Area of Basin (A)	Plan area of the watershed (km^2) GIS Software analysis	[36]
Perimeter of Basin (P)	Perimeter of watershed (km)	[36]
Stream Order (u)	Hierarchical rank	[36]
Basin Length (L_b)	Length of basin (km)/GIS software analysis	[34] [35] [41]
	$L_b = 1.321 \times A^{0.568a}$	[17]
Stream Length (L_u)	Length of the stream (km)	[36]
Linear Parameters		
Bifurcation Ratio (R_b)	$Rb = N_u/N_u + 1$, where	[37]
	$N_u + 1$ = no. of segments of the next higher order	
Drainage Density (D_d) (km/km^2)	$D_d = L_u/A$, Where	
	L_u + total stream length of all orders (km)	[36]
	A = area of the watershed (km^2)	
Stream Frequency(F_u) (no./km^2)	$F_u = N_u/A$, where	
	N_u = total no. of steams of all orders	[36]
	A = area of the basin(km^2)	
Texture Ratio (T) (no./km^2)	$T = N_u/P$, where	
	N_u = total no. of streams of all orders	[36]
	P = perimeter (km)	
Length of Overland Flow (km) L_o	L_o = ½ Dd, where	[36]
	D_d = drainage density	
Shape parameters		
Form Factor (R_f)	$R_f = A/L_b^2$, where	
	A = area of the basin (km^2)	[36]
	L_b = basin length (km)	
Shape Factor (B_s)	$B_s = L_b^2/A$, where	
	L_b = basin length (km)	[17]
	A = area of the basin (km^2)	
Elongation Ratio (R_e)	$Re = 1.128\ \sqrt{A / Lb}$, where,	
	A = area of the basin (km^2)	[37]
	L_b = basin length (km)	
Compactness Coefficient (C_c)	$Cc = \dfrac{P}{2\sqrt{\pi A}}$, where	[36]
	P = perimeter of the basin (km)	
	A = area of the basin (km^2)	
Circularity Ratio (R_c)	R_c = 4 × п × A/P^2, where п = 3.14	
	A = area of the basin (km^2)	[38]
	P = perimeter (km)	

according to Strahler's method of hierarchical system [41]. Based on drainage order, W. Shueib catchment is classified as a fifth-order basin (**Figure 4**) with an area of 177.8 km^2, 23.5 km of length, and perimeter of 85.2 km. The total number of streams (Nu) is 345, and the first-order streams account for 79.9% of the total number of streams in the entire watershed.

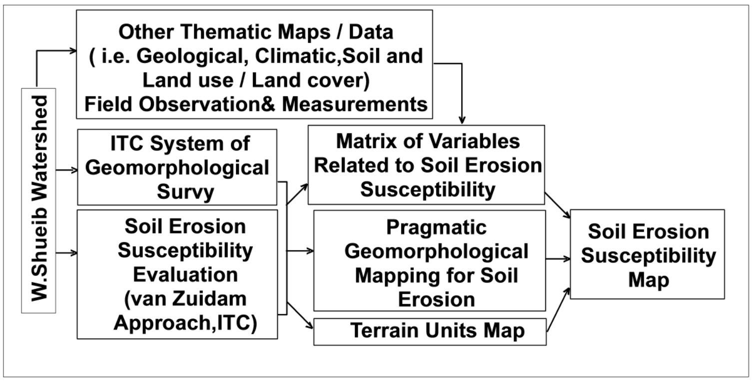

Figure 3. Methodology of soil erosion susceptibility survey.

Table 2. Morphometric parameters of W. Shueib.

Par. No.	Parameters	Stream Order				
1	Stream order (u) (5)	I	II	III	IV	V
2	No. of streams order (Total) (N_u) (345)	269	56	14	5	1
3	Stream length (L_u) (km) (268.925)	123.581	64.805	36.404	25.056	19.079
4	Mean stream length (L_{sm}) (km) (0.779)	0.459	1.157	2.600	5.011	19.079
5	Stream length ratio (R_L)		0.524 II/I	0.561 III/II	0.688 IV/III	0.761 V/Iv
6	Bifurcation ratio (R_b)	4.803 I/II	4 II/III	2.8 III/IV	5 IV/V	
7	Mean bifurcation ratio (R_{bm})	4.581				
8	Basin perimeter (P) (km)	85.190				
9	Basin length (L_b)	23.480				
10	Basin area (A) (km^2)	177.800				
11	Basin relief (B_h) (m)	1347				
12	Relief ratio (R_r)	0.057				
13	Elongation ratio (R_e)	0.640				
14	Circularity ratio (R_c)	0.307				
15	Lemniscate ratio (K)	0.775				
16	Drainage density (D_d) (km/km^2)	1.512				
17	Stream frequency (F_u)	1.940				
18	Form factor (R_f)	0.322				
19	Shape factor (B_s)	3.100				
20	Texture ratio (T)	4.049				
21	Dissection index (D_{Is})	1.230				
22	Ruggedness number (R_n)	2.036				
23	Drainage intensity (D_i)	1.283				
24	Length of overland flow (L_o) (Km)	0.756				
25	Hypsometric integral (H_i)	0.715				

