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Geospatial Analysis for Tectonic Assessment and Soil Erosion Prioritization: A Case Study of Wadi Al-Lith, Red Sea Coast, Saudi Arabia

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Abstract: An investigation into tectonics and erosion reveals that they play an important role in causing uplifting, valley incision, and soil erosion. The analysis of drainage basins at different scales is irreplaceable in the development of sustainable plans, particularly in arid regions. Morphotectonics and morphometric characterization analyses are very effective methods for defining the evolution of different landforms, current-day tectonic activity, and hydrological and morphological signatures of basins under investigation. The reorganization of critical drainage basins and sub-basin risk priority ranking are essential for effective and accurate sustainable plans for drainage basin management and water resources. In this study, the coupling of geospatial techniques and statistical strategies was used to examine the tectonic activity and priorities in terms of soil erosion for 15 sub-basins of Wadi Al-Lith along the Red Sea coast of Saudi Arabia. Two effective models, namely, the relative tectonic activity model and the weighted sum analysis model, were applied for examining each geomorphological and hydrological characteristic based on an analysis of the morphotectonics and morphometric parameters. Regarding the relative tectonic activity model, the 15 sub-basins were classified into three classes of tectonic activity: low, moderate, and high. Sub-basins 5, 6, 13, and 15 were considered to be in class 1 (high relative tectonic activity). On the other hand, the weighted sum analysis model assigned the sub-basins into three different ranks: low-, moderate-, and high-soil-erosion priorities. The current study's results suggest that sub-basins 5, 6, 10, 13, and 15 were recorded within the high-soil-erosion zone and highly relative tectonic activity, covering approximately 53.52% of the total sub-basin areas. The relative tectonic activity and weighted sum analysis models proved their validity in the risk studies, which will be very useful for decision makers in various fields, including natural resources and agriculture.

Keywords: morphotectonics and morphometric analysis; drainage basin analysis; geospatial technique; Wadi Al-Lith Basin; Saudi Arabia

Citation: Bashir, B.; Alsalman, A. Geospatial Analysis for Tectonic Assessment and Soil Erosion Prioritization: A Case Study of Wadi Al-Lith, Red Sea Coast, Saudi Arabia. *Appl. Sci.* **2023**, *13*, 12523. https://doi.org/10.3390/app132212523

Academic Editors: Yannis Maniatis and Yosoon Choi

Received: 8 August 2023
Revised: 21 October 2023
Accepted: 8 November 2023
Published: 20 November 2023

1. Introduction

The interaction between tectonics and erosion has been a significant issue of discussion for several years among many scientists. Since the tectonic impacts on the Earth's surface processes have been observed and investigated widely, the erosional impacts have recently been recognized and linked to them [1]. The simplest queries raised regarding this issue concern the relationship between tectonics and erosion and determining the implication of this interaction. Tectonic geomorphology is one of the most helpful techniques for investigating the different processes of the Earth's surface, providing important clues regarding its general topography and erosional effects [1]. The drainage patterns and complex flow systems of a river are active processes in nature that change randomly through both space and time and are controlled by various parameters such as the geomorphology, geology, climatology, soil, and vegetation of a given landscape [2,3]. An analysis of different watersheds presents important insights into a catchment's evolution and present-day tectonic and soil erosion characteristics. Morphotectonic and morphometric analyses are two of the most significant quantitative tools that provide a wide range of parameters, extracting very valuable information in order to examine and assess the Earth's surface processes. It is highly recommended that watershed characteristics and hydrological conditions are evaluated through these analyses in order to help decision makers implement effective and suitable plans.

In terms of a literature review concerning the current topic, geomorphological analyses of various watersheds for an active tectonic assessment have been widely applied by many researchers in different regions. For example, Abdullah et al. [4] studied the relative tectonic activity and analyzed the deformation signals of watersheds west of Dokan Lake in Iraq using basin morphometric analysis and their drainage systems; Agrawal et al. [5] applied a morphometric approach to recognize active zones of deformation in a Meghalaya watershed in India; and Khalifa et al. [1] studied the watersheds of the entire East Anatolian Fault in eastern Turkey, resulting in the recent evolution of this major transform fault and enhancing our knowledge of the tectonic activity of continental major faults. On the other hand, the watershed prioritization method has been used and developed by several researchers for soil erosion studies. For example, Shekar et al. [6] prioritized the sub-watersheds of the Wyra basin in India using a morphometric analysis for soil erosion, and Rahmati et al. [7] have developed an automated GIS-based method for watershed prioritization in order to reduce possible uncertainties. Additionally, applying a morphometric analysis and watershed prioritization for flash flood hazard assessment were broadly presented by many previous studies, and López-Pérez and Fernández-Reynoso [8] presented a watershed prioritization analysis using morphometric analysis and GIS in tropical and some subtropical areas in Mexico. Several factors, such as soil loss, morphometric parameters, socio-economic activities of inhabitants, etc., may help in detecting and classifying subwatersheds based on watershed prioritization processes [9].

Several scientists have applied this method successfully and broadly in watershed prioritization projects. For example, the authors of [10] recognized a suitable location for a check dam in the Tarafeni River in the southwestern part of West Bengal. This was based on watershed prioritization using remote sensing, GIS, a sediment yield sediment model, and a morphometric analysis.

The purpose of this study is to explore the parameters related to the Earth's surface processes, topography, and hydrology conditions. An analysis of morphotectonic and morphometric parameters aims to investigate the activity change and soil variation of one of the main basins along the eastern Red Sea coast in Saudi Arabia. A comprehensive model of the relationship between tectonic activity changes and soil erosion priorities presents how these signals are distributed in the Wadi Al-Lith watershed. Due to the results, this paper provides decision makers and other interested authorities with a tectonic versus erosion model of an important region in Saudi Arabia, providing an example for researchers who intend to apply the same topic to different regions.

2. Study Area

Wadi Al-Lith is one of the most important basins along the Red Sea coast of the Kingdom of Saudi Arabia. Wadi Al-Lith is south of Jeddah City by approximately 200 km, in the western part of Saudi Arabia. It is located between longitudes of 40°10′ and 40°50′ N and latitudes of 20°00′ and 21°15′ E, with a total area of 3224.31 km^2 (Figure 1).

In terms of the geomorphology of the study basin, Wadi Al-Lith presents a typical wadi system with wide range of variations in basin topography. A maximum topographic elevation of 2657 m (a.s.l.) is observed along the high-relief mountainous range at the northern zone of the Wadi Al-Lith basin, whereas a minimum elevation is recorded toward the sea coastal plain in the southern part of the basin. Due to the general surface slope topography from the sea level, the Wadi Al-Lith basin could be classified into three different topographic classes as follows: (1) The first class is a maximum elevated mountainous upstream class (class c), which provides elevations between 500 m and 2657 m (a. s. l.).

This class zone is characterized by maximum-degree slopes and high rugged mountain areas. This class generally provides a number of sub-basins and tributaries joining the main channel of the Wadi Al-Lith basin. (2) The second class is a transition zone (class b) of small mountains with elevations between 100 m and 500 m (a.s.l.). It includes the Wadi Al-Lith mid-main stream and comprises the main waterways and channels coming from upstream [11]. This zone class shows a moderate level of gradient and the highest degree of incised wadies. (3) The third class is the sea coastal plain downstream zone containing different sizes of alluvial deposits. This pediment plain zone ranges in elevation between nearly zero and 100 m along the Red Sea shore line [11].

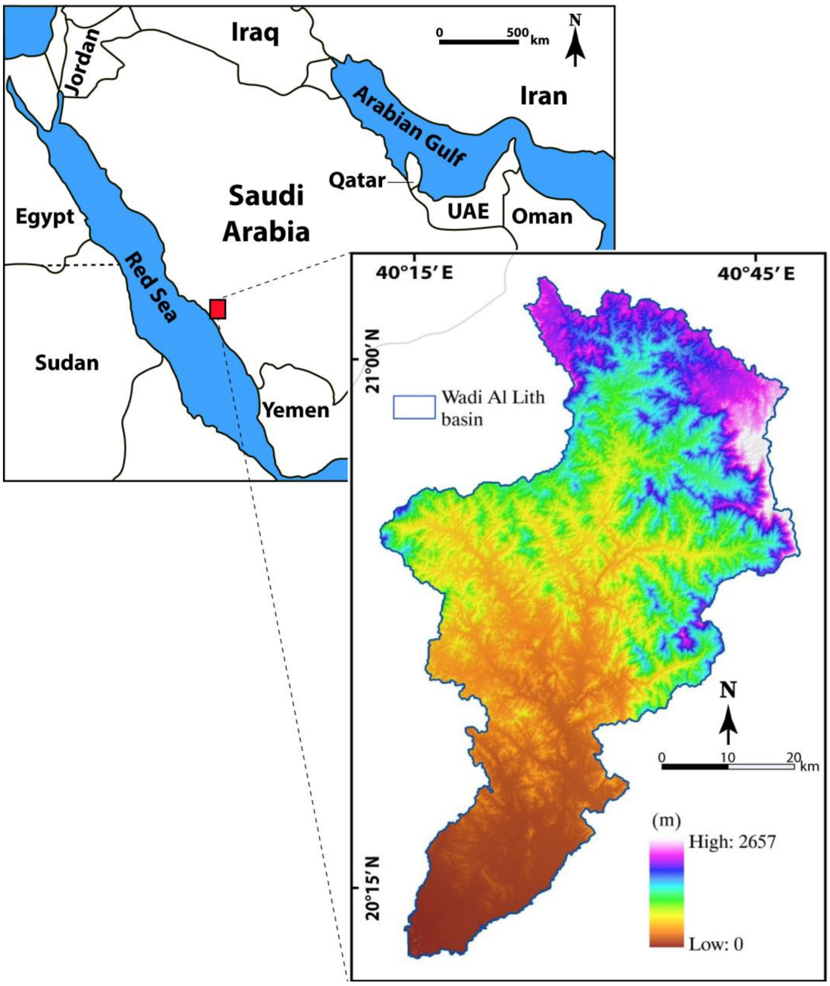

Figure 1. Location map of Saudi Arabia and digital elevation model of Wadi Al-Lith basin. The elevations are in m (M.S.L.).

