Prioritization of W. Mujib Catchment (South Jordan) through Morphometric and Discriminant Analysis, GIS, and RS Techniques

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Abstract

GIS and remote sensing were utilized for prioritizing the W. Mujib catchment. Fifty three fourth-order sub-watersheds were prioritized based on morphometric analysis of linear and shape parameters. ASTER DEM (v.2), topographical maps, and Arc GIS (10.1) software, have been employed to delineate the 53 sub-basins, to extract the drainage networks, and to compute the required basic, linear, and shape parameters, and to compile the necessary thematic maps such as elevation and slope categories. The land use/land cover map was generated using ERDAS Imagine (2015), LANDSAT 8 image, and supervised classification (Maximum Likelihood Method). Soil map was digitized using the Arc GIS tool. Each sub-basin is prioritized by assigning ranks based on the calculated compound parameter (Cp). The final score for each sub-basin is ascribed as per erosion threat. The 53 sub-watersheds were grouped into four categories of priority: very high (15 sub-basins, 28.3% of the total), high (17 sub-basins, 32% of the total), moderate (16 sub-basins, 30.2% of the total), and low (5 sub-basins, 9.5% of the total). Sub-basins categorized as very high and high priority (60.3% of the total) are subjected to high erosion risk, thus, creating an urgent need for applying soil and water conservation measures. The validity of the prioritized four groups was tested statistically by means of Discriminant Analysis (DA), and a significant difference was found between the four priority classes. A relatively complete separation exists between the recognized priority classes; thus, they are statistically valid, distinct, and different from each other. The present results intend to help decision makers pay sufficient attention to soil and water conservation programs, and to encourage tree plantation over the government-owned sloping land. Such procedures are essential in order to minimize soil erosion loss, and

to increase soil moisture on farms, thus, reducing the impact of recurrent droughts and the possibility of flooding downstream.

Keywords

Morphometric Analysis, Prioritization, Discriminant Analysis, GIS, Soil Conservation, W. Mujib

1. Introduction

Land degradation in Jordan is attributed mainly to soil erosion by water, land use abuse, and agricultural intensification. Continuous woodland cutting at present following the rise in oil prices, land fragmentation, soil compaction, and low soil organic matter, are also contributing factors underlying land degradation in the rainfed highlands of Jordan [1]. Such processes were active prehistorically and historically in the rainfed highlands. It has been argued that historical soil erosion, intense agriculture, and contour stone terraces have dominated the highlands since the Iron Age [2]. A geo-archaeological survey carried out on W. Wala deposits suggests that the deterioration of vegetation cover caused severe soil erosion rates at least since the Nabatean period 3000 years ago [3]. Jebari *et al.* [4] reported that the practice of using a successive agricultural system in other parts of the Mediterranean caused an intensive exploitation of land resources, land use/land cover abuse, and soil degradation over a long period of time. Since the 1960's, various qualitative and quantitative studies have been undertaken on soil erosion and conservation in the country. Soil erosion caused by running water has been estimated for the eastern Rift watersheds to be 1.328 million tons·yr⁻¹ [5]. Similarly, the estimated total sediment inflow to King Talal Reservoir (Zarqa River) ranges from 1.7 to 3.84 MCM (million cubic meters) yr⁻¹, with an average of 2.813 MCM yr⁻¹ [6] [7] [8] [9]. Also, the predicted average annual sediment yield using SWAT model for W. Wala and W. Mujib was 131.94 and 341.887 tons·yr⁻¹ respectively [10] [11]. Examples of *in situ* field measurements of soil erosion in plots over the rainfed highland of Jordan, indicate that the average splash erosion for the sub-humid Mediterranean climate region (Salt, Jerash, and Ajlune area) ranges from 4.713 to 14.707 ton·ha⁻¹·yr⁻¹. For semi arid climate (Muwaqar area), it varies from 2.59 to 16.3 ton·ha⁻¹·yr⁻¹, and for the arid climate (Azraq area), it ranges from 2.8 to 7.39 ton·ha⁻¹·yr⁻¹. By contrast, the measured runoff erosion for the same sites and over the three climatic zones ranges from 0.581 to 2.382 ton·ha⁻¹·yr⁻¹, 1.05 ton·ha⁻¹·yr⁻¹, and 0.14 ton·ha⁻¹·yr⁻¹ respectively [12] [13] [14] [15]. In the southern highlands (Shawbak-Wadi Musa area), the measured average splash erosion varies from 1.39 to 30.15 ton·ha⁻¹·yr⁻¹ [16]. Several qualitative surveys on soil erosion and conservation were carried out during the 1960's for W. Hasa [17]; and southern highlands of Jordan [18]; for W. Shueib and W. Kufrein, Central Jordan [19]; and for

W. Ziqlab, northern Jordan [20]. Such surveys are considered descriptive and general reconnaissance surveys. The most interesting products of these surveys are: a map which shows soil erosion features; slope categories (%) map; and a conventional land capability map only for W. Ziqlab. Moreover, the estimated soil loss categories for W. Kufranja, northern Jordan were: low ($0 - 5 \text{ ton}\cdot\text{ha}^{-1}\cdot\text{yr}^{-1}$), moderate ($15 - 25 \text{ ton}\cdot\text{ha}^{-1}\cdot\text{yr}^{-1}$), severe ($25 - 50 \text{ ton}\cdot\text{ha}^{-1}\cdot\text{yr}^{-1}$) and extreme ($>50 \text{ ton}\cdot\text{ha}^{-1}\cdot\text{yr}^{-1}$) [21]. Likewise, the estimated soil loss categories for W. Kerak, southern Jordan were: extremely high ($>150 \text{ ton}\cdot\text{ha}^{-1}\cdot\text{yr}^{-1}$), very high ($60 - 150 \text{ ton}\cdot\text{ha}^{-1}\cdot\text{yr}^{-1}$), high ($25 - 60 \text{ ton}\cdot\text{ha}^{-1}\cdot\text{yr}^{-1}$), moderate ($12 - 25 \text{ ton}\cdot\text{ha}^{-1}\cdot\text{yr}^{-1}$), and slight ($0 - 12 \text{ ton}\cdot\text{ha}^{-1}\cdot\text{yr}^{-1}$) [1]. It is obvious that the estimated average annual soil loss rate almost exceeds the acceptable soil loss tolerance limit, which ranges from 2 to $12 \text{ ton}\cdot\text{ha}^{-1}\cdot\text{yr}^{-1}$ for the Mediterranean environment [22] [23] [24]. Consequently, high soil erosion rates, and high predicted sediment yield, indicate that future sustainable agriculture is seriously threatened by intense soil erosion. This is disturbing in light of the rapid population growth ($2.8\% - 3.0\%/ \text{yr}^{-1}$) and chronic shortage of food in the country. Further, the predicted high sediment production, and high soil erosion rates will seriously endanger the present and the future dams in the highland region of Jordan [25] [26]. Quantitative morphometric analysis of drainage basins was elaborated and adopted recently to prioritize sub-basins for soil and water conservation measures [27]-[41]. Linear and shape morphometric parameters, or “the erosion risk parameters” must be extracted and computed to prioritize sub-watersheds for soil conservation. The pioneers who elaborated this approach [27] [29] have argued that linear parameters restrain a direct relationship with erodibility. Hence, the highest value of the linear variable was ranked 1; therefore, the lower their values, the greater the erodibility. Consequently, the lowest value of shape variable was rated as rank 1 and the second lowest as rank 2 and so on. Compound parameter (C_p) was calculated by adding up all the ranks of linear variables, as well as shape variables, and then, dividing by the number of all parameters. Following the rating of every single morphometric parameter, the ranking values of all linear and shape parameters related to each sub-basin are added up for each of the sub-basins to achieve the score of the compound parameter (C_p) based on the average value of these parameters. Furthermore, the sub-basin having the lowest compound parameter score was assigned the highest priority, the next higher value was referred as second priority and so on [42]. Highest priority indicates the greater degree of soil erosion, or prone-erosion areas in that particular sub-basin. Consequently, it is considered a potential area for applying soil conservation measures [36]. In watershed prioritization, several methods of analysis were employed. **Table 1** displays the methods elaborated to perform watershed prioritization. It is obvious that the most common and appropriate method developed is the morphometric analysis method. Other researchers combined the morphometric analysis method with sediment yield index (SYI) and sediment yield product rate (SPR). However, several other studies, and in

Table 1. Methods of watershed prioritization.