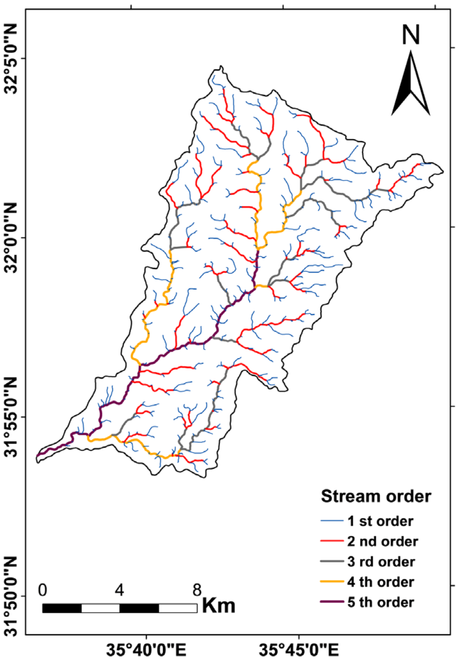

Figure 4. Stream order of W. Shueib.

4.1.1. Basic Parameters

Basic parameters were computed for the fourteen mini-watersheds area: the area (A), perimeter (P), stream order (u), basin length (L_b), and stream length (L) (**Table 3**).

1) Mini-watershed area (A) and perimeter (P)

The drainage area is considered the most significant hydrological characteristics of a watershed. It reflects the volume of water that can be generated from precipitation.

The present study shows that mini-watershed no.4 covers the maximum area of 12.64 km^2, while mini-watershed no.7 has a minimum area of 2.45 km^2. The basin perimeter represents the length of the line that demarcates the surface divide of the mini-watershed. The maximum and minimum values are 20.61 km for mini-watershed no.12, and 6.07 km for mini-watershed no.7.

2) Stream order (u)

The stream order parameter was elaborated by Horton [36] and Strahler [34] [35] [41] to describe the drainage network in a quantitative manner. The first order stream has no tributary, and its flow depends totally on the surface overland flow to it. Similarly, the second-order stream is formed by the junction of the two first-order streams and thus, has a higher surface flow and the third-order streams receive flow from two second-order streams [14]. In the present case study, all selected fourteen mini-watersheds are of third-order, and the number of first-order streams (N_1) varies from one watershed to another. It ranges from 21 first-order streams (MW no.4) to 4 first-order streams (MW no.7). By contrast, the number of first-order streams for the eastern part of W. Shueib watershed is higher than the other parts of the catchment. The number ranges here between 13 to 21 streams. Similarly, the number of streams (N_u) for each mini-watershed range from 26 to 7. It is expected therefore, that mini-watersheds on the eastern flank of W. Shueib receive a higher surface flow than other mini-watersheds. Furthermore, the W. Shueib structure extends spatially along the eastern flank of the Wadi. Here, deformation and rock weakness are remarkable compared to other parts of the watershed, where several springs issue along the incised basal slopes. Thus, it is expected that soil erosion susceptibility and shallow landslide activity are higher on this part of the catchment.

3) Total length of streams (L_u)

The number of streams of various orders for each mini-watershed was counted and their lengths measured (**Table 3**). The first-order stream has no tributary and its flow depends totally on the surface overland flow connected with it. Similarly, the second-order stream is formed by the junction of two first-order streams and as such has a higher surface flow, and the third-order streams receive flow from two second-order streams [21].

Table 3. Morphometric parameters of the fourteen mini-watersheds.