Generally, the Kingdom of Saudi Arabia is one of the countries that are highly exposed to flash flood events that regularly cause various losses and damages [12]. Recently, the study basin was affected by huge floods, in November and December 2009 and 2010, resulting in a long list of victims and damage to properties. The Wadi Al-Lith basin is located within an arid to hyper-arid region. In terms of climatic conditions, the Wadi Al-Lith basin area receives its highest evaporation rate during the month of July at approximately 200 mm, while February holds the lowest evaporation record (111 mm) [12]. The rainfall is observed only during the winter season (November–March), providing a small quantity of rain over just a few days [12]. The general direction of the wind about the study basin was recorded from west to southwest and northwest to west during the summer and winter, respectively [12]. The highest wind speed reading that was recorded over this basin was

39 k/h, while the lowest speed was approximately 17.3 km/h, recorded in September and December, respectively [12].

3. Material and Methods

In this study, high-resolution datasets were collected and analyzed. The analysis of the ALOS PALSAR digital elevation model (ALOS DEM) with a 12.5 m spatial resolution was at the core of this work. The remotely sensed data of the DEM's raw form were acquired from the Earthdata website (ASF Data Search Vertex), https://search.asf.alaska.edu/, accessed on 15 May 2023. Six ALOS PALSAR scenes were collected and mosaicked to set up one digital elevation image. Additionally, topographic maps (1:50,000) of the Wadi Al-Lith basin were digitized and processed. Integration between ALOS DEM and topographic data assists with extracting and delineating many basin characteristics. The collected data were processed and analyzed using ArcGIS 10.4 and QGIS software 3.16. These two geospatial programs were used broadly and successfully in processing related data and extracting morphometric results. The raw data went through several steps in order to be ready for processing and extracting the results. The basic methodology applied in this study is illustrated in Figure 2. The current methodology began with rectification, calibration, and dataset corrections. Gap filling correction, flow direction, flow accumulation, pour point, snap pour point, stream orders, stream numbers, and stream length were applied via the hydrology tools in geospatial software to detect drainage networks, watershed delineations, and the cumulative calculations. The drainage systems extracted from ALOS DEM accurately matched the real drainage systems digitized from the topographic sheets. In this study, the Wadi Al-Lith basin presented 15 sub-basins utilizing the third order.

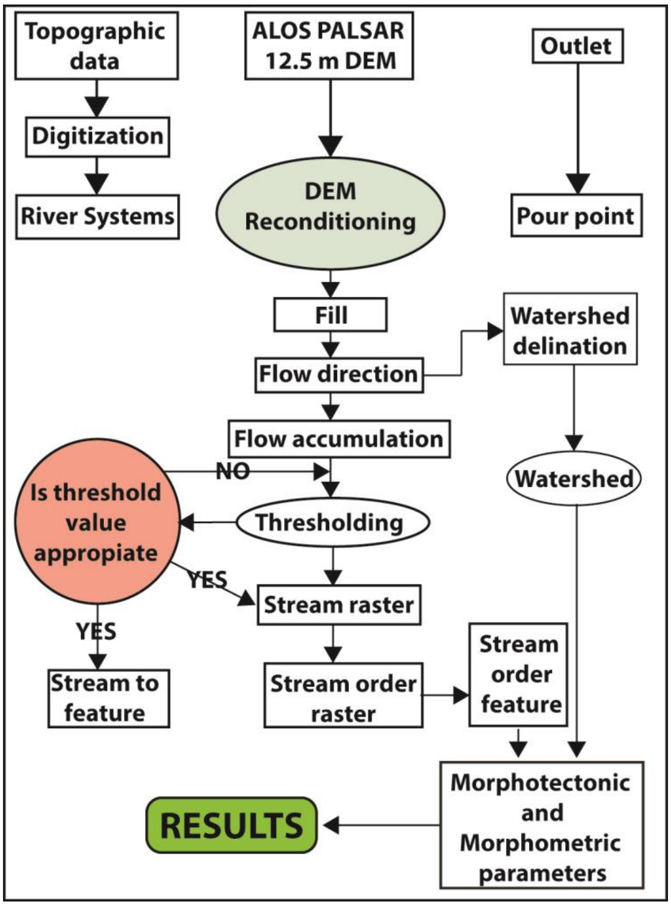

Figure 2. Flowchart of method applied in this study.

3.1. Morphotectonic Analysis

3.1.1. Valley Floor Width to Valley Floor Height Ratio (V_f)

The V_f parameter defines the uplifting and valley base plane. It is very useful to identify the valley shape and incision [13]. V_f is calculated as

$$V_f = 2V_{fw}/[(E_{ld} - E_{sc}) + (E_{rd} - E_{sc})]$$

where V_{fw} measures the valley floor width; E_{ld} and E_{rd} are the right and left valley elevations, respectively; and E_{sc} represents the average elevation of the valley floor [14].

3.1.2. Asymmetry Factor (A_f)

The A_f parameter is an effective parameter detecting the asymmetry level of catchments in order to evaluate their degree of tectonic activity [15]. This parameter is calculated through the following equation:

$$A_f = (A_r/A_t) \times 100$$

where A_r is the total area of the catchment to the right of the main catchment river, while A_t is the total area of the proposed catchment.

3.1.3. Drainage Basin Shape (B_s)

Young catchments are elongated in shape and consider a high level of tectonic activity that tends to cover active regions. Elongated catchments turn circular as the tectonic activity is decreased with time [16]. This parameter is detected as follows:

$$B_s = B_i/B_w$$

where B_i measures the length of a catchment from the headwaters to the mouth, and B_w measures the widest part of the catchment walls.

3.1.4. Hypsometric Integral (H_i)

The Hi parameter is a very useful index to show the distribution of elevations of a specific area, particularly a drainage catchment. This index helps to calculate the volume of a catchment that has not undergone any erosion actions. Hack [17] has expressed a simple formula to calculate this index as follows:

$$H_i = Elev_{mean} - Elev_{min/}Elev_{max} - Elev_{mean}$$

where $Elev_{mean}$ presents the average catchment elevation, $Elev_{max}$ presents the maximum catchment elevation, and $Elev_{min}$ defines the minimum catchment elevation.

3.1.5. Hypsometric Curve (H_c)

This parameter is also called the hypsographic curve. A hypsometric curve is a specific graph representing the part of land that exists at different elevations. It is illustrated by plotting relative areas versus relative heights [18].

3.2. Relative Tectonic Activity Model (RTAM)

In this study, the relative tectonic activity (RTAM) cumulative model was used for 15 sub-catchments. The average values of five computed indexes were estimated to yield the RTA and to aid in presenting the distribution of the relative active tectonics of the proposed catchment. For the RTA evaluation, we assigned the morphotectonic parameters into different tectonic activity classes, as high (class 1), moderate (class 2), and low (class 3).

3.3. Morphometric Analysis

The morphometric analyses applied in this study along with their mathematical equations and/or formulae are tabulated in Table 1. One of the main aims of this study was prioritizing sub-basins with respect to erosion level and flood hazard. Morphometric areal parameters such as drainage texture and density, stream frequency, elongation ratio, circularity ratio, form factor, and compactness coefficient were applied for the evaluation of the sub-basins prioritization method. In addition, morphometric linear parameters, such as bifurcation ratio, basin length, and overland flow average length, and morphometric relief parameters such as ruggedness number and relief ratio were also applied.

The authors in [19] have highlighted that basin prioritization and basin management practice mainly rely on the precise delineation of sub-basins, which, in turn, provides accurate detection of stream flow traces and its enclosing basin area [9]. The authors in [9] extracted its study drainage systems from SRTM DEM and provided spatial variation from the ground truth, particularly that close to the basin outlet [9]. They stated that this could be contributed to by a little differentiation in the general topography within the region of the plain.