Watershed/location	Method of watershed prioritization	References
Nine watersheds/Midnapore district, West Bengal, India	Morphometric analysis, Sediment yield index method (SYI)	[27]
10 sub-watersheds/Teesta River, India	Morphometric analysis, Sediment production rate (SPR) method	[28]
Tarafeni River, West Bengal, India	Morphometric analysis, Sediment Yield index (SYI) method	[29]
Mohr watershed, Gujarat India	Morphometric analysis	[30]
Bago watershed, Myanmar	Morphometric analysis and USLE model for estimating soil erosion loss	[72]
Bavdhan micro-watersheds Pune district, India	Morphometric analysis and runoff potential	[73]
Sub-watersheds, Gund district, India	Morphometric analysis and land use analysis	[31]
Jaggar watershed, Karauli district, India	Morphometric analysis, Land use/Land cover	[32]
Lower Tapi Basin, Gujarat, India	Morphometric analysis	[33]
Malesari watershed, Gujarat, India	Morphometric analysis	[34]
Ujjaini watershed, Ahmednagar, India	Morphometric analysis, Weighted Sum Analysis technique	[35]
Manot River, Mandla district, India	Morphometric analysis	[65]
Kallar watershed, Western Ghats, India	Morphometric analysis, Fuzzy Analytical Hierarchy Process	[78]
Shakkar River, Madhya Pradesh, India	Morphometric analysis, Principal Component Analysis	[36]
Haraz watershed, Mazandaran, Iran	Morphometric analysis, RUSLE model, and Analytical Hierarchy Process (AHP)	[74]
Kuttiyadi River, Kerala, India	Morphometric analysis, Analytical Network Process	[75]
Chopan watershed, Madhya Pradesh, India	Morphometric analysis Sediment Yield Index (SYI), land use/cover	[37]
Limkheda watershed, Gujarat, India	Morphometric analysis	[42]
Wadi Kerak Catchment, Southern Jordan, Jordan	Morphometric analysis, RUSLE model	[38]
Wadi Shueib catchment, Central Jordan, Jordan	Morphometric analysis, Soil erosion Susceptibility analysis	[79]
Zarqa River, Northern Jordan, Jordan	Morphometric analysis, Principal Component Analysis	[39]
Hasdeo River, Chattisgarh, India	Morphometric analysis	[40]
Dangri River, Panchkula, India	Morphometric analysis Snyder's method of unit hydrograph, Land use/cover	[41]
W. Wala (Southern Jordan)	Morphometric and Discriminant analysis	[77]
W. Mujib (Southern Jordan)	Morphometric and Discriminant analysis	[76]

parallel with morphometric analysis, land use, land cover, sediment yield index, and Snyder's Synthetic Unit Hydrograph method, have been incorporated in the analysis (**Table 1**). Other investigations also, adopted soil loss modeling (USLE or RUSLE models), and soil erosion susceptibility analysis in order to recognize potential sub-basins for planning and designing conservation works/structures.

Information on soil type, slope, and current land use/land cover is recommended to guide in suggesting suitable soil conservation measures for each sub-basin priority group covering the W. Mujib catchment [31] [32]. Prioritization research demonstrates the role of the powerful GIS, RS, and morphometric analysis method in ranking different sub-basins in relation to the order in which they have to be taken for conservation measures [36]. Quantitative analysis of drainage basins in this regard is the key approach to understanding the hydro-morphological processes acting over drainage networks. Basic, linear, and shape parameters can be measured and calculated using DEM's, Arc GIS software, and the mathematical equations developed elsewhere [43] [44] [45] [46] [47]. Morphometric analysis of linear parameters (bifurcation ratio, drainage density, stream frequency, texture ratio, and over land flow); and shape parameters (circularity ratio, elongation ratio, shape factor, form factor, and compactness coefficient) are the common approaches utilized to calculate the compound parameter (Cp) on which prioritization of sub-basins is designated [27] [29] [34]. It has been argued that the suggested linear and shape morphometric parameters for prioritization are consistent in relation to erodibility. Thus, they considered the most efficient parameters for watershed prioritization and conservation planning compared with other methods of prioritization [39]. However, the limitations pointed out regarding morphometric analysis method in prioritization has been examined in the present study, where the validity of the priority classes was tested statistically using Discriminant Analysis. The present investigation is intended to:

- 1) Prioritize 53 sub-basins for soil and water conservation with reference to the morphometric analysis method using GIS and RS,
- 2) Assess the final priority ranks for the 53 sub-basins based on analyzing linear and shape parameters,
- 3) Generate a spatial map illustrating the final priority classes for the 53 sub-basins,
- 4) Test statistically the validity of the achieved priority classes by means of Discriminant Analysis (DA).

2. Study Area

Watershed prioritization was carried out on the W. Mujib catchment draining to the Jordan Rift. It flows westward and merged with the W. Wala tributary 3 km before what is known as W. Mujib-Wala discharges into the Dead Sea at an elevation of -431 m (b.s.l). The watershed extends between latitudes 30°39' and 36°33'N, and longitudes 35°30' and 36°30'E (**Figure 1**). The W. Mujib catchment

Figure 1. Location of the study area.

covers an area of 4507.8 km². Elevation varies from -431 (b.s.l) at the outlet, to 1277 m (a.s.l) east of Mazar town (**Figure 2(a)** and **Figure 2(b)**). The climate of the high plateau is classified as dry Mediterranean with relatively cold winters and hot summers, whereas the spectacular canyons downstream and the lower reaches close to the Dead Sea are arid. Mean annual rainfall ranges from 164 mm at W. Mujib weather station, 311 mm at Qasr, and 335 mm at Rabba. Rainfall is concentrated in winter (October to March). Temperatures exhibit large seasonal and diurnal variations, with daily temperatures ranging from a maximum of >40°C in August (at W. Mujib weather station, and close to the Dead Sea), to a minimum of -5°C in January close to Mazar town. Progressive lowering of the Dead Sea base level, uplifting of the eastern shoulder of the Dead Sea escarpment, and the renewed down-ward movement of the rift during late Tertiary and Quaternary tectonics [48] caused continuing rejuvenation, river incision and down-cutting of W. Mujib. Consequently, flat-undulating (0° - 10°) and moderate slope (10° - 15°) categories dominate the eastern catchment whereas, steep slopes (>35°) and highly, rugged and dissected terrain characterize the western part (**Figure 3**). High hypsometric integral (HI) values (0.70% - 0.80%, 0.80 - 0.85, and 0.85% - 89%) predominate in the catchment, denoting that W. Mujib and the 53 sub-basins are at the youth-age stage of geomorphic development. Consequently, the sub-watersheds are of high soil erosion rates, high sediment yield production [11], high possibility of flooding, and landslide activity, especially in the western part of the watershed. The W. Mujib watershed is covered by a wide range of rock types, ranging in age from Cambrian sandstones to Quaternary fluvial and lacustrine deposits. The Kurnub sandstones of Lower Cretaceous are exposed along parts of deeply incised streams in the western part of the watershed. It consists of white and multi-colored, and grey sandstone, mostly medium to coarse-grained with beds of grey and brownish siltstone. The

Figure 2. DEM (a), and contours of W. Mujib watershed.