Mini-Basin	A (km^2)	P (km)	Lb (km)	Lu (km)	N_u	N1	R_b	D_d (km/km^2)	F_u (Nu/km^2)	T	L_o	R_f	B_s	R_e	C_c	R_c
1	9.13	13.59	5.46	15.55	18	13	2.92	1.70	1.97	0.95	0.85	0.30	3.26	0.62	1.27	0.62
2	5.17	9.98	3.69	7.32	8	5	2.35	1.42	1.55	0.50	0.71	0.38	2.63	0.69	1.24	0.65
3	12.05	15.84	4.65	18.14	18	13	3.42	1.51	1.49	0.82	0.76	0.56	1.79	0.84	1.28	0.60
4	12.64	19.40	7.35	18.87	26	21	5.04	1.49	2.06	1.08	0.75	0.23	4.27	0.53	1.54	0.43
5	5.65	11.24	4.49	8.41	15	12	5.29	1.48	2.65	1.07	0.74	0.28	3.56	0.60	1.33	0.56
6	11.07	17.04	6.26	17.45	19	15	4.63	1.57	1.71	0.88	0.79	0.28	3.53	0.60	1.44	0.47
7	2.45	6.07	2.08	3.56	7	4	2.00	1.45	2.85	0.66	0.73	0.56	1.76	0.85	1.09	0.84
8	5.99	11.37	4.32	10.24	14	10	3.25	1.71	2.34	0.88	0.86	0.32	3.11	0.63	1.33	0.58
9	6.98	11.55	4.47	11.81	15	11	3.51	1.69	2.15	0.95	0.85	0.34	2.86	0.66	1.23	0.66
10	4.41	8.23	2.80	6.41	11	8	3.53	1.45	2..49	0.97	0.73	0.56	1.77	0.85	1.10	0.82
11	10.91	14.88	5.87	15.01	19	16	7.61	1.38	1.74	1.08	0.69	0.32	3.15	0.63	1.27	0.62
12	10.71	20.61	7.95	17.08	25	20	4.82	1.59	2.33	0.97	0.80	0.17	5.90	0.46	1.77	0.32
13	3.45	7.64	3.04	7.02	10	7	3.12	2.03	2.90	0.92	1.01	0.37	2.67	0.68	1.16	0.74
14	3.29	8.52	3.63	5.10	8	5	2.35	1.55	2.43	0.59	0.78	0.25	4.01	0.56	1.32	0.57

All mini-watersheds are of 3rd order streams, but they vary in terms of the total number of first-order streams (N_1), and the total stream length of all orders. Among the fourteen mini-watersheds, MW no. 4, 12, 11, and 6 have 21, 20, 16, and 15 first-order streams respectively. Similarly, all these mini-watersheds have relatively the greatest total length of streams (18.87, 17.08, 15.01 and 17.45 km) respectively.

4) Basin length (L_b)

Patel *et al*. [14] stated that the (L_b) parameter is crucial in hydrological computation and increases as the drainage increases and vice versa. It is defined as the distance measured along the main channel from the watershed outlet to the basin divide. Thus, the basin length is measured along the principal flow path, and constitutes a basic input parameter to calculate the major shape parameters. Accordingly, basin length in the fourteen mini-watersheds varies between 2.08 km and 7.95 km (**Table 3**).

4.1.2. Linear Parameters

Linear parameters include bifurcation ratio, drainage density, stream frequency, texture ratio, and length of overland flow.

1) **Bifurcation Ratio (R_b)** is the ratio of the number of the streams of a given order to the number of streams of the next higher order [36]. The bifurcation ratio is introduced by Horton [36] as an index of relief and topographic dissection. Bifurcation ratios vary between 2 for flat or rolling catchments, and 6 for watersheds distorted remarkably by geological structure. On the contrary, low values of R_b are indicative of structurally less disturbed watersheds, or alternatively without any clear distortion of drainage pattern [35]. It is postulated that a small range of variation in R_b values exists between different geomorphic environments, except where geological control prevailes. **Table 3** shows a prominent variation in the bifurcation ratio (R_b) of Wadi Shueib mini-watersheds. Mini-watershed no.7, for example, has a minimum R_b of 2.0, whereas mini-watershed no.11 has maximum ratio of 7.61. The R_b value for the entire W. Shueib is 4.8. It is obvious that the values of R_b are relatively high, especially for the mini-watershed affected largely by Wadi Shueib structure on the eastern part of the watershed.

2) **Drainage Density (D_d)** refers to the closeness of spacing of channels. It is a measure of the total length of streams in a watershed per unit area, and therefore, it is a measure of topographic dissection and runoff potential of the catchment. Thus, D_d parameter has units of reciprocal of length (1/L). A high value of D_d would indicate a relatively high density of streams, high runoff, a quick stream response, and consequently a low infiltration rate. Whereas, low drainage density of a basin implies low runoff and high infiltration [42]. The main morphological factors controlling drainage density are relative relief and slope steepness.

Strahler [35] reported that low D_d occurs when basin relief is high as in the case of W. Shueib(basin relief (B_h) is 1347 m). Other important factors determining D_d are infiltration-capacity of the soil, and initial resistance of terrain against erosion. The poorly drained basins have a drainage density of 2.74, while a well-drained one has a density of 0.73, or one fourth as great [36]. Regardless of the degraded vegetation cover, the D_d values are low, which indicates the presence of highly dissected, steep topography and impervious underlying rock. In this context, the marly-clay unit and the limestone marl unit are exposed in the upper watershed where a series of springs issued. The D_d value for W. Shueib watershed is 1.512, while D_d values for the fourteen mini–watersheds range from 1.38 (MW no.11) to 2.03 (MW no.1) (**Table 3**).