Table 1. Morphometric parameters applied in this study.

Morphometric Parameters	Formula	References
Basin area (*A*)	Projected area enclosed by sub-basin boundary	[20]
	Horizontal projection of length of basin divide	[20]
Basin perimeter (*P*)	Distance between outlet and farthest point on basin boundary	[20]
Basin length (*Lb*)	Hierarchical order	[14]
Stream orders (*Lu*)	$Nu = N1 + N2 + \ldots Nn$	[21]
Stream numbers (*Nu*)	$Rb = Nu/Nu + 1$, where Nu is the number of streams of any	[22]
Bifurcation ratio (*Rb*)	given order, and $Nu + 1$ represents the number for the next higher order	
Channel length (*Lc*)	Lc = longest water path length in a given basin	[9]
Fitness ratio (*Rf*)	$Rf = Lc/P$	[23]
Form factor (*Ff*)	$Ff = A/Lb^2$	[24]
Shape factor (*Sh-f*)	$Sh\text{-}f = 1/Ff$	[14]
Relative perimeter (*Rp*)	$Rp = A/P$	[20]
Length area relation (*Lr*)	$Lr = 1.4 \times A^{0.6}$	[17]
Rotundity coefficient (*Rc*)	$Rc = Lb^2 \times \pi/4A$	[14]
Basin width (*Wb*)	$Wb = A/Lb$	[25]
Drainage texture (*Dt*)	$Dt = Nu/P$	[21]
Compactness coefficient (*Cc*)	$Cc = 0.282 \times P/\sqrt{A}$	[21]
Elongation ratio (*Re*)	$Re = Dc/Lb$	[20]
Circularity ratio (*Rc*)	$Rc = 4\ \pi\ A/P^2$	[26]
Drainage density (*Dd*)	$Dd = Lu/A$	[14]
Stream frequency (*F*)	$F = Nu/A$	[25]
Channel maintenance constant (*C-cm*)	$C\text{-}cm = 1/Dd$	[20]
Infiltration number (*Inf*)		
Drainage intensity (*Di*)	$Inf = F \times Dd$	[27]
Basin overland flow length (*Lg*)	$Di = F/Dd$	[28]
Basin relief (*H*)	$Lg = 0.5 \times Dd$	[21]
	$H = Z–Z$, where Z and z are the highest elevation and lowest	[29]
Relief ratio (*Rhl*)	elevation, respectively	
Ruggedness number (*Rn*)	$Rhl = H/Lb$	[28]
Melton ruggedness number (*MRn*)	$Rn = Dd \times (H/1000)$	[14]
	$MRn = H/0.5\ A$	[9]

3.4. Basin Prioritization Model (BPM)

The basin prioritization model has been widely applied in soil erosion studies [6,7,30]. The prioritization of the sub-watersheds model was applied based on the distribution of several morphometric features to assess the detection of soil erosion spots [31,32]. This model was designed based on the weighted sum approach (WSA), which was used for identifying the final priority of soil erosion impact at the scale of sub-basins. In this technique, the relative value for every single parameter was recognized, assessing the weightage of each single parameters regarding its significance in terms of the soil erodibility potential [6].

4. Results

4.1. Geometric Characteristics

The extracted values of the sub-basins' geometric characteristics (basin area, basin perimeter, basin length, average basin elevations, stream number, and stream length) are illustrated in Table 2.

Table 2. Basic geometric values of the studied sub-basins, stream number (Nu), and stream length (Lu).

Sub-Basins	Area (A) in km^2	Perimeter (P) in km	Length (Lu) in km	Elevations in m	Nu (I, II, III, IV, and V)	Lu in km
1	76.83	40.13	10.89	1:191	36 (18, 10, 6, 1, and 1)	52.95
2	223.28	92.61	27.18	41:618	73 (37, 15, 13, 8, and 0)	137.40
3	54.32	41.30	14.42	134:701	17 (9, 4, 4, 0, and 0)	30.76
4	188.40	76.12	21.22	188:1121	83 (42, 24, 11, 6, and 0)	118.37
5	458.20	118.5	39.31	181:1893	161 (81, 36, 21, 23, and 0)	273.28
6	190.92	70.32	21.22	336:1507	69 (35, 14, 17, 3, and 0)	109.62
7	39.30	27.68	8.27	608:1577	9 (5, 2, 2, 0, and 0)	18.43
8	21.75	25.59	6.21	844:2208	7 (4, 2, 1, 0, and 0)	12.47
9	146.08	77.53	18.59	1083:2142	53 (27, 14, 7, 5, and 0)	91.35
10	203.51	93.55	22.99	1082:2517	72 (36, 18, 7, 10, and 1)	134.56
11	35.57	25.96	8.61	1017:1901	15 (8, 4, 3, 0, and 0)	21.03
12	278.09	82.21	23.63	682:2585	103 (52, 26, 15, 10, and 0)	158.92
13	328.08	89.43	28.48	404:2657	123 (62, 29, 24, 8, and 0)	197.31
14	82.09	41.74	12.43	347:1978	31 (16, 8, 7, 0, and 0)	44.86
15	177.71	71.77	24.24	204:2099	65 (33, 12, 20, 0, and 0)	99.41

4.2. Morphotectonic Analysis

4.2.1. Valley Floor Width to Valley Floor Height Ratio (V_f)

The V_f parameter was calculated for 15 sub-basins along the streams and rivers of the study basin. The V_f extracted values ranged from 0.25 to 2.2, suggesting that most of the valleys were V-shaped. The lowest value of V_f was calculated for basins 2 and 10, while the highest values were defined for basin 2.2 in the most northern part of the study basin (Figure 3). Regarding this parameter, just two classes of tectonic activity were assigned as moderate and high. This classification presented moderate tectonic signals for six sub-basins, against nine sub-basins with high tectonic activity.

4.2.2. Asymmetry Factor (A_f)

The results of the asymmetry factor parameter presented various degrees of basin asymmetry. Values of V_f indicated that the symmetrical sub-basin features were observed for six sub-basins (basins 1, 4, 8, 11, 13, and 15). Accordingly, the remaining sub-basins showed three asymmetrical divisions: class 1 asymmetry was recorded for sub-basins 3, 4, 5, and 9; class 2 asymmetry was observed for sub-basins 2, 7, 10, and 12; and class 3 asymmetry was recognized for just sub-basin 13 (Figure 4).

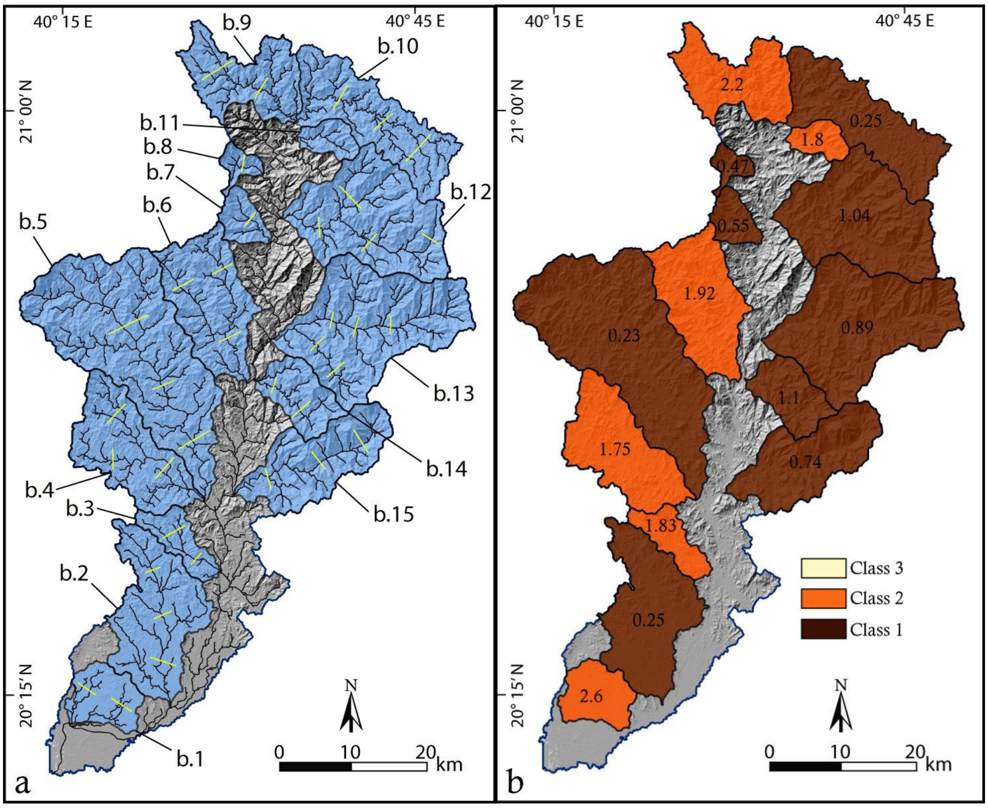

Figure 3. (**a**) Locations of V_f calculated sections. (**b**) Values and classes of V_f parameter for the studied 15 sub-basins.