Figure 3. Slope categories.

Kurnub sandstones are overlain by the Turonian-Cenomanian strata, which consists of the Nodular limestone unit (or the marly clay unit), and the Echinoidal limestone unit (or the limestone marl unit). The Eocene-Senonian rock unit (mainly chert, limestone, chalk and marl) occupies the eastern and southern parts of the catchment [48] [49]. The Kurnub sandstones, Nodular limestone, and Echinoidal limestone units represent soft rocks of low shearing resistance; thus, it is considered a major factor influencing slope stability and soil erosion loss. Apart of the Kerak-Al-fiha fault system and the subsidiary dense branching faults, southwest of W. Mujib, a series of major and relatively parallel north-west, south-east faults of early Miocene influenced the catchment. They are often obscured under the materials pertaining to the old landslide complexes [49]. The watershed Shihan plateau basalt, and W. Balue basalt at the lower reaches of the catchment are of late Miocene/Early Pliocene age. Quaternary deposits in the catchment are restricted to three fluvial terrace levels which were exposed in the central Mujib canyons. These terrace accumulations are of early Holocene, Early and Middle Pleistocene age [50]. The yield of the W. Mujib reservoir is 16.8 MCM and is aimed to provide water to the southern Ghor irrigation project, the Arab Potash Company, the Dead Sea Chemical Complex, and for tourism development of the eastern shore of the Dead Sea.

3. Materials and Methodology

3.1. Extraction of the Morphometric Parameters

The basic parameters calculated for the 53 fourth-order sub basin are: Sub-basin area (A) (km^2), Perimete (P) (km), stream order (u), basin length (L_b) (km) and total length of streams (L_u) (km).

3.1.1. Sub-Basin Area (A), and Perimeter (P)

The sub-basin area is the plan area of the drainage sub basin (km^2). It is considered the most significant hydrological characteristics of a catchment [43]. Thus, it reflects the volume of water that be generated from precipitation. Basin area has been computed using Arc GIS (10.1) software. The present study shows that sub-basins no. 12 has a minimum area of 20 km^2 , while, sub-basin no. 48 has a maximum area of 168 km^2 .

The watershed perimeter refers to the length of a line that delineates the water divide of the sub-basin. P parameter can be utilized as an indicator of sub-basin shape and size [43]. The maximum and minimum perimeter values are 128 km for sub-basin no. 48, and 18 km for sub-basin no. 12.

3.1.2. Stream Order (u), Basin Length (L_b), and Total Stream Length (L_u)

Strahler's method [44] [45] of stream ordering is adopted due to simplicity, and because it is the most commonly used system in hydrological investigation. All the sub-basins in the current study are of fourth-order. Basin length (L_b) variable refers to the ratio of the largest dimension of catchments to its main channel. It

is measured along the main channel from the catchment outlet to the basin divide. L_b parameter is essential in hydrological computation and increases as the drainage increases and vice versa [34]. The basin length for the 53 sub-basins in the current study (fourth-order sub-watersheds) ranges from 5.153 km to 25.584 km, and the total stream length of all orders varies noticeably. Sub-basin no. 48 has the greatest total length of streams (164.301 km), whereas, sub-basin no. 49 has the lowest total length of streams (29.403 km). It is obvious, that the greatest total length of streams is connected with sub-basins deformed by major faults and the associated lineaments influencing W. Mujib.

The linear morphometric parameters are: the bifurcation ratio (R_b), drainage density (D_d), stream frequency (F_s), Texture ratio (T_r), and length of over land flow (L_o).

The bifurcation ratio (R_b) is described as the ratio of streams number of a given order to the number of the streams of the next higher order [43] [44], and it is calculated by:

$$R_b = N_u / N_{u+1} + 1, \quad (1)$$

where N_u = total number of stream segments of order " u ",

N_{u+1} = no. of segments of the next higher order.

Bifurcation ratio (R_b) is defined as an index of relief and dissection. R_b values range from 2 for flat-undulating or rolling terrain, to 6 to watersheds where drainage networks deformed by geological structure. High R_b values denote high overland flow and early hydrograph peak with a high potential of the possibility for flash flooding associated with heavy rainstorms [51], which in turn increase soil erosion rates and sediment discharge in the main channel.

Drainage density (D_d) is described as the total length of streams in a drainage basin per unit area [43] [52], or

$$D_d = L_u / A, \quad (2)$$

where A = the basin area;

L_u = is the total stream length.

Drainage density is a measure of topographic dissection and runoff potential of the drainage basin. High D_d value implies high runoff, a quick stream response and in turn, a low infiltration rate and vice versa [53].

Stream frequency (F_s) refers to the ratio of the total number of streams (N_u) of all orders in a catchment to the watershed area (A). It is represented by the following equation:

$$F_s = N_u / A \quad (3)$$

F_s parameter is positively correlated with D_d values of a watershed. High stream frequency indicates more infiltration, and thus high groundwater potential, and vice versa [54].

Texture ratio (T_r) is defined as the ratio of the total number of streams of the first order (N_1) to the perimeter (P) of the drainage basin [43] [44]. T_r is deter-

mined by:

$$N_u / p, \quad (4)$$

where N_u = the total number of streams of all orders,

p = Perimeter (km).

3.1.3. Length of Overland Flow (L_o)

L_o parameter is calculated by:

$$L_o \text{ (km)} = 1/2 D_d, \quad (5)$$

where D_d = drainage density.

L_o is the length of water over the ground before it becomes concentrated in definite stream channels, and is equal to half of drainage density. It is one of the most significant independent parameters affecting both hydrologic and hydro-graphic development of drainage basins. L_o variable is related inversely to the average slope of the channel and is equivalent to the length of sheet flow to a large extent [43].

The shape morphometric parameters are: form factor (R_f), shape factor (B_s), elongation ratio (R_e), compactness coefficient (C_c) and circulating ratio (R_c).

Form factor (R_f) is computed according to the following formula:

$$R_f = A / L_b^2 \quad (6)$$

R_f parameter refers to the ratio of the area of drainage basin to the square of the basin length [44]. Higher values of R_f -values imply a more circular shape of a catchment, while smaller R_f -values (<0.45) indicate that the basin is elongated.

Shape factor (B_s) is defined as the ratio of the square of the basin length to the area of the basin, or

$$B_s = L_b^2 / A \quad (7)$$

B_s parameter provides a notion regarding the circular character of the catchment. The greater the circular character, the greater the fast response of the catchment following an intense rainstorm [55].

Elongation ratio (R_e) is expressed by the following:

$$R_e = 1.128 \sqrt{A / L_b} \quad (8)$$

Low R_e values imply that the watershed is more elongated. Where the R_e values approach 1.0, the shape of the watershed becomes a circular [47].

Compactness coefficient (C_c) is determined following Gravelius [56], and refers to the ratio of perimeter of a catchment to circumference of circle area, which is equal to the area of the catchment. C_c is computed according to the following equation:

$$C_c = \frac{P}{2\sqrt{\pi A}} \quad (9)$$

P = perimeter of the basin (km);

A = area of the basin (km²).