3) **Stream Frequency (F_u)**

Stream frequency (F_u) denotes the ratio of total number of streams (N_u) in a catchment to the catchment area (A). It is recognized as the number of streams per unit of area [36]. F_u values vary from 3.91 to 9.99, depending in this context mainly on the lithology of the catchment. Thus, reflecting the texture of drainage network. The F_u value is positively correlated with D_d values of the watershed, which means that the increase in stream population is connected to that of drainage density [43]. The values of D_d and F_u for small and large drainage basins are not directly comparable because they usually vary with the size of the drainage area. High stream frequency means more percolation with respect to drainage density, and thus, more groundwater potential [44]. The value of stream frequency (F_u) ranges from 1.49 (MW no.3) to 2.9 (MW no.13) (**Table 3**), and the F_u value for W. Shueib catchment is 1.94.

4) **Texture Ratio (T)** refers to the ratio of the total number of streams of first order (N_1) to the perimeter (P) of the basin. It is one of the most significant factor in drainage basins morphometry. Texture ratio depends on the underlying lithology, infiltration capacity, and relief aspect of the terrain [45]. The value of the texture ratio for W. Shueib watershed is 4.05, and for the mini-watersheds ranges from 0.50 to 1.08. Such figures indicate

that the catchment is of moderate runoff.

5) **Length of Overland Flow (L_o)** represents the length of water over the ground before it gets concentrated into definite stream channels, and is equal to half of drainage density [36]. The length of overland flow relates inversely to the average channel slope [14], and is considered one of the most important independent parameters influencing both hydrologic and hydrographic development of drainage basins [36] [45]. The length of overland flow (L_o) for the entire W. Shueib is 0.756, and for the mini-watersheds ranges from 0.69 to 1.01 (**Table 3**).

4.1.3. Shape Parameters

Shape parameters include form factor, shape factor, elongation ration, compactness coefficient (ratio), and circularity ratio.

1) **Form Factor (R_f)** can be defined as the ratio of the area of the basin to the square of the basin length [34]. R_f parameter has been elaborated to predict the intensity of a basin of a defined area. The value of R_f would always be less than 0.79, for a perfectly circular basin [11]. The smaller the value of form factor (<0.45), the more the basin will be elongated. The basins with high form factor are characterized with high peak flow of shorter duration, whereas an elongated sub-basin with a low form factor, indicate a low peak flow of longer duration. The R_f value for W. Shueib is 0.322, and for the fourteen mini-watersheds ranges from 0.17 to 0.56, which denote the dominance of elongated shape for the mini-watersheds, thus characterized by flatter peak flow for longer duration.

2) **Shape Factor (Bs)** represents the square of the basin length to the area of the basin. This morphometric parameter is in inverse proportion to form factor [17] [36]. Shape factor affords a notion regarding the circular character of the catchment. The greater the circular character of the basin, the greater in the fast response of the catchment following a rainfall storm event [46]. The shape factor value of W. Shueib is 3.1, whereas, the fourteen mini-watershed exhibit a range of 1.76 - 5.9 (**Table 3**), which indicates that the elongated shapes dominate the mini watersheds.

3) **Elongation Ratio (R_e)** is the ratio between the diameter of the circle of the same area as presented by the drainage basin to the maximum basin length [37]. Strahler [35] reported that the values of R_e generally vary between 0.6 and 1.0 over a wide range of climatic and geological environments. Values close to 1.0 are characteristic of areas with very low relief, whereas values in the range of 0.6 - 0.8 are representative of catchments described with high relief and steep slopes. The low values of R_e denote that a particular mini-basin is more elongated than others. Where the R_e approaches 1.0, the shape of the drainage basin approaches a circle [37]. It has been argued that a circle basin is more efficient in runoff than an elongated one [47]. Based on R_e values, catchments were grouped into five categories, *i.e.* circular (0.9 - 1.0), oval (0.8 - 0.9), less elongated (0.7 - 0.8), elongated (0.5 - 0.7), and more elongated (<0.5). The elongated ratio of W. Shueib is 0.64, whereas values of R_e for the fourteen mini-watersheds range from 0.46 to 0.85 (**Table 3**), thus, the mini-basins are of less elongated to oval shape.

4) **Compactness Coefficient (C_c)** is also known as the Gravelius index (GI). According to Gravelius [48], the compactness coefficient of a watershed is the ratio of perimeter of watershed to circumference of circular area, which equals the area of the watershed. The C_c is independent of size of the watershed and dependent only on slope [36]. A circular basin yields the shorter time of concentration before peak flow occurs in the basin. $C_c > 1.0$ indicates more deviation from the circular nature [45]. Lower values of this parameter denote more elongation of the basin and less erosion, while higher values indicate less elongation and high erosion. In the present study, the highest value of C_c is 1.77 (MW no.12) (**Table 3**), which means high erosion, whereas the lowest value is 1.09 (MW no.7), which reflects less erosion.