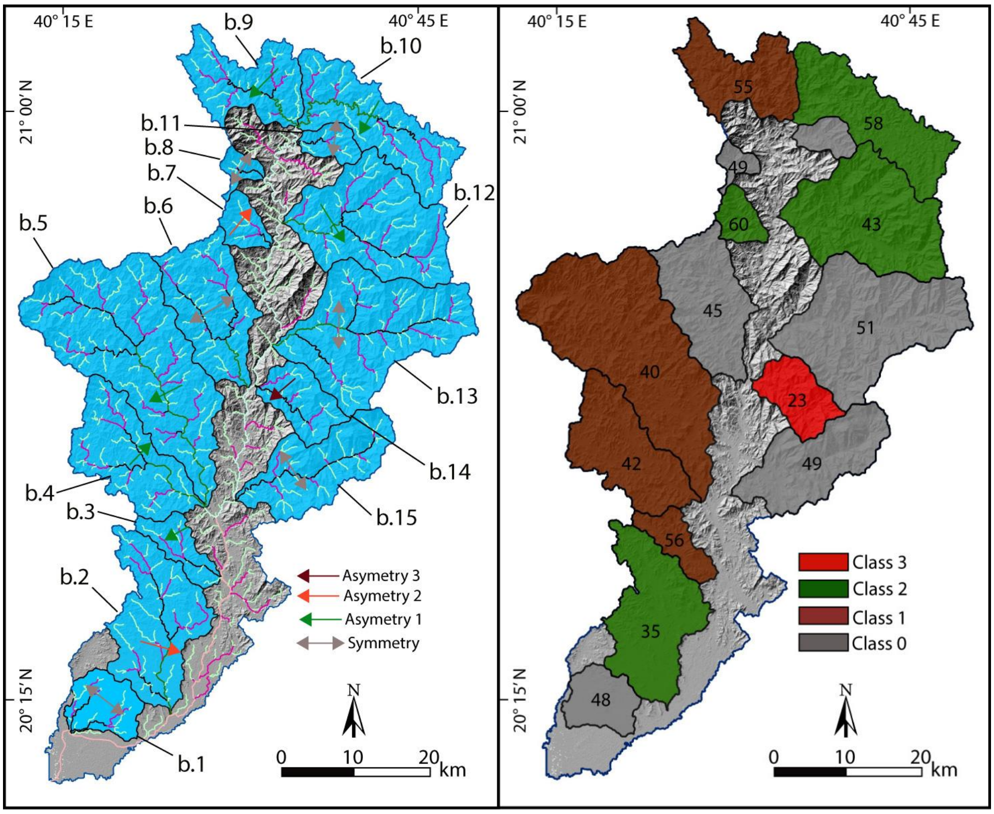

Figure 4. Map showing the sub-basin tilting directions and the different symmetry classes.

4.2.3. Drainage Basin Shape (B_s)

In this study, the Bs parameter presented values between 0.68 and 2.80. The lowest value was defined for sub-basin 9 at the northern part of the study basin, while the highest value was recognized for sub-basin 3 at the southern part of the study basin. The results of this parameter demonstrated that six sub-basins had low tectonic activity including sub-basins 7, 8, 9, 11, 12, and 13. On the other hand, only three sub-basins demonstrated a high level of tectonics (sub-basins 3, 4, and 15) (Figure 5).

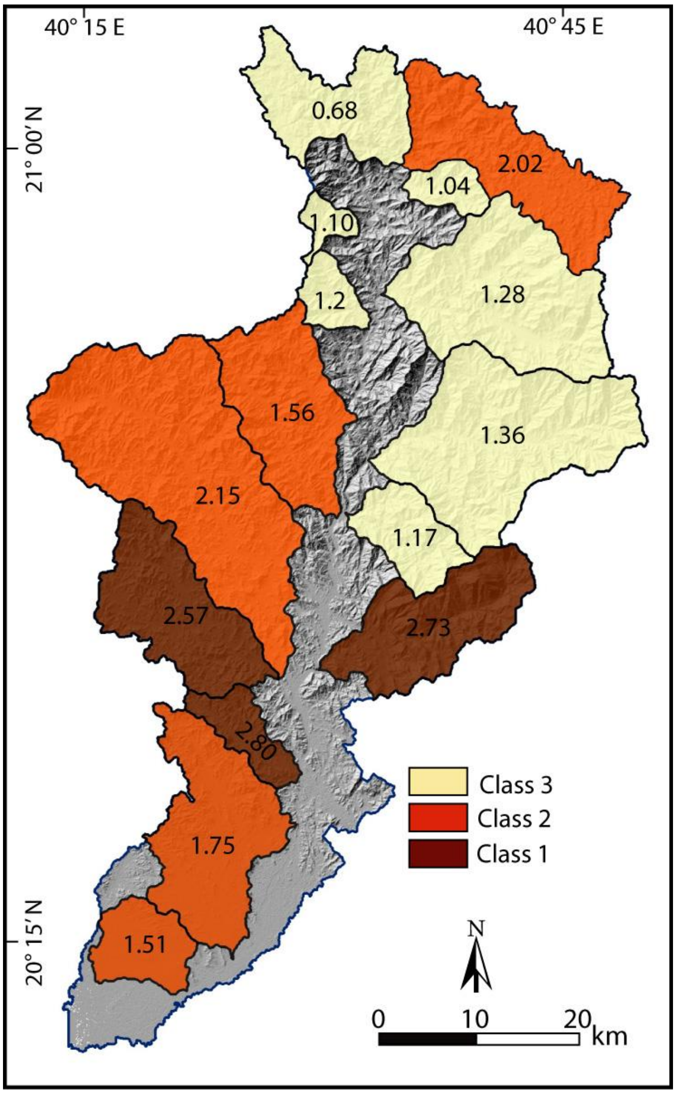

Figure 5. Map illustrating drainage basin shape parameter (B_S) values and their tectonic classes.

4.2.4. Hypsometric Integral (H_i)

The hypsometric integral parameter values ranged between 0.18 and 0.48. The results for this parameter suggested that the majority of the sub-basins were high in tectonic activity (sub-basins 2, 4, 5, 6, 9, 10, 12, and 15), covering most areas of the study basin. Only one sub-basin was low in tectonic activity (sub-basin 14) (Figure 6).

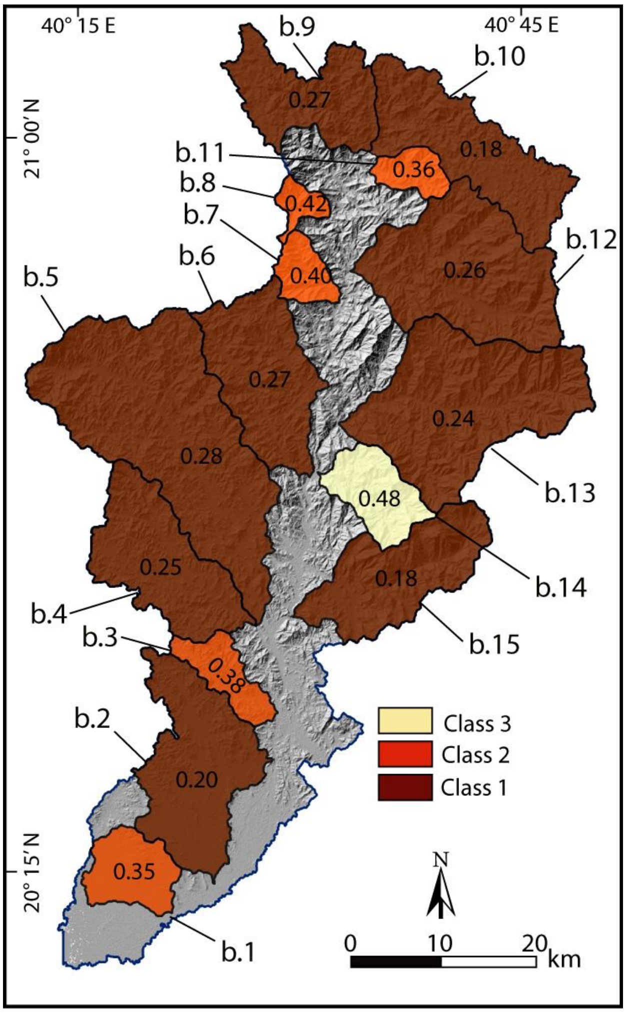

Figure 6. Map illustrating hypsometric integral parameter (H_i) values and their tectonic classes.

4.2.5. Hypsometric Curves (H_c)

Most of the sub-basins had straight hypsometric curves representing a moderate class of tectonic activity, including sub-basins 2, 3, 4, 7, 8, 9, 11, 12, 14, and 15. For this parameter, a concave hypsometric curve was initiated for sub-basin 1, while convex curves were illustrated for sub-basins 5, 6, 10, and 13 (Figure 7).