Where a C_c value approaching 1, denotes that the catchment is close to a circle in shape. If the C_c value is 1.28, the basin is more square in shape, whereas the basin is considered a very elongated one when the C_c value is >3.0 [57].

The circularity ratio (R_c) of a watershed is computed based on:

$$R_c = 4\pi \times A / P^2, \quad (10)$$

where (A) is the area of the basin, and (P) is the perimeter [46]. If R_c is close to 1, the shape of the watershed is circular. Low, medium, and high values of R_c indicate young, mature, and old stages of geomorphic development of the watershed respectively.

3.2. Tools, Data Used, and Statistical Techniques

The 53 fourth-order sub-basins of W. Mujib were prioritized based on morphometric analysis, using topographic sheets, ASTER DEM and GIS software. Topo sheets of scale 1:50,000 were acquired from the Royal Jordanian National Geographic Center, Amman, and were scanned, geo-referenced, and converted to a zone 36 N projection system using Arc GIS 10.1, and the associated tools. Then ASTER DEM of 30 m resolution was employed to derive the drainage networks using the Arc Hydro tool. Stream order was determined using Strahler's method of stream ordering [44] [45]. The W. Mujib catchment is classified as a seventh-order drainage basin. Five basic morphometric parameters, five linear parameters, and five shape parameters were computed using DEM and GIS [29] [43] [47] [45].

To illustrate the morphometric characteristics of the 53 sub-basins, five basic parameters were derived. These are: area (A), basin length (L_b), perimeter (P), stream order (u), and stream length (L_u). Moreover, five linear and five shape parameters were considered in prioritization of the 53 sub-basins based on morphometric analysis. These are: bifurcation ratio (R_b), drainage density (D_d), stream frequency (F_s), texture ratio (T_r), length of overland flow (L_o), shape factor (B_s), circularity ratio (R_c), form factor (R_f), compactness coefficient (C_c), elongation ratio (R_e). A landuse/land cover map (Figure 4) was generated using LANDSAT 8 (July 2017), ERDAS Imagine 2015, (v.15), and supervised classification. The Maximum Likelihood Method of classification techniques was adopted to classify landuse/cover, based on the classification system designated by Anderson *et al.* [58]. A soil map was digitized from the National Soil Survey maps and reports (Figure 5) pertaining to the National Soil and Land Use Maps [59]. A slope categories map was executed using ASTER DEM (Figure 3). A noticeable variation exists in slope categories. The eastern and southeastern part of the W. Mujib watershed is dominated by $0^\circ - 5^\circ$, $5^\circ - 10^\circ$, and $10^\circ - 15^\circ$ slope categories. Whereas, slope categories of $15^\circ - 20^\circ$, $2^\circ - 30^\circ$, and $45^\circ - 90^\circ$ stand out in the western part of the catchment, with the presence of vertical cliffs bordering the canyons downstream west of the W. Mujib bridge. The development of efficient and cost-effective GIS and RS techniques enables researchers to extract,

Figure 4. Land use/cover.

Figure 5. Soil types.

measure, calculate and process precisely the basic, linear, shape, and relief morphometric parameters. Furthermore, the availability of free access Digital Elevation Models (*i.e.*, ASTER and STRM DEM's) with a reasonable resolution (30 m and 90 m respectively) have improved the quantitative analysis approach in drainage basin morphometry, and morphometric parameters mapping, thus, expanding the application of morphometric analysis to other fields of research. Discriminant Analysis (DA) was employed to test statistically the validity of priority classes of sub-basins generated using morphometric analysis, and to determine if they are significantly different from each other, and also to help explain the regional spatial differences among the fourth-order sub-watersheds in terms of prioritization.

4. Results and Discussion

4.1. Morphometric Analysis

4.1.1. Basis Parameters

The basin area (A) is a major component in hydrological processes [60]. In this connection Chorley *et al.* [61] reported that the maximum discharge of flood per unit area, is inversely related to the size of the drainage basin. The total area of W. Mujib is 4507.8 km², and for the 53 sub-basins, it ranges from 15 km² to 168 km². The basin length (L_b) corresponds to the maximum length of the watershed and sub-basins measured parallel to the main drainage line. The length of W. Mujib basin is 136.84 km, and the perimeter is 512.271 km (Table 2); the perimeter for the sub-basins ranges from 18 km to 128 km (Table 3). Sub-basin no. 12 represents the shortest, and sub-basin no. 48 is the longest. The W. Mujib catchment is classified as a seventh-order basin (Figure 6), while all the demarcated 53 sub-basins are of fourth-order. Stream length is measured from the origin of a stream to the drainage divide. The total stream length of W. Mujib is 6358.9 km, and the first order streams account for 50.6% of the total stream length. The following linear and shape parameters will be illustrated with reference to their significance for morphological and hydrological properties of the sub-watersheds.

4.1.2. Linear Parameters

1) Bifurcation ratio (R_b)

The bifurcation ratio (R_b) is defined by Horton [43] as an index for relief and dissection. The mean bifurcation ratio (R_{bm}) for W. Mujib is 4.1, and for the 53 sub-basins it varies from 2.67 to 11.3 (Table 3).

High R_b values indicate the impact of tectonic and structural disturbances on drainage networks. R_b values constitute a true reflection of W. Mujib major faults and dense lineaments in drainage distortion [62].

The drainage density (D_d) for the entire W. Mujib is 1.411, and for the 53 sub-basins varies from 1.291 to 1.599, which implies moderate to well-drained catchments. A slight variation in D_d values exist between the eastern and

Table 2. Morphometric characteristics of W. Muijb watershed.

Par. no.	Morphometric parameters total	Stream order						
		I	II	III	IV	V	VI	VII
Drainage network								
1	Stream order (u) (7)							
2	No. of streams (N_u) (5472)	4232	949	222	53	11	4	1
3	Stream length (L_u) (km) (6358.89)	3220.3	1549.95	836.93	362.60	166.47	159.40	63.24
4	Mean stream length (L_{sm}) (km)	0.76	1.63	3.77	6.84	15.13	39.85	63.24
5	Stream length ratio (R_L)		II/I	III/II	IV/III	V/VI	I/V	VII/VI
			0.48	0.54	0.43	0.45	0.95	0.39
6	Bifurcation ratio (R_b)		II/I	III/II	IV/III	V/VI	VI/V	VII/VI
			4.45	4.27	4.18	4.18	2.75	4
7	Mean bifurcation ratio (R_{bm})				4.082			
Basin geometry								
8	Basin perimeter (P) (km)				512.271			
9	Basin length (L_b)				136.840			
10	Basin area (A) (km ²)				4507.805			
11	Shape factor (B_s)				4.154			
12	Texture ratio (T_r)				10.682			
13	Elongation ratio (R_e)				0.553			
14	Circularity ratio (R_c)				0.216			
15	Lemniscate ratio (T_r)				3.263			
16	Drainage texture (T)				1.388			
17	Form factor (R_f)				0.214			
18	Compactness coefficient (C_c)				4.305			
Drainage texture								
19	Drainage density (D_d) (km/km ²)				1.411			
20	Stream frequency (F_s)				1.214			
21	Length of overland flow (L_o)				0.705			
Relief characteristics								
22	Basin relief (B_h) (m)				1708			
23	Relief ratio (R_r)				12.482			
24	Ruggedness number (R_n)				2.409			
25	Hypsometric integral (HI)				87.4%			

southeastern sub-basins (D_d values > 1.45). This is attributed to relatively higher rainfall, and degradation of vegetation cover, whereas, the southeastern sub-basins are characterized by high relief, steep slopes, and the Kerak-Al-Fiha fault system which caused greater runoff, and thus, more surface erosion [63].