5) **Circularity Ratio (R_c)** refers to the ratio of basin area (A) to the area of circle having the same circumference as the perimeter of the basin [38]. R_c is affected by the length and frequency of the streams, geological structures, land use/land cover, climate, relief, and slope steepness of the watershed. Drainage basins with a range of circularity ratios of 0.4 to 0.5, were described by Miller [38], denoting that they are strongly elongated. High values of R_c indicate young, mature, and old stage of the geomorphic cycle of the watershed [43]. The circularity ratio value (0.44) of the watershed demonstrates Miller's range, which indicates that the watershed is elongated in shape, with low discharge of runoff and high permeability of the subsoil condition. If the circularity in the main watershed is low, then the discharge will be slow as compared to the others, and so the possibility of erosion will be less [14]. The circularity ratio for W. Shueib is 0.307, whereas, R_c values for the present mini-watersheds range from a minimum value of 0.32 (MW no.12) to a maximum value of 0.84 (MW no.7). 50% of

the mini-watersheds have R_c values ranging from 0.60 to 0.85 (**Table 3**), which indicates a high possibility of rapid discharge and active erosion.

4.2. Prioritization of Mini-Watershed Based on Morphometric Analysis

Morphometric analysis was employed successfully for prioritization of watersheds at different scales [12] [14] [15] [17]-[21] [24] [49]-[53] including sub-watersheds, mini-watersheds, and micro-watersheds. For prioritizing watersheds, erosion risk parameters related to linear and shape morphometric attributes were employed [21]. The linear parameters are: bifurcation ratio (R_b), drainage density (D_d), stream frequency (F_u), texture ratio (T), length of overland flow (L_o), and the shape factors which include: form factor (R_f), shape factor (B_s), compactness coefficient (C_c), elongation ratio (R_e), and circularity ratio (R_c). It has been reported that linear parameters have a direct relationship with erodibility. Thus, the highest values of the linear parameter were rated as rank 1, the second highest value as rank 2 and so on [12] [17]. By contrast, the shape parameters have an inverse relation with linear parameters, so that the lower their value, the greater the erodibility [14] [50]. Therefore, the lowest value of shape parameter was rated as rank 1 and second lowest as rank 2 and so on. Compound factor (C_f) was calculated by adding up all the ranks of linear parameters, as well as shape parameters and then dividing by the number of all parameters (which is here 10). From the group of mini-watersheds, highest prioritized rank was assigned to mini-watersheds having the lowest compound factor and vice versa [14].

Finally, all mini-watersheds were grouped into four priority categories based on the range of compound factor(C_f) values [17]:

1) Very high priority (5.0 - 5.9)
2) High priority (6.0 - 6.9)
3) Moderate priority (7.0 - 7.9)
4) Low priority (8.0 - 8.9)

With reference to the fourteen mini-watersheds of W. Shueib, MW no.10 is given rank 1 with the lowest compound factor at 5.6. It is succeeded by the mini-watershed no.11 and 7, as second and third respectively. The values of C_f and related ranks for all mini-watersheds are illustrated in (**Table 4** and **Figure 5**).

Similarly, out of fourteen mini-watersheds, MW no.12, 13, 8, 6 and 1 are classified as high priority, MW no. 9, 5, and 3 are ranked as moderate priority. By contrast, MW no. 2 and 4 are ranked as low priority (**Table 4** and **Figure 5**). It can be concluded that nine mini-watersheds (64.3% of the total) are classified as very high and high priority.

Table 4. Calculation of compound factor and prioritized ranks for the fourteen mini-watersheds.

Mini-watersheds	R_b	D_d (Km/Km^2)	F_u (Nu/Km^2)	E	L_o	R_f	B_s	R_e	C_c	R_c	Compound factor	Prioritized ranks	Priority
1	11	3	10	4	3	6	6	7	7	6	6.3	5	High
2	12	12	13	10	11	2	11	3	8	5	8.7	11	Low
3	8	8	14	7	7	1	12	2	6	7	7.2	9	Moderate
4	3	9	9	1	8	8	2	10	2	12	8.7	11	Low
5	2	10	3	2	9	6	4	8	4	10	7.2	9	Moderate
6	5	6	12	6	5	6	5	8	3	11	6.4	6	High
7	13	11	2	8	10	1	14	1	12	1	5.8	3	Very high
8	9	2	6	6	2	5	8	6	4	8	6.7	7	High
9	7	4	8	4	3	4	9	5	9	4	7.3	10	Moderate
10	6	11	4	3	10	1	13	1	11	2	5.6	1	Very high
11	1	13	11	1	12	5	7	6	7	6	5.7	2	Very high
12	4	5	7	3	4	9	1	11	1	13	6.2	4	High
13	10	1	1	5	1	3	10	4	10	3	6.9	8	High
14	12	7	5	9	6	7	3	9	5	9	5.8	3	Very high

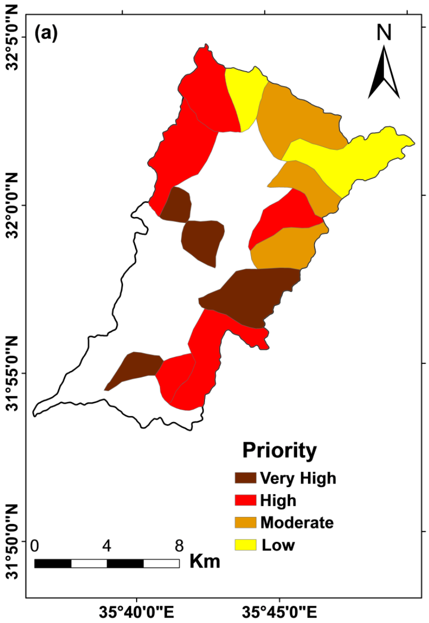

Figure 5. Priority of mini-watersheds based on morphometric analysis.