4.3. Relative Tectonic Activity Model (RTAM)

Five different morphotectonic parameters were applied and quantified for the Wadi Al-Lith sub-basins. These parameters were categorized by defining an average morphotectonic model, called the relative tectonic activity model (RTAM) (Table 3). Accordingly, this model was assigned three different classes of tectonic activity: class 1, indicating high levels of tectonic activity; class 2, describing moderate tectonic activity levels; and class 3, defining low levels of tectonic activity. The results suggest that class 1 was assigned for sub-basins 5, 6, 13, and 15, while class 3 was recorded for sub-basins 7, 11, and 14. Finally, sub-basins 1, 2, 3, 4, 8, 10, and 12 were denoted as moderate basins of tectonic activity (Table 3; Figure 8).

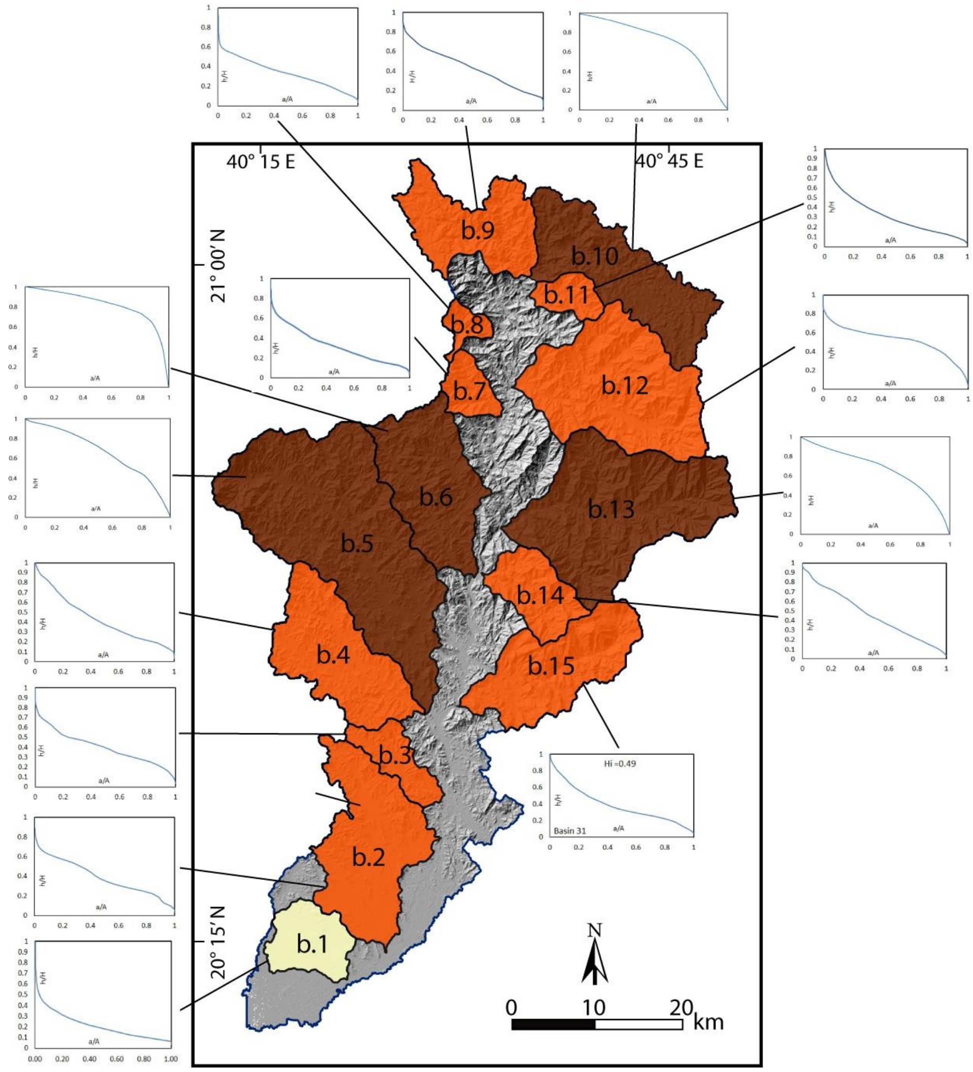

Figure 7. Map showing hypsometric curve parameter (H_c) values and their tectonic classes.

Table 3. Values and classes of morphometric parameters and relative tectonic activity model (RTAM).

Sub-Basins	Vf Class	Af Class	Bs Class	Hi Class	Hc Class	Average	*RTAM Class*
1	2	-	2	2	3	1.8	2
2	1	2	2	1	2	1.6	2
3	2	1	1	2	2	1.6	2
4	2	1	1	1	2	1.4	2
5	1	1	2	1	1	1.2	1
6	2	-	2	1	1	1.2	1
7	1	2	3	2	2	1.8	3
8	1	-	3	2	2	1.4	2
9	2	1	3	1	2	1.8	3
10	1	2	2	1	1	1.4	2
11	2	-	3	2	2	2.2	3
12	1	1	3	1	2	1.6	2
13	1	-	3	1	1	1.2	1
14	1	3	3	3	2	2.2	3
15	1	-	1	1	2	1	1

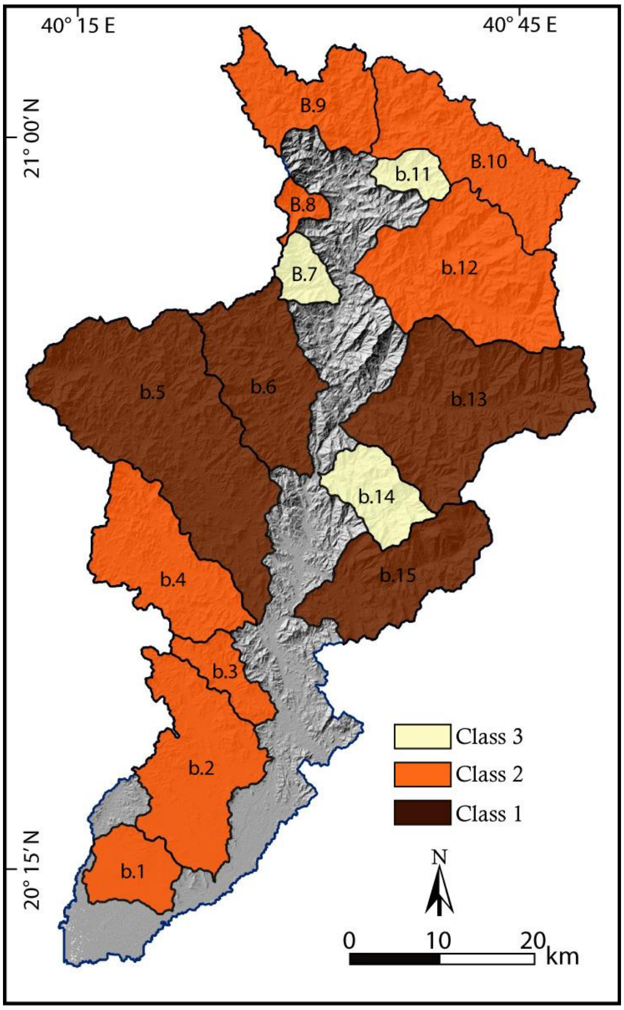

Figure 8. Map illustrating the distribution of the relative tectonic activity model (RTAM) of the study.

4.4. Morphometric Analysis

The calculated results of the applied morphometric parameters of the Wadi Al-Lith basin and its fifteen sub-basins are tabulated in Tables 1 and 2. The analysis of the main river of the Wadi Al-Lith basin demonstrated that the Wadi Al-Lith river was a sixth-order river. The estimated total length of the examined sub-basins was 1502.7 km with a total average bifurcation ratio of approximately 35.123, while the total number of stream segments reached 932.

The form factor parameter produced results between 0.26 and 0.64 for sub-basins 3 and 1, respectively. Similarly, the calculated numerical values of the elongation ratio (*Re*) of the study sub-basins ranged from 0.39 for sub-basin 3 to 1.19 for sub-basin 8 (highest value) (Figure 9). In this study, the numerical values of Cc varied between 1.22 and 1.84 for sub-basins 11 and 10, respectively, at the northeastern part of the study basin (Figure 9). The values of the drainage texture parameter varied from 0.27 for sub-basin 8 to 1.35 for sub-basin 5 along the western side of the Wadi Al-Lith basin. The values of the stream frequency ranged from 2.28 to 4.68. The highest value of this parameter was observed as 0.46 for sub-basin 1 at the most southern part of the study basin, while the lowest value was recorded at the northwestern part of the study area for sub-basin 7. The Dd values of all sub-basins varied between 0.46 and 0.68. The highest value was recorded for basin 1, while the lowest value was observed for basin 7. The values of the remaining 13 sub-basins are illustrated in Figure 9. Infiltration ratio parameter values were recorded between 10.73 and 32.28. The highest value of this parameter was recorded for sub-basin 1, while the lowest value was observed for sub-basin 7. In this study, the *Lg* parameter provided values from 0.234 for sub-basin 14 to 0.344 for sub-basin 1. Therefore, the southern part of the study basin tended to provide soil erosion conditions, compared with other parts of the study basin. Sub-basin 8 had a relatively higher relief ratio (0.21) compared with the other sub-basins (Figure 9). The Rn parameter results ranged from 0.13 to 1.23 for sub-basins 1 and 13, respectively.