2) Stream frequency (F_s)

Stream frequency (F_s) values are positively correlated with D_d of all sub-watersheds. Thus, any increase in stream population caused an increase in D_d value [64]. Low D_d values denote low infiltration rate of surface water; thus, low groundwater potential is expected [54]. The stream frequency of W. Mujib is

Table 3. Morphometric characteristics of the 53 sub-basins.

Mini-watershed no	Basic Parameters					Linear Parameters					Shape Parameters						
	<i>A</i>	<i>P</i>	<i>N_a</i>	<i>L_b</i>	<i>L_a</i>	<i>R_b</i>	<i>D_d</i>	<i>F_s</i>	<i>T_r</i>	<i>L_o</i>	<i>R_f</i>	<i>B_s</i>	<i>R_e</i>	<i>C_c</i>	<i>R_c</i>		
1	0.286	3.742	0.795	2.014	0.497	0.686	1.723	1.256	1.372	3.733	9.928	9.389	55	43.888	43.776		
2	0.451	2.979	0.847	1.774	0.564	0.744	2.147	1.442	1.489	2.929	0.736	6.371	33	25.259	22.878		
3	0.196	4.513	0.560	4.054	0.247	0.706	1.950	1.382	1.411	3.708	8.880	12.352	52	49.064	37.629		
4	0.247	4.026	0.764	2.178	0.459	0.660	1.600	1.213	1.319	4.493	13.856	13.601	103	65.752	84.916		
5	0.115	5.907	0.502	5.050	0.198	0.680	1.609	1.183	1.359	4.813	19.421	24.180	137	112.662	115.783		
6	0.190	4.591	0.621	3.295	0.303	0.741	1.859	1.255	1.482	4.219	10.861	15.202	88	68.154	70.135		
7	0.241	4.077	0.564	3.996	0.250	0.646	1.594	1.234	1.291	3.778	8.897	14.945	69	54.027	55.894		
8	0.292	3.701	0.693	2.648	0.378	0.648	1.516	1.169	1.297	2.967	3.461	8.243	30	33.229	25.659		
9	0.324	3.514	0.837	1.817	0.550	0.794	2.106	1.325	1.589	3.167	2.600	7.026	36	32.460	27.165		
10	0.442	3.008	0.743	2.308	0.433	0.673	1.465	1.089	1.345	11.333	2.768	8.612	35	30.220	32.136		
11	0.283	3.761	0.642	3.090	0.324	0.720	1.741	1.210	1.439	3.433	2.337	10.840	46	41.103	38.028		
12	0.755	2.302	0.699	2.604	0.384	0.768	2.118	1.379	1.536	2.722	0.307	7.271	28	18.385	20.299		
13	0.242	4.066	0.559	4.068	0.246	0.708	1.522	1.075	1.415	4.028	9.349	15.560	64	55.602	59.514		
14	0.261	3.918	0.639	3.112	0.321	0.721	2.233	1.548	1.443	3.024	1.865	8.389	35	33.018	22.610		
15	0.270	3.851	0.742	2.313	0.432	0.713	2.064	1.447	1.426	3.375	1.781	8.386	44	37.637	30.400		
16	0.248	4.015	0.526	4.606	0.217	0.665	1.484	1.116	1.330	2.833	6.841	10.748	28	35.642	25.082		
17	0.191	4.572	0.581	3.767	0.265	0.723	1.645	1.137	1.446	3.937	9.880	15.866	76	66.245	66.822		
18	0.193	4.552	0.648	3.030	0.330	0.751	1.941	1.291	1.503	3.828	2.950	12.633	68	58.551	52.665		
19	0.262	3.907	0.692	2.654	0.377	0.701	1.969	1.404	1.402	3.400	5.480	9.221	45	39.203	32.042		
20	0.376	3.260	0.748	2.275	0.440	0.668	1.776	1.328	1.337	2.683	3.458	7.168	30	27.461	22.589		
21	0.176	4.773	0.933	1.460	0.685	0.668	1.510	1.130	1.337	4.028	9.785	10.482	85	73.373	75.227		
22	0.302	3.636	0.507	4.945	0.202	0.689	1.570	1.139	1.379	3.452	3.548	13.824	44	40.069	38.647		
23	0.227	4.197	0.538	4.404	0.227	0.645	1.298	1.007	1.289	4.367	5.463	14.934	51	52.938	50.642		
24	0.290	3.712	0.939	1.444	0.692	0.800	2.610	1.632	1.599	2.967	0.348	5.153	30	28.207	18.384		
25	0.275	3.816	0.630	3.205	0.312	0.666	1.673	1.256	1.332	3.978	6.428	13.365	70	50.490	55.729		
26	0.332	3.472	0.623	3.273	0.305	0.682	1.611	1.181	1.365	3.792	18.368	14.419	75	49.047	63.516		
27	0.258	3.941	0.699	2.603	0.384	0.668	1.381	1.033	1.336	3.417	3.731	10.648	45	46.100	43.554		
28	0.270	3.847	0.532	4.490	0.223	0.729	1.565	1.074	1.457	3.119	8.695	12.438	37	40.024	34.454		
29	0.231	4.159	0.632	3.185	0.314	0.710	1.886	1.327	1.421	4.000	13.644	14.280	85	58.989	64.033		
30	0.144	5.279	0.596	3.582	0.279	0.709	1.905	1.343	1.418	4.267	7.088	16.492	102	81.541	75.939		
31	0.718	2.360	0.975	1.339	0.747	0.780	2.399	1.539	1.559	3.405	0.739	6.117	43	22.114	27.945		
32	0.100	6.331	0.425	7.049	0.142	0.708	1.874	1.325	1.415	4.562	18.189	25.584	123	108.142	92.860		
33	0.488	2.863	0.550	4.211	0.237	0.697	1.816	1.302	1.394	3.250	2.011	9.849	30	24.357	23.035		
34	0.237	4.109	0.678	2.767	0.361	0.663	1.576	1.188	1.327	3.574	7.040	10.793	50	47.256	42.095		
35	0.189	4.602	0.526	4.594	0.218	0.688	1.753	1.274	1.377	4.970	18.565	23.415	152	89.114	119.349		

Continued

36	0.2633.9020.5813.7740.2650.7281.8441.2661.456 3.310 7.844 11.053 41 39.355 32.375
37	0.2733.8250.5903.6610.2730.7982.1241.3301.597 3.333 7.032 11.615 49 41.157 36.849
38	0.2044.4240.5184.7340.2110.7660.4490.2931.532 5.106 7.736 23.431 34 84.448 115.971
39	0.3183.5460.7112.5190.3970.7301.8581.2721.460 3.625 4.960 9.950 50 39.397 39.295
40	0.2494.0110.6323.1840.3140.7472.1591.4441.495 3.208 4.907 9.391 40 37.417 27.700
41	0.3093.5990.6552.9650.3370.7421.9761.3331.483 3.910 8.967 12.917 75 47.854 56.278
42	0.4672.9280.5783.8080.2630.6521.9041.4621.303 2.833 5.365 8.841 30 23.512 20.526
43	0.3023.6370.6602.9250.3420.7442.1191.4241.488 3.167 1.875 8.949 39 33.727 27.380
44	0.1934.5470.7742.1230.4710.7311.9421.3281.462 3.750 6.130 10.581 70 58.515 52.721
45	0.1974.5040.7582.2130.4520.6931.6241.1721.385 3.955 1.881 10.819 62 58.063 52.892
46	0.3023.6370.5833.7410.2670.7821.9181.2271.563 3.667 1.206 12.469 51 41.564 41.562
47	0.2773.8020.5464.2630.2350.6931.5431.1131.386 2.976 6.362 11.412 34 37.245 30.551
48	0.1285.5800.6503.0150.3320.7121.7901.2571.424 5.837 20.97822.494211 128.136 167.849
49	0.5252.7610.6293.2200.3110.7542.2411.4861.508 2.667 1.780 7.059 23 19.253 15.476
50	0.2034.4410.6003.5320.2830.7611.8211.1961.523 4.625 12.943 18.188112 76.182 93.665
51	0.2374.1100.5564.1150.2430.7272.1181.4561.455 3.264 3.760 11.277 45 40.492 30.902
52	0.2074.4000.5384.3880.2280.7311.8211.2461.461 3.867 3.628 14.413 59 53.661 47.342
53	0.2264.2060.6453.0560.3270.6981.8411.3201.396 4.244 5.609 14.437 90 61.562 68.204