4.3. Soil Erosion Susceptibility Analysis

The method employed to assess soil erosion risk is based on soil erosion susceptibility mapping [30]-[40] using sixteen rated parameters which cover slope (steepness, length, and form), soil and geology (depth of unconsolidated materials, surface sealing susceptibility, consolidation and/or jointing rate of the subsoil and structure of underlying strata, and depth of impermeable layer below surface), vegetation and land use in relation to climatic condition (vegetation, land use, and heavy rainstorms), conservation practice (in plan and in drainage ways), and erosion rating of sheet, rill, gully, and ravine erosion. According to this system W. Shueib is systematically divided into terrain units using photo-interpretation (air photos of 1:10000 scale) and field checks. The delineation of soil erosion susceptibility pertained to each terrain unit is finally executed based on the various data related to the parameters mentioned above [39] [40].

According to this quantitative approach, every terrain parameter must be classified, rated and noted on the mapping card. The susceptibility class of each terrain unit results from the summation of all ratings, except the vegetation as one rating. (**Figure 3**) illustrates the methodology adopted in this regard. Van Ghelue and Van Mole [54] evaluated statistically the results of this approach against the results obtained from the USLE model for a part of the Rio Guadalhorce Catchment (southern Spain). A Spearman rank correlation was carried out on the results of the two empirical approaches, and yielded a high correlation coefficient. Moreover, a linear regression was carried out between the rating values, and the USLE soil less estimates, and also yielded a high correlation coefficient (r = 0.89).

Four soil erosion susceptibility classes were recognized (**Figure 6**) and considered for prioritization of W. Shueib mini-watersheds. These classes are as follows:

1) Terrain of Extremely High Susceptibility to Erosion

This class is restricted to steep valley-side slopes (26˚ - 35˚) characterized by old landslide complexes and active slides. Often, the main road along W. Shueib is affected by rotational landslides every few years. Soil slumping and mudflows are repetitive phenomena in winter following heavy rainstorms. Vegetation cover is degraded due to wood cutting and overgrazing. The maximum area (100%) under this erosion class is reported from MW no.13, whereas the minimum area (0.62%) is reported for MW no.3. The mini-watershed with a high percentage of this erosion class has been given higher priority, while mini-watersheds having a low percentage of this erosion class are assigned lower priority.

2) Terrain of Very High Susceptibility to Erosion

This erosion class is characteristic of the dissected fault-scarp overlooking the rift (the dominated slope

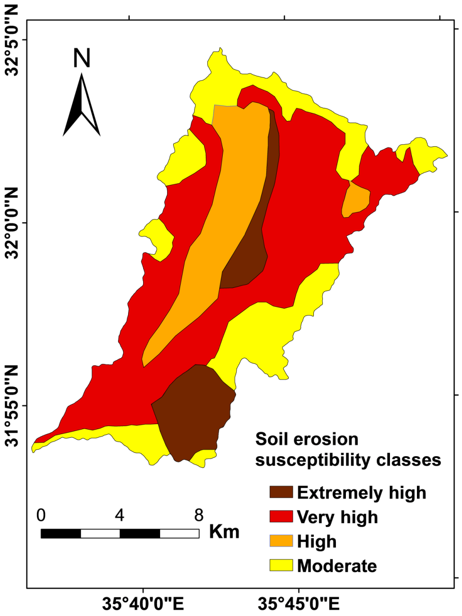

Figure 6. Soil erosion susceptibility classes.

categories are: 16˚ - 25˚ and > 35˚), and the highly and moderately dissected denudational slopes, ridges, cuestas, hogbacks, and structural benches at the eastern part of the catchment. At the upper part of the catchment (the Al-Salt area) rainfed and irrigated agriculture are practiced, and remnants of degraded forest are still present. The highest area under this erosion class is reported from mini-watershed no.8 with 100%, whereas the lowest area is reported from mini-watershed no.1 with 3.6%. Higher priority has been given to the mini-watershed having a high percentage of land characterized by very high susceptibility to erosion and *vice versa*.

3) Terrain of High Susceptibility to Erosion

This class is characteristic of the denudational slopes (16˚ - 25˚), dissected structural benches, sandstone mining area, and the remnants of erosion surfaces. Severe rill and gully erosion is predominant. Soil slumping and shallow landslides are activated in winter due to heavy rain storms. The maximum area which represents this erosion class is observed in mini-watershed no.10 (78.59%), while the minimum area is reported from mini-watershed no.7 (4.76%). Mini-watersheds having higher percentage of high susceptibility to erosion were given high priority and *vice versa*.