Paramters	Sub-basins	Sb-1	Sb-2	Sb-3	Sb-4	Sb-5	Sb-6	Sb-7	Sb-8	Sb-9	Sb-10	Sb-11	Sb-12	Sb-13	Sb-14	Sb-15
Linear aspects	*Rb*	0.49	0.62	0.33	0.64	1	0.69	0.36	0.22	0.48	0.56	0.35	0.87	0.94	0.50	0.64
	Lc	0.21	0.6	0.28	0.53	1	0.52	0.19	0.16	0.5	0.85	0.2	0.67	0.64	0.28	0.56
Aerial aspects	*Rf*	0.58	0.71	0.76	0.76	0.92	0.81	0.76	0.68	0.72	1	0.88	0.89	0.79	0.75	0.86
	Ff	1	0.46	0.40	0.64	0.45	0.65	0.88	0.87	0.65	0.59	0.74	0.76	0.62	0.83	0.46
	Sh-f	0.40	0.86	1	0.62	0.88	0.61	0.45	0.46	0.61	0.67	0.54	0.52	0.64	0.48	0.86
	Rp	0.49	0.62	0.33	0.63	1	0.69	0.36	0.22	0.48	0.56	0.35	0.87	0.94	0.5	0.63
	Lr	0.34	0.64	0.27	0.58	1	0.59	0.22	0.16	0.5	0.61	0.21	0.74	0.81	0.35	0.56
	Rc	0.40	0.86	1	0.62	0.88	0.61	0.45	0.46	0.61	0.67	0.54	0.52	0.64	0.48	0.86
	Wb	0.59	0.69	0.31	0.75	0.99	0.76	0.4	0.29	0.66	0.75	0.35	1	0.97	0.56	0.62
	Dt	0.64	0.56	0.29	0.79	0.98	0.71	0.23	0.19	0.49	0.55	0.41	0.91	1	0.54	0.65
	Cc	0.7	0.94	0.85	0.84	0.84	0.77	0.67	0.83	0.97	1	0.66	0.75	0.75	0.7	0.82
	Re	0.91	0.52	0.32	0.43	0.42	0.38	0.65	1	0.68	0.4	0.45	0.68	0.64	0.44	0.38
	Rc	0.89	0.48	0.58	0.61	0.61	0.72	0.97	0.62	0.46	0.44	1	0.77	0.77	0.89	0.65
	Dd	1	0.9	0.82	0.91	0.86	0.84	0.67	0.84	0.91	0.97	0.86	0.83	0.80	0.8	0.88
	F	1	0.69	0.66	0.94	0.75	0.77	0.48	0.68	0.78	0.75	0.89	0.79	0.79	0.80	0.77
	C-cm	0.68	0.76	0.82	0.74	0.78	0.81	1	0.81	0.74	0.7	0.92	0.81	0.85	0.85	0.83
	Inf	1	0.62	0.54	0.85	0.64	0.64	0.33	0.57	0.7	0.72	0.77	0.65	0.63	0.63	0.63
	Di	0.93	0.74	0.77	0.98	0.82	0.86	0.67	0.78	0.81	0.75	1	0.90	0.96	0.96	0.91
	Lg	1	0.89	0.82	0.91	0.86	0.83	0.68	0.83	0.9	0.95	0.85	0.82	0.8	0.79	0.81
Relief aspects	*Rhl*	0.08	0.1	0.18	0.23	0.21	0.26	0.52	1	0.26	0.29	0.47	0.38	0.37	0.62	0.37
	Rn	0.1	0.28	0.26	0.47	0.82	0.54	0.36	0.63	0.53	0.77	0.42	0.07	1	0.72	0.86
	MRn	0.03	0.04	0.16	0.07	0.05	0.09	0.39	1	0.11	0.11	0.39	0.10	0.10	0.31	0.17

Figure 9. The values of morphometric parameters of the 15 sub-basins of Wadi Al-Lith basin using non-dimensional technique. Colors indicate calculations of linear, aerial, and relief aspects.

4.5. Soil Erosion Priorities and the Weighted Sum Method

The soil erosion priorities and priority ranks are tabulated and illustrated in Tables 4 and 5.

Table 4. Sub-basin classes due to morphometric parameters for soil erosion.

Sub-Basins	*Rb*	*Ff*	*Dt*	*Dd*	*F*	*Re*	*Rc*	*Cc*	*Lg*	*Rhl*	*Rn*	Compound Class	Priority
S-b1	10	15	7	1	15	14	12	3	1	15	14	9.72	15
S-b2	7	3	8	5	4	9	3	13	5	14	12	7.54	7
S-b3	14	1	13	12	2	1	4	12	12	13	13	8.81	10
S-b4	6	7	4	4	14	6	5	11	3	11	9	7.271	6
S-b5	1	2	2	8	5	5	6	10	6	12	3	5.45	1
S-b6	4	8	5	9	7	3	9	7	8	10	7	7	4

Table 4. *Cont.*

Sub-Basins	*Rb*	*Ff*	*Dt*	*Dd*	*F*	*Re*	*Rc*	*Cc*	*Lg*	*Rhl*	*Rn*	Compound Class	Priority
S-b7	12	14	14	15	1	11	15	2	11	3	11	9.90	14
S-b8	15	13	15	10	3	15	7	9	9	1	6	9.36	13
S-b9	11	9	11	3	9	13	2	14	4	9	8	8.45	9
S-b10	8	5	9	2	6	4	1	15	2	8	4	5.81	2
S-b11	13	11	12	7	13	8	14	1	7	4	10	9.09	11
S-b12	3	12	3	11	10	12	11	5	10	5	15	8.18	8
S-b13	2	6	1	13	11	10	10	6	14	6	1	7.270	5
S-b14	9	10	10	14	12	7	13	4	15	2	5	9.18	12
S-b15	5	4	6	6	8	2	8	8	13	7	2	6.27	3

Table 5. Classification of compound parameter values into three priority ranks.

Morphometric Parameters	Priority	Priority Rank
S-b1	15	Low
S-b2	7	Moderate
S-b3	10	Moderate
S-b4	6	Moderate
S-b5	1	High
S-b6	4	High
S-b7	14	Low
S-b8	13	Low
S-b9	9	Moderate
S-b10	2	High
S-b11	11	Low
S-b12	8	Moderate
S-b13	5	High
S-b14	12	Low
S-b15	3	High

5. Discussion

5.1. Discussion of Relative Tectonic Activity

Numerous numerical and field laboratory methods of research have been analyzed to investigate drainage networks that evolve along natural hazards, including seismicity, flooding, and soil erosion [33,34]. In some previous studies, researchers assessed the relative tectonic activity based on mountain front analysis without taking into account the evaluation of regional tectonic activity [13,35]. Others applied the average of the different morphotectonic parameters to assign tectonic activity signals into three different classes, which has provided a useful key and scheme in understanding the different geomorphological characteristics [31]. However, to date, such morphotectonic studies of Wadi Al-Lith have been very limited.