1.214, and the highest value of F_s (1.632) was observed in sub-basin no. 24, while the lowest values (1.033) were observed in sub-basin no. 27. High F_s values comply with areas of high density of lineaments.

3) Texture ratio (T_r)

The T_r value for W. Mujib is 10.682, and for the 53 sub-basins, it ranges from 1.381 (sub-basin no. 27) to 2.61 (sub-basin 24). The texture ratio values imply that the sub-watersheds are of high runoff.

4) Length of overland flow (L_o)

L_o parameter is one of the most significant independent parameters affecting the hydrographic and hydrologic development of a drainage basin [43]. The length of overland flow for W. Mujib is 0.705 km, whereas, the L_o values for the 53 sub-basins vary from 0.646 km (sub-basin no. 0.7) to 0.800 km (sub-basin no. 24).

4.1.3. Shape Parameters

1) Form factor (R_f)

R_f parameter is a dimensionless morphometric property and employed as a quantitative expression of the shape of watersheds [36]. High R_f values indicate a high peak flow of short duration. By contrast, an elongated catchment with low form factor has a low peak flow of longer duration. The R_f value for the entire W. Mujib is 0.214, and for the 53 sub-basins ranges from 0.142 (sub-basin no.

Figure 6. Stream order of W. Mujib Watershed.

32) to 0.692 (sub-basin no. 24). A considerable number of sub-basins have R_f which varies from 0.2 to 0.5, indicating that these sub-basins are elongated and more elongated in shape. Thus, they are characterized as having low peak flow of longer duration, and consequently have lower probability for severe flooding [39].

2) Shape factor (B_s)

The shape factor for W. Mujib is 4.154, while B_s values for the 53 sub-watersheds vary from 1.339 (sub-basin no. 31) to 7.049 (sub-basin no. 32), which denotes that elongated shape characterizes most of the sub-watersheds.

3) Elongation ratio (R_e)

R_e values for watersheds with low relief and simple topography come close to 1.0. Whereas values range from 0.6 to 0.8 for R_e parameter, and are restricted to watersheds with high relief, rugged topography, and steep slopes. The elongation ratio for W. Mujib watershed is 0.553, while it ranges from 0.425 (sub-watershed no. 32) to 0.975 (sub-watershed no. 31), where sub-basin no. 31 is a nearly circular sub-basin.

4) Compactness coefficient (C_c)

C_c parameter is independent of size of the catchment and depends mainly on slope. Low C_c values imply greater elongation and high erosion rates [43] [45]. The C_c value of W. Mujib is 4.305, while the C_c values for the 53 sub-basins vary

from 2.302 (sub-basin no. 12) to 6.331 (sub-basin 32); thus, high surface erosion is characteristic.

5) Circularity ratio (R_c)

R_c parameter is a highly useful morphometric measure in correlation with stream discharge. R_c is influenced by physical factors such as: geology, morphology climate, land/use, land cover of the watershed [46]. The R_c value for W. Mujib is 0.26, whereas the circularity ratios for the 53 sub-basins range from 0.100 (sub-basin no. 5) to 0.755 (sub-basin no. 12). R_c values indicate that W. Mujib and the 53 sub-basins are at the youth-age stage of geomorphic development, and most of them are elongated in shape.

4.2. Prioritization of Sub-Watersheds Based on Morphometric Analysis

Over the past decade, the morphometric analysis method has been elaborated and employed for prioritization of drainage basins of different sizes (sub-watersheds, mini-watersheds, and micro-watersheds) for soil and water conservation [27] [29] [31] [32] [34] [36] [37] [39] [42] [65]. The erosion risk parameters utilized for prioritization of 53 sub-basins connected to W. Mujib are: five linear parameters (bifurcation ratio (R_b), stream frequency (F_s), drainage density (D_d), length of overland flow (L_o), and texture ratio (T_r)). In addition, five shape parameters employed in the process include: shape factor (B_s), form factor (R_f), compactness coefficient (C_c), circularity ratio (R_c), and elongation ratio (R_e). Based on the range of calculated compound parameter (C_p) values and ranks (Table 4) for the 53 sub-basins of W. Mujib, they were classified into four groups:

- 1) Very high priority (<15);
- 2) High priority (15 - 30);
- 3) Moderate priority (30 - 45);
- 4) Low priority (45 - 60).

The spatial distribution of the four priority classes was determined. Figure 7 illustrates the 53 sub-basins classified into four priority groups based on the compound parameter (C_p) values. Out of 53 sub-basins, 15 sub-watersheds (28.3% of the total) came under very high priority (sub-basins nos. 1, 2, 3, 9, 12, 16, 27, 30, 34, 35, 37, 47, 50, 51, and 53). The second category of sub-basins is classified as high priority. It consists of 17 sub-basins (32% of the total) as follows: 3, 11, 14, 15, 17, 18, 20, 22, 25, 26, 32, 38, 39, 43, 44, 46, and 49). Although some of these sub-basins are connected with rangeland, bare land is also present. However eight sub-basins are located in the rejuvenation belt, while other sub-watersheds are part of the eastern sector of W. Mujib, an area which is less impacted by rejuvenation. Scattered irrigated agriculture based on pumping wells (Figure 8(a)), and rainfed cultivation (mainly cereals) is predominate (Figure 4). All sub-basins categorized as very high and high priority for soil conservation have greater erosional potential with high erosion risk. Thus, it is

Table 4. Calculation of compound parameters and prioritized ranks and classes based on morphometric analysis method.