4) Terrain of Moderate Susceptibility to Erosion

The moderate soil erosion susceptibility class occupied the remnants of erosion surfaces of gentle slopes (1˚ - 5˚), and slightly dissected structural and fluvial terraces. Such areas at present are utilized for rainfed farming and grazing. Native forest area has been deteriorated due to wood cutting and overgrazing. The maximum area (79.6%) under this erosion class is in MW no.7 (1.37%). Mini-watersheds having a higher percentage of this soil erosion susceptibility class were given higher priority and *vice versa*.

4.4. Prioritization of Mini-Watershed Based on Soil Erosion Susceptibility Analysis

Degradation of vegetation cover including forest across W. Shueib, and the existence of W. Shueib structure along the eastern part of the watershed, caused serious soil erosion and landsliding activity, and thus, increased flooding and sediment discharge into the W. Shueib reservoir during the rainy season. Rainfed and irrigated farming, and grazing are the dominant sector on which the livelihood of the local people is dependent. Therefore, soil and water conservation are of high priority. Rangeland, old landslide areas, terrain units affected by rilling and gullying are also of prime concern in watershed management of the catchment. High priority has been assigned to the mini-watersheds having higher percentage by area of any soil erosion susceptibility class, whereas low priority has been ascribed to mini-watersheds having lower percentage by area of any soil erosion susceptibility class. The rankings of individual soil erosion susceptibility class for each mini-watershed were averaged (**Table 5**) in order to arrive at a compound value using such ranking. Based on the average value of the

Table 5. Ranks and priorities of mini-watersheds in W. Shueib based on soil erosion susceptibility.

Mini-watersheds	Soil erosion susceptibility classes					
	Extremely high (%)	Very high (%)	High (%)	Moderate (%)	Cp value	Priority
1	-	3.61 [12]	38.44 [2]	57.94 [2]	5.333	4 (High)
2	5.86 [5]	29.14 [9]	29.65 [3]	35.35 [6]	5.750	7 (Low)
3	0.62 [6]	60.48 [7]	-	38.90 [4]	5.666	6 (Moderate)
4	-	63.73 [6]	8.52 [5]	27.71 [8]	6.333	9 (Low)
5	-	88.79 [3]	11.21 [4]	-	3.500	2 (Very high)
6	-	56.45 [8]	5.43 [6]	38.11 [5]	6.000	9 (Low)
7	-	93.87 [2]	4.76 [7]	1.37 [9]	1.000	8 (Low)
8	-	100 [1]	-	-	6.000	1 (Very high)
9	-	71.07 [5]	-	28.88 [7]	5.666	8 (Low)
10	20.30 [3]	1.11 [13]	78.59 [1]	-	5.500	6 (Moderate)
11	-	20.42 [10]	-	79.56 [1]	5.333	5 (Moderate)
12	51.22 [2]	4.39 [11]	-	44.33 [3]	1.000	4 (High)
13	100 [1]	-	-	-	4.000	1 (Very high)
14	17.35 [4]	82.64 [4]	-	-		3 (High)

compounded parameter, the mini-watersheds having the lowest rating value were assigned the highest priority number 1. Finally, the mini-watersheds were categorized into four classes as: very high (1 - 2), high (3 - 4), moderate (5 - 6), and low (>6) priority. It is found that the highest average value occurred in the MW no.13, 8, and 5, which are of extremely high and very high soil erosion susceptibility. Thus, they are considered of very high priority for soil and water conservation measures. These are followed by MW no.14, 12, and 1, where these mini-watersheds are characterized by extremely high soil erosion susceptibility, and thus, are also of high priority for conservation intervention. By contrast, mini-watersheds no.6, 7, 9, 4 and 2 are of low priority (**Figure 7**). However, without exception, all mini-watersheds are either of very high or of high priority due to the influence of W. Shueib structure and the occurrence of landslides. Priority of mini-watersheds based on soil erosion susceptibility analysis is illustrated in **Figure 7**. An integration of the results achieved from the morphometric analysis method, and soil erosion susceptibility method was conducted through superimposition of the two produced maps. Such a process makes it possible to identify the common mini-watersheds falling under each category of priority. The correlation reveals only two mini-watersheds (no.3 and no.2) as the common mini-watersheds ranked under moderate and low priority respectively. Two mini-watersheds (no.8 and no.13) are ranked in the category of high priority based on morphometric analysis, and are classified in the category of very high priority based on soil erosion susceptibility analysis (**Figure 8**). Similarly, mini-watershed no.14 comes under the category of very high priority based on morphometric analysis, and is ranked under the category of high priority based on soil erosion susceptibility analysis. Accordingly, it can be concluded that a reasonable number of mini-watersheds are classified in the categories of moderate, high, and very high priority based on both morphometric and soil erosion susceptibility analysis. Therefore, they should be prioritized for soil and water conservation measures.