In this study, we assigned RTAM into three different classes, with class 1 representing high signals of tectonic activity, class 2 indicating moderate characteristics of tectonic activity, and class 3 recognizing the lowest level of tectonic activity deformation. The distribution of these RTAM classes is illustrated in Figure 8 and listed in Table 3. In this section, we discuss every single parameter that was applied in this study. The V_f values were effectively used to define valley geometries, and they were distinguished into V- and U-shaped valleys. While the lowest values of this parameter indicated V-shaped valleys and could be used to define an uplifting-related incision and active tectonic deformations, high values represented U-shaped valleys that had faced few tectonic activity signals. In this study, low V_f values were present for most of the Wadi Al-Lith area, referring to possible tectonic activity and continuous deformations. In contrast, moderated V_f values that were calculated for the eastern part of the study basin indicated signatures of some neotectonic movements (Figure 3). No high values were recorded in the study area, suggesting that all sub-basins posed tectonic signals. Therefore, we can infer that the Wadi Al-Lith area has been undergoing tectonic characteristics. Several researchers applied the basin block tilting measures to investigate the tectonic framework of basins [35,36]. The A_f parameter was applied in tectonic geomorphology to define the basin tilting degree due to the basin asymmetry factor. The basins were classified into horizontal basins or tilting basins. Tilting basins were classified into three classes due to their tilting degrees. A_f values provided A_f-50, which is the difference between a neutral value (50) and the calculated values [31]. In order to evaluate the RTAM, several researchers assigned four classes of tilting or asymmetry: symmetrical ($A_f < 5$), low degree of asymmetry (A_f between 5 and 10), moderate tilting (A_f between 5 and 10), and high degree of tilting ($A_f > 15$) (Figure 4). Generally, the elongated drainage basins are more likely to be found in areas characterized by high tectonic activity, and they tend to lose their shape, becoming more circular as the activity decreases [13]. Therefore, high values of the Bs parameter are directly correlated with the basin elongation rates. Accordingly, in this study, class 2 Bs values were represented by five sub-basins (1, 2, 5, 6, and 10) at the southern, eastern, and northern parts of the study area (Figure 5). Class 2 occupied the majority of the study area, while class 1 was recorded only for three sub-basins (3, 4, and 15). The hypsometric integral (Hi) is a factor for the distribution of elevations of the study basin where high values of this parameter might point to young, uplifting, active tectonic regions, and low values indicate possibly eroded areas that are characterized by low tectonic activity [31]. The majority of the Wadi Al-Lith study area is mainly represented by low values of hypsometric integral presenting class 1 tectonic activity. In this study, class 1 was recorded for sub-basins 2, 4, 5, 6, 9, 10, 12, 13, and 15. The highest value of the Hi was recorded for sub-basin 14, presenting low tectonic activity signals (Figure 6). The RTAM results showed that the majority of the sub-basins were controlled by medium to high tectonic activity, while the low class of tectonic activity was represented by just three small sub-basins. The RTAM analysis suggested that class 1 included four sub-basins, and class 2 comprised eight sub-basins (Figure 8). Thus, more than two-thirds of the studied sub-basin area demonstrated moderate to high tectonic activity due to the apparent morphological response.

5.2. Discussion of Soil Erosion Priorities

Despite the advantages of the geospatial techniques in processing raster and vector data and running mathematical models, the toolboxes of this software still contain gaps during morphometric analysis processing [9]. They require various datasets, including digital elevation models, topographic maps, stream orders shapefiles, and sub-basin delineation. These data should all be projected in the same coordinate systems.

The applied morphometric parameters in the aerial, linear, and relief aspects, as described previously, were recognized as erosion force assessment factors and have been applied for sub-basin prioritization. The authors in [8,9,37] highlighted that morphometric parameter aspects such as the drainage texture, bifurcation ratio, drainage density, overland flow length, ruggedness number, relief ratio, and stream frequency are directly proportional to the erodibility forces. Thus, the first level is described by the morphometric parameters providing the largest values, while the lowest morphometric parameter values indicate the last level of the erodibility factor. Conversely, other morphometric parameter aspects of basin characterization such as the compactness coefficient, elongation ratio, form factor, and circularity ratio present an opposite relationship with the linear morphometric aspects. Therefore, the first level or class of the erodibility factor provides the morphometric parameters representing the minimum value, and the last class describes the morphometric parameters with the highest values. Following Ref. [9], the weightages technique applied in this study was assigned to 30% for linear morphometric aspects, 40% for areal morphometric aspects, and 30% for relief morphometric aspects. These weightages were distributed equally with the two linear aspects, seven areal aspects, and two relief aspects. These various weightages were applied to these three different morphological parameter aspects to prevent the calculations from focusing only on the areal aspects. This was because it provided seven parameters in comparison with the other two aspects that had only two parameters for each. The general assessment of soil erosion suggests that higher soil erosion levels (high priorities) provide small numbers, whereas low priorities of soil erodibility are given high numbers in values reflecting a low condition in terms of soil erosion risk. All fifteen sub-basins of the Wadi Al-Lith basin were provided with a soil erosion priority level from 1 to 15 due to the characteristics of every single morphometric parameter. Each priority level was then assigned by its related weightage, and the final sum of all the applied morphometric parameters for every sub-basin was the general compound level or class for a given sub-basin. Due to the computed class of compound ranks, the sub-basins were recognized as a soil erosion priority level. The largest numerical result in terms of compound rank was assigned the lowest class of priorities, class 15, providing conditions for low vulnerability in terms of soil erosion. On the other hand, the compound rank lowest numerical value was assigned to the highest level of soil erosion priority (class 1), providing the most vulnerable conditions in terms of soil erosion risk. Finally, the fifteen soil erodibility classes of all of the sub-basins were classified into five priority ranks including low, moderate, and high.

The analysis of the morphometric parameters provides significant insight into landscape and landform characteristics and their natural conditions. In particular, examining the morphometric areal, linear, and relief aspects of catchments aids in understanding and assessing the geomorphological and hydrological conditions of the given watersheds [28,32]. Complete and comprehensive modeling of morphometric results could help accurate decision makers to go through precious development plans, particularly in terms of water resources and soil erosion management. The important morphometric parameter bifurcation ratio is mainly controlled by the change in the drainage systems during the development of the landscapes [9]. The authors in [9] highlighted that bifurcation ratio values that fall between 3 and 5 indicate the development of normal drainage systems over homogenous soils and rocks. Higher numerical bifurcation ratio parameter values provide well-dissected and deformed drainage catchments [21] with lower conditions for erosion and flood risks [34]. Form factor is recognized as the relationship ratio between the basin area and the square of the basin length. The smaller the numerical number of the form factor, the more elongated in shape the basin is [34]. The form factor parameter provides results between 0.26 and 0.64. Higher values of the form factor parameter indicate more circularity in the basins. Therefore, sub-basin 3 was the most elongated sub-basin found in the Wadi Al-Lith basin, and the sub-basin tended to be perfectly circular in shape. As the elongation ratio is recognized as a ratio between the circle diameter of the same area to a given catchment and the maximum length of the same basin, it is very useful to differentiate basins in terms of circularity levels. The authors in [36] defined five classes of Re due to the given numerical values: more elongated (<0.5), elongated (0.5–0.7), less elongated (0.7–0.8), elongated (0.5–0.7), and circular (0.9–0.1).

Accordingly, the classes of basins can be classified in terms of their circularity ratios into high, moderate, and low, indicating old, mature, and young stages of the basins [9]. The compactness coefficient parameter is usually used to examine the relationship between catchment hydrological characteristics and that of a circular catchment providing the same space as the hydrologic catchment [36]. The authors in [38] applied a compactness coefficient in their study and highlighted that if $Cc > 1$, then the catchment had an increased deflection from the circular shape; however, if $Cc = 1$ or less, the catchments behaved as a circular catchment. Accordingly, all sub-basins had record-high values, indicating that all sub-basins provided deviation from circularity; thus, they provided an increased concentration time before reaching peak water flow [37]. The drainage texture (*Rt*) is one of the most effective morphometric parameters in defining the ratio of the total numbers of rivers and streams of all orders to the perimeter of a given catchment that is affected by infiltration rate [21]. In this study, according to the authors in [28], textures could be classified into the following categories: very fine texture ($Dt > 8$), fine texture (Dt = 6:8), medium texture (Dt = 4:6), coarse texture (2:4), and very coarse texture (<2). The analysis of this parameter indicated that all sub-basins were providing information regarding very coarse texture conditions. The stream frequency (*F*) parameter can be described as the ratio between the total number of streams in a basin per square kilometer, reflecting the texture conditions of the drainage systems. The stream frequency parameters were classified in Ref. [9] into five classes as follows: very high ($F > 20$), high (F = 15:20), moderate (F = 10:15), low (F = 5:10), and very low ($F < 5$). The drainage density parameter (Dd) is a very effective indicator to define various environmental conditions and variables [38]. Many researchers have suggested a positive relationship between drainage density and rainfall conditions [39]. Generally, the high *Dd* values are associated with impermeable rocks. The author in [21] applied the length of overland flow (*Lg*) in his study, indicating that a low value of *Lg* (<0.4) is a signal of a strong channel and river erosion, while higher numerical values indicate strong conditions of soil erosion. The relief ratio parameter (*Rhl*) measures the general basin steepness, indicating the intensity rate of the erosion action. It is calculated by dividing the basin relief by the maximum length of the same basin [20]. The ruggedness number (*Rn*) can be defined as the result of the relationship between the maximum relief of a basin and drainage density [21]. The Rn results could be evaluated based on the elevation, variability, and slope of the contours. Sub-basin 13 had the lowest *Rn* value, indicating that the sub-basin was less prone to soil erosion and provided structural deformation in association with drainage density and relief. The remaining *Rn* values can be seen in Figure 9. Additionally, the lower Rn values suggested a low chance of soil erosion.