Mini-watershed no	R_b	D_d	F_s	T_r	L_o	R_r	B_s	R_e	C_c	R_c	C_p	Priority Class/Rank
1	53	5	5	5	5	5	5	5	5	5	9.8	V.H 6
2	53	5	5	5	5	5	5	5	5	5	9.8	V.H 6
3	53	5	5	5	5	5	5	5	5	5	9.8	V.H 6
4	50	12	12	12	12	12	12	12	12	12	15.8	H 13
5	49	38	38	38	38	38	38	38	38	38	39.1	M 36
6	48	52	52	52	52	52	52	52	52	52	51.6	L 46
7	47	30	30	30	30	30	30	30	30	30	31.7	M 36
8	46	46	46	46	46	46	46	46	46	46	46.0	L 43
9	45	7	7	7	7	7	7	7	7	7	10.8	V.H 8
10	44	40	40	40	40	40	40	40	40	40	40.4	M 38
11	43	26	26	26	26	26	26	26	26	26	27.7	H 26
12	42	11	11	11	11	11	11	11	11	11	14.1	V.H 11
13	41	45	45	45	45	45	45	45	45	45	44.6	M 41
14	40	14	14	14	14	14	14	14	14	14	16.6	H 15
15	39	21	21	21	21	21	21	21	21	21	22.8	H 21
16	38	3	3	3	3	3	3	3	3	3	6.5	V.H 5
17	37	18	18	18	18	18	18	18	18	18	19.9	H 17
18	36	17	17	17	17	17	17	17	17	17	18.9	H 29
19	35	39	39	39	39	39	39	39	39	39	38.6	M 35
20	34	23	23	23	23	23	23	23	23	23	24.1	H 23
21	33	35	35	35	35	35	35	35	35	35	34.8	M 32
22	32	27	27	27	27	27	27	27	27	27	27.5	H 25
23	31	43	43	43	43	43	43	43	43	43	41.8	M 39
24	30	32	32	32	32	32	32	32	32	32	31.8	M 30
25	29	20	20	20	20	20	20	20	20	20	20.9	H 19
26	28	15	15	15	15	15	15	15	15	15	16.3	H 14
27	27	8	8	8	8	8	8	8	8	8	9.9	V.H 7
28	26	51	51	51	51	51	51	51	51	51	48.5	L 44
29	25	53	53	53	53	53	53	53	53	53	50.2	L 45
30	24	10	10	10	10	10	10	10	10	10	11.4	V.H 9
31	23	47	47	47	47	47	47	47	47	47	44.6	M 41
32	22	28	28	28	28	28	28	28	28	28	27.4	H 24
33	21	36	36	36	36	36	36	36	36	36	34.5	M 31
34	20	2	2	2	2	2	2	2	2	2	3.8	V.H 2

Continued

35	19	13	13	13	13	13	13	13	13	13	13.6	V.H 10
36	18	37	37	37	37	37	37	37	37	37	35.1	M 33
37	17	9	9	9	9	9	9	9	9	9	9.8	V.H 6
38	16	29	29	29	29	29	29	29	29	29	27.7	H 26
39	15	25	25	25	25	25	25	25	25	25	24.0	H 22
40	13	41	41	41	41	41	41	41	41	41	38.2	M 34
41	13	33	33	33	33	33	33	33	33	33	31.0	M 28
42	12	48	48	48	48	48	48	48	48	48	44.4	M 40
43	10	24	24	24	24	24	24	24	24	24	22.6	H 20
44	9	31	31	31	31	31	31	31	31	31	28.8	H 27
45	8	50	50	50	50	50	50	50	50	50	45.8	L 42
46	7	22	22	22	22	22	22	22	22	22	20.5	H 18
47	6	4	4	4	4	4	4	4	4	4	4.2	V.H 3
48	5	49	49	49	49	49	49	49	49	49	44.6	M 48
49	4	19	19	19	19	19	19	19	19	19	17.5	H 16
50	3	16	16	16	16	16	16	16	16	16	14.7	V.H 12
51	2	6	6	6	6	6	6	6	6	6	5.6	V.H 4
52	1	44	44	44	44	44	44	44	44	44	39.7	M 37
53	11	1	1	1	1	1	1	1	1	1	2.0	V.H 1

*V.H Very high priority; H high priority; M moderate priority; L low priority.

Figure 7. Final priority classes for the 53 sub-watersheds.

(a)

(b)

(c)

Figure 8. Irrigated agriculture based on pumping wells (a); rainfed farming on table lands (annual rainfall > 300 mm) (b); and irrigated agriculture based on the Mujib reservoir (c)
Source: Google Earth bro 1/1/2017.

considered necessary that potential areas should adopt soil conservation measures. Rill, gully and ravine erosion and landsliding activity are common on steep slopes (20° - 25° , and $>25^{\circ}$) where soft carbonate rocks of low shearing resistance are exposed. Sheet erosion is also active on gentle slopes (0 - 2°), mainly over table lands bordering the canyons downstream of W. Mujib (*i.e.*, the Qasr-Rabba area). Physical and anthropogenic factors account for high erosion loss. High topography, steep slopes of 10 - 15, 15 - 20, and >25 slope categories, the Kerak-Al-fiha fault and the northwest-southeast fault system and the branching minor faults and lineaments, largely contribute to high soil erosion loss.

Silty loamy soils have a high proportion of silt and fine sand, with low content of organic matter ($<3\%$), thus making them more susceptible to erosion [1]. Moreover, degraded rangeland, which occupies a vast area of W. Mujib watershed due to low annual rainfall, and marginality (semiarid and arid conditions), has a significant role in accelerating soil erosion. Rainfed agriculture is practiced over the western sub-basins (**Figure 8(b)**) ranked as very high, high, moderate and low priority for soil conservation. The expansion of cereals cultivation over the rangeland with annual rainfall (200 mm), increases the susceptibility to soil erosion [66]. Apart from the scattered irrigated farming, the eastern sub-basins form a poor grazing land with high soil erodibility. The third category of sub-basins is assigned as moderate priority. It consists of 16 sub-basins (30.2% of the total) as follows: 5, 7, 10, 13, 19, 21, 23, 24, 31, 33, 36, 40, 41, 42, 48, and 52). Sub-basins of this category overlap with sub-basins ranked as very high and high priority. Four of these sub-basins are located in rejuvenation belt, while the rest of these sub-basins are located in the eastern sector within the degraded range land and bare land, and all of them are subjected to the same physical and anthropogenic factors causing land resource degradation. Owing to high soil erosion rates and high sediment load discharge to W. Mujib reservoir [11], these sub-basins need urgent attention for implementing soil conservation practices, where the Mujib reservoir is promising to expand irrigated agriculture (**Figure 8(c)**). Irrespective of overlapping observed spatially, between the four priority classes; physical and anthropogenic factors were responsible for such a distribution, as illustrated earlier. However, the very high and high priority is more agglomerated than other priority classes. Sub-basins nos. 1, 2, 3, 9, 12, 16, 27, 30, 34, 35, 37, 47, 50, 51, and 53, are categorized as very high priority for soil conservation measures. Rainfed farming occupied the southwestern sub-basins subjected to rejuvenation, severe soil erosion and over-grazing, whereas the remaining sub-basins constitute rangeland areas. In northern Jordan, the rainfed farmers are aware of serious soil erosion, and its impact on future agricultural sustainability. They believe that effective land management is urgently needed to restore intensively exploited soil resources [67]. Other farmers are convinced that tree planting and afforestation are decisive in reducing soil erosion rates. The effects of conservation structures established during the 1980s (stone bunds,