The comparison of final priority for mini-watersheds based on the two previous methods, indicate that in case of shortage, or non-availability of conventional soil erosion information, this kind of investigation could be employed in prioritizing sub-or mini-watersheds for soil and water conservation measures using remote sensing and GIS techniques.

5. Conclusions

The present study demonstrates that ASTER DEM and topo-sheets coupled with GIS techniques are competent tools in geomorphometric analysis, delineation of mini-watersheds and associated drainage networks. Morphometric analysis of linear and shape parameters, and soil erosion susceptibility analysis is found to be capable tools for prioritization of W. Shueib mini-watersheds. In this context, watershed prioritization is considered a

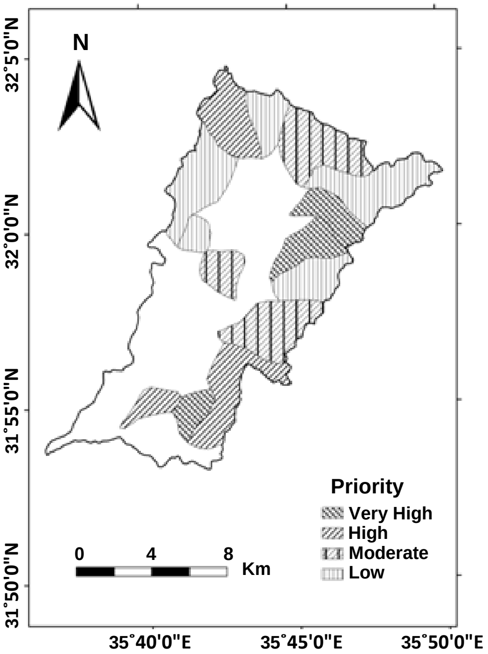

Figure 7. Priority of mini-watersheds based on soil erosion susceptibility.

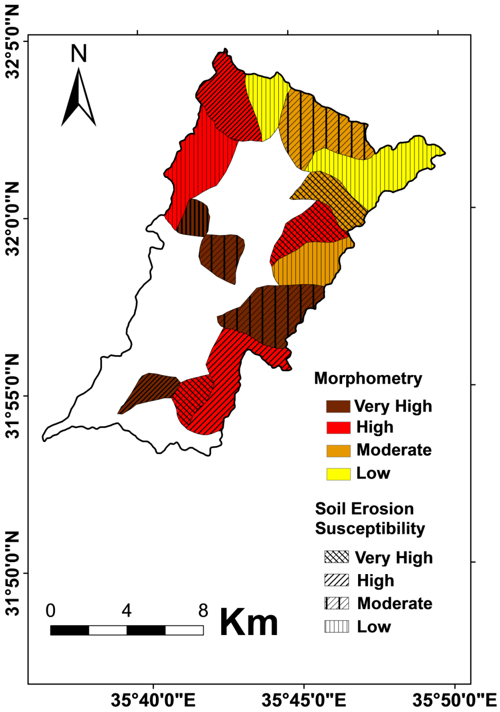

Figure 8. Priority of mini-watersheds based on superimposition of morphomtric and soil erosion parameters.

pragmatic methodology which can be employed for watershed management, development of natural resources, and soil and water conservation. Prioritization of watersheds is also crucial to reduce runoff, soil erosion rates, landsliding and flooding potential.

Based on morphometric analysis, the results of prioritization indicate that 64.3% of the mini-watersheds in W. Shueib are ranked as very high and high priority. Mini-watersheds no.14, 11, 10, and 7 are classified as very high priority, whereas, mini-watersheds no.12, 13, 8, 6 and 1 are categorized as high priority. By utilizing soil erosion susceptibility analysis, it is found that six of the W. Shueib mini-watersheds are either of very high (MW no.5, 8, 13), or of high priority (MW no.4, 12, 1) due to the influence of W. Shueib structure, and landslide activity. Through integration of the results or the morphometric analysis method, and soil erosion susceptibility method, the mini-watersheds no.3 and no.2 are the common mini-watersheds that come under moderate priority and low priority respectively. Two mini-watersheds (no.8 and no.13) are classified in the category of high priority based on morphometric analysis, and rank in the category of very high priority based on soil erosion susceptibility analysis. Similarly, mini-watershed no. 14 comes under the category of very high priority based on morphometric analysis, and is categorized in the class of high priority based on soil erosion susceptibility. It can be concluded that most of the mini-watersheds of W. Shueib can be classified in categories of moderate, high, and very high priority based on both morphometric, and soil erosion susceptibility analysis. Consequently, the entire W. Shueib watershed must be prioritized for protection through the construction of appropriate soil and water conservation measures using remote sensing and GIS techniques to minimize soil erosion rates, to reduce the sediment yield into W. Shueib reservoir, to stabilize steep slopes against landsliding, and to decrease potential flooding in the future.

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