The fifteen sub-basins examined in this study for priority zonation showed different stream orders. Sub-basin 10 presented the maximum stream order (fifth-order stream) (Table 2). All sub-basins provided fourth orders distributed over the entire Wadi Al-Lith Basin (Table 2). The extracted values of the sub-basin's geometric characteristics (basin area, basin perimeter, basin length, and average basin elevations) were as follows: the largest sub-basin in area and perimeter was basin number 5, covering approximately 458.20 km^2 and 118.5 km, respectively, at the eastern part of the study basin. Additionally, the geometric analysis of this basin revealed that the shortest basin length was recorded for sub-basin 8, located in the northeastern corner of the study basin. In terms of elevation, the highest elevation was recorded for sub-basin 13, at the eastern part of the basin, whereas the lowest elevation was observed for sub-basin 1. The elevation results showed that the general slope was toward the southern parts of the study basin. The results for the analyzed sub-basins are shown in Figure 5, and the stream orders and numbers are illustrated in Table 2. The authors in [40] applied the morphometric analysis in their study and suggested that morphometric parameters such as basin overland flow length, bifurcation ratio, relief ratio, ruggedness number, drainage texture, stream frequency, and drainage density provide a direct influence on soil erosion. Meanwhile, other morphometric parameters including the form factor, circularity ratio, compactness coefficient, and elongation ratio have an inverse relationship with the soil erosion process [9]. This suggestion could be translated as follows: in those morphometric parameters, where a direct relationship exists with the soil erosion process, a higher class (lower numerical values) should be expressed by the highest values of the applied morphometric parameters, namely, related morphometric parameters. In other words, the fifteen sub-basins in this study were exposed to analysis through every single parameter of the related parameters; then, the sub-basins were ordered from class 1 to class 15 due to the value of the applied morphometric parameter. Therefore, the lowest parameter value described class 1, while the highest parameter value was given for the sub-basin of class 15 (Table 5). In terms of this new scheme, the bifurcation ratio resulted in its lowest value for sub-basin 5, which, in turn, was translated to class 1. Thus, sub-basin 5 (class 1; low related morphometric parameter value) provided the highest conditions of soil erodibility compared with the other 14 sub-basins.

As another example, the drainage texture parameter resulted in it highest value for sub-basin 8, which, in turn, was described by class 15. Thus, sub-basin 8 (class 15; high related morphometric parameter value) provided the lowest conditions of soil erodibility compared with the other 14 sub-basins. On the other hand, the second group of morphometric parameters that showed an inverse relationship to the soil erosion process was applied in this study. These inverse parameters provided higher classes for the higher morphometric parameters. Additional explanation and comparison are included in Figure 9. Then, an average assessment was built to distinguish between the 15 sub-basins, due to the results extracted from the areal, linear, and relief morphometric aspects (Table 4; Figure 10). This technique is called the weight sum analysis (WSA) [41].

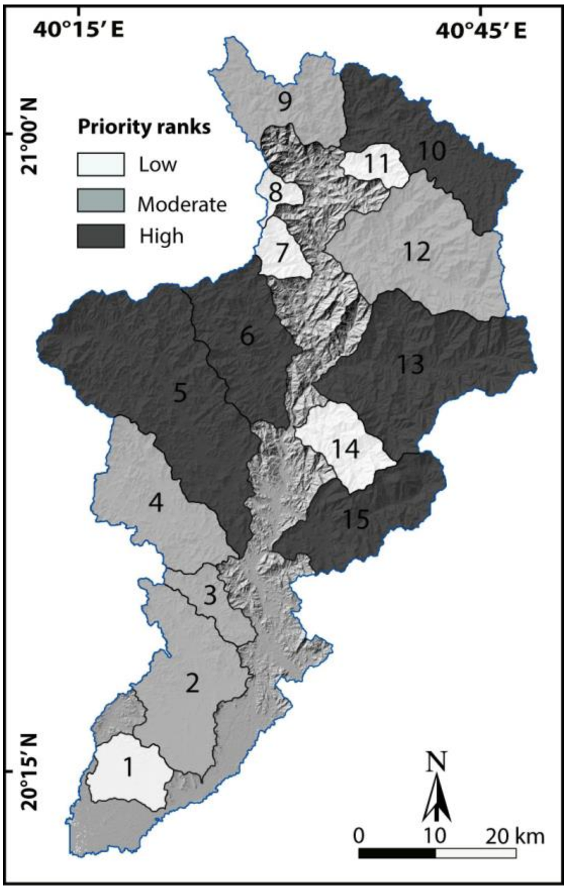

Figure 10. The priority classification of sub-basins at Wadi Al-Lith basin.

To provide additional explanation, the sub-basins were ordered in relation to their compound classes as sub-basin 5, sub-basin 10, sub-basin 15, sub-basin 6, sub-basin 13, sub-basin 4, sub-basin 2, sub-basin 12, sub-basin 11, sub-basin 3, sub-basin 11, sub-basin 14, sub-basin 8, sub-basin 7, and sub-basin 1. From this study, the results from this analysis state that sub-basin 5 was the most exposed sub-basin to soil erosion processes, while sub-basin 1 was the less vulnerable sub-basin to the influence of soil erosion (Table 4; Figure 10). Furthermore, the sub-basins of the Wadi Al-Lith basin were categorized into three priority ranks, high (1–5), moderate (6–10), and low (11–15), from the calculated parameter values, as tabulated in Table 5 and Figure 10.

In this study, the applied method of basin prioritization included several processing steps such as the digitization of contours and stream networks from the topographic maps, segmentation of rivers and streams to detect stream orders, measurements of stream length, numbering streams, and computing the geometries of every single sub-basin (area, perimeter, basin length, and elevations). The geospatial software was adopted and adjusted in this study to analyze the morphometric parameters and assist in investigating the sub-basin priorities against the soil erosion process. Studying the risks related to basins is a very important task and could be useful for several purposes including infrastructure development, recreational activities, cultivation, forestry, etc. [9]. Thus, knowledge of soil conditions and characteristics is highly recommended to aid in evaluating basin prioritization related to different kind of risks including flooding, soil erosion, and even uplifting signatures. The current study processed different sets of data including ALOS PALSAR DEM and topographic maps to achieve its target; however, it could be further enhanced and improved through a deep investigation of land cover, land use, and soil characterization.

6. Conclusions

In this study, a coupling of effective models and statistical methods was applied to prove the usefulness of remote sensing and geospatial analysis techniques in understanding the watershed behaviors and evaluating the relative tectonic activity and soil erosion priorities of 15 sub-basins of the Wadi Al-Lith basin. Different drainage basins provide different tectonic signals and hydrological conditions due to their morphological, hydrological, and soil characterizations. Thus, studying and investigating drainage basins plays a very important role in tectonic evolution and watershed management plans. The geomorphological signatures extracted via the analysis of the areal, linear, and relief aspects present consistency with the behaviors of the drainage basins. In addition, they assist in defining the relative tectonic activity classes and prioritization of different hydrological units. In the current study, the steps in terms of delineating the 15 sub-basins and quantifying the morphotectonic and morphometric parameters were explained through geospatial programs and high-spatial-resolution data. Then, effective techniques or models, relative tectonic activity (RTA), and weighted sum analysis (WSA) schemes were applied and formulated successfully in classifying the sub-basins in terms of relative tectonic activity and soil erosion prioritization. The relative tectonic activity model presented three classes of activity. Sub-basins 5, 6, 13, and 15 showed high tectonic activity signals, while the northern and southern parts provided moderate signals of tectonic activity. The WSA analysis suggested that sub-basin 5 presented a first-class soil erosion priority due to the integrated analysis. Priority classification helped in detecting the conceivable zones for further management under the prevailing hydrological and geomorphological conditions. The final prioritization ranks suggested that sub-basins 5, 6, 10, 13, and 15 fell within the high-soil-erosion zone. This indicated potential regions to be considered for preferential water-saving and soil conservation efforts for effective and accurate future planning in relation to drainage management. This is consistent with the RTA model that shows high tectonic activity signals with the same sub-basins. Therefore, precisely detecting the potential region for conservation management can provide favorable conditions in terms of sustainable development and the initiation of scale measures in similar regions. Integrating remotely sensed data, geospatial techniques, and statistical computation extracted as proof of the relative tectonic activity and weighted sum analysis is one of the advanced and effective methods in seismic hazard assessment and prioritization strategies. Moreover, this study presents useful data and information for decision makers, aiding them with a comprehensive model of seismic hazard assessment and soil erosion priority zonation of the Wadi Al-Lith basin along the Red Sea coast of Saudi Arabia. Therefore, this could be applied to other basins, particularly to those whose hydrological, geomorphological, and soil erosion processes are not well studied.

Author Contributions: Conceptualization, B.B. and A.A.; methodology, B.B.; software, A.A.; validation, B.B. and A.A.; formal analysis, B.B.; investigation, A.A.; resources, B.B.; data curation, B.B.; writing—original draft preparation, B.B. and A.A.; writing—review and editing, B.B. and A.A.; visualization, B.B.; supervision, A.A.; project administration, B.B. and A.A.; funding acquisition, B.B. and A.A. All authors have read and agreed to the published version of the manuscript.

Funding: This research was supported by the Researchers Supporting Project number (RSP2023R296), King Saud University, Riyadh, Saudi Arabia.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data are contained within the article.

Acknowledgments: The authors are grateful to the academic editor for the great editorial handling of the manuscript. The authors also thank the anonymous reviewers for their valuable suggestions and comments.

Conflicts of Interest: The authors declare no conflict of interest.

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