contour stone terraces, and check dams) in the hilly lands of northern Jordan were significant in minimizing soil erosion rates. After launching a governmental program for conservation practice in the late 1980s, the estimated sediment yield for the years 1987-1990 in the KTD (Zerqa River) was considerably reduced [8]. It is also feasible to enhance the soil and water conservation techniques in practice by altering C, P, and LS factors of the RUSLE model which are considered the principal parameters in soil erosion. Also, by modifying farmers environmental attitudes and practices, these factors can be altered significantly [68] with the support of local governmental experts. C, P, and LS factors can be improved noticeably to reduce soil erosion rates, and to conserve moisture in the soil at the farm, hillslope, or sub-basin scale so as to maintain crop productivity. Slope length and steepness (LS) can be modified by shortening the length and reducing slope steepness. Traditionally, the highland rainfed farmers in Jordan have practiced terraced agriculture since the Iron age [2]. They modified LS factor by the construction of contour stone terraces combined with tree planting on different slopes (0° - 25°) to control soil erosion. The advantages of the intensification of present soil conservation measures, and applying the structural solutions to sub-basins ranked as very high, high, and moderate priority will aid in controlling soil erosion loss, and will protect soils from future erosion, reduce sediment loads to control high sedimentation in W. Mujib reservoir, and minimize peak flows across these sub-basins and the entire W. Mujib catchment. Stone terraces were normally placed in long rows along the contours at various intervals depending on the length and steepness of slope [69]. Terraced farming has been used extensively by farmers to control soil erosion and to conserve soil and water on the farm. Such techniques have been adopted since the Nabatean period, some 3000 years ago [3]. The structural remedy chosen was also aimed to minimize surface runoff, thereby increasing water infiltration in the soil. It is evident from historical and present-day experience that structural choice in soil conservation can be applied on both gentle and steep slopes particularly over sub-basins categorized as very high (sub-basins nos. 1, 9, 16, 34, and 35) and high priority (sub-basins nos. 4, 11, 17, 22, 25, 26, 32, and 46). All these sub-basins are utilized mainly for rainfed farming. Severe soil erosion and high sediment yields were recorded recently [11].

Nevertheless, structural solutions should be integrated with technology improving farming practice (*i.e.*, rotation and contour ploughing) of rainfed cultivation to reduce soil loss and improve crop productivity. Irrespective of the installation of effective conservation structures, enhancing the cropping practice is essential to control soil erosion on different slope categories, and terrain units connected with sub-basins classified as high and very high priority for soil conservation. Recent experimental results on soil erosion control and moisture conservation, indicate that the presence of rock fragments on soil surface were highly efficient in reducing runoff and soil erosion. Thus, at an ascertained level

of surface stone coverage (5% to 15%), runoff has been reduced by an average of 17% and 30% respectively [69]. Furthermore, the corresponding reduction in soil loss for both stone treatments above were estimated as large as 35% and 53% respectively. Nevertheless, the optimal utilization for these sub-basins is to protect the present vegetation cover, redeveloping of the natural vegetation, plantation of specific species of plant suitable for grazing, and planning for effective rangeland management [70]. Likewise, Sharaiha and Ziadat [71] suggest an alternative cropping system to control soil erosion in arid and semiarid areas of Jordan resembling W. Mujib. They argue that contour strip intercropping cultivation at a proper planting density (*i.e.*, 350 plants/m²) was found to be a promising farming practice to reduce runoff and soil erosion.

4.3. Validation of Priority Classes: Discriminant Analysis (DA)

The validity of prioritization of the 53 sub-basins was tested statistically using Discriminant Analysis. The intention is to test the hypothesis that there is a significant differences between the four priority classes achieved through the morphometric analysis method employed earlier, and if this hypothesis is substantiated to establish a system of a coordinate axis which discriminates between the recognized four priority groups (Figure 9). It is evident that there is a significant difference between the priority classes (1, low priority, to 4, very high priority). Statistical testing was conducted using Discriminant Analysis on a data matrix representing the four priority groups (*i.e.*, 5 × 11; 16 × 11; 17 × 11; and 15 × 11) with the associated ranking values (related to the linear and shape parameters) and including the Cp scores. The F test of Wilks lambda obtained is F ratio 89.3 with the degree of freedom V1 = 3 and V2 = 49. Referring to the table of

Figure 9. The scores of each sub-watershed connected to each priority class on the two discriminant functions: the 53 sub-basins are completely separated.

percentage points of the F-distribution, with $V1 = 3$ and $V2 = 49$, it is found that at 99.9 percent of confidence, the tabulated value is 6.17, which is significantly exceeded by the computed F ratio (89.3). Consequently, there is a high significant difference between each of the priority groups (Low, moderate, high, and very high), and the four priority classes are completely separate and distinct. Furthermore, 99.5 percent of the difference between the four priority classes is attributed to Discriminant function 1 (98.2 percent) and Discriminant function 2 (1.2 percent). It was also revealed that Discriminant function 1 is positively correlated with the ten erosion risk parameters (the linear and shape variables). Correlation values range from 0.841 to 0.870. By contrast Discriminant function 2 is also positively correlated with the erosion risk parameters, where a correlation values varies from 0.225 to 0.473. The scores of each sub-basin of the four priority groups on the Discriminant function 1 and 2 were plotted in figure. The plot illustrates highly distinct priority groups that are completely separated. With reference to the present results, it can be concluded that prioritization based on morphometric analysis is proven to be statistically valid, consistent and reliable, and of high capacity using the GIS plat form. The potential of the morphometric analysis approach as developed and elaborated by the pioneers [27] [29] [30] [31] [34] is highly appreciated and recommended for prioritization research.

5. Conclusion

High soil erosion rates are seriously threatening rainfed cultivation and rangeland over most of the sub-basins. The W. Mujib reservoir received a large amount of sediments annually following heavy rainstorms which are common in southern Jordan. In the current research, an integrated morphometric analysis method, GIS, and remote sensing approach were employed to prioritize 53 fourth-order sub-basins relating to W. Mujib. Appropriate soil conservation measures were then proposed. All sub-basins are ascribed a rank based on the priority for adopting soil and conservation measures. Consequently, all sub-basins ranked as very high, high, and moderate priority should be prioritized for soil conservation measures, so as to maintain the sustainability of rainfed farming. The results of prioritization based on Cp scores, reveal that sub-basin no. 53 has been ranked 1 with the lowest Cp score at 2.0; while sub-basin no. 34 is ranked as the second with compound parameter at 3.8, and sub-basin no. 47 ranked third; sub-basin no. 51 ranked fourth (the Cp score is 5.6). All these sub-basins are with very high priority (Figure 7). By contrast, sub-basins nos. 6, 8, 28, 29, and 45, are ranked as: 46, 43, 44, 45, and 42 with Cp scores at 51.6, 46, 48.5, 50.2, and 45.8 respectively and with low priority. All sub-watersheds with compound parameters less than 15 are ranked as very high priority, whereas, sub-basins with Cp scores ranging from 45 to 60 are ranked as low priority (Figure 7). W. Mujib and W. Wala have experienced severe soil erosion historically and pre-historically, and immense destruction of vegetation cover and environmental

degradation. With reference to prioritization of the 53 sub-basins, and the supplementary information regarding soil, slope, and land use/land cover, proper soil and conservation measures were suggested to minimize the adverse effect of soil erosion on environmental resources, rainfed farming, rangeland, and sedimentation rates in reservoirs in the W. Mujib basin and sub-basins. Past experience in soil conservation practice, and field observations indicate that farmers are acquainted with older traditional conservation techniques, and with the aid of help, they revive the traditional stone bunds, contour stone terraces, and check dams through the governmental soil conservation program started early in the 1980s. Furthermore, improvement of cropping practice was made and adopted to control soil erosion. The validity of prioritization of the 53 sub-basins was tested using Discriminant Analysis. It is evident that there is a significant difference between the priority groups (Low, moderate, high, and very high), and the four priority classes are completely separated, and distinct from each other. Consequently, it can be concluded that prioritization based on the morphometric analysis method is proven to be statistically valid, consistent, and reliable, and of high capacity using a GIS platform. The adoption of GIS and remote sensing, and the morphometric analysis method confirm the efficiency of this approach in prioritization of the W. Mujib sub-basins, and verify the competence of morphometric parameters in prioritization within a GIS environment. The current results are expected to help governmental officials in identifying priority sub-basins which need immediate adaptation of appropriate conservation measures, and efficient rangeland management.

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