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Assessment of Flash-Flood Hazard in Arid Watersheds of Jordan

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Abstract

Flash flood hazard initiated by heavy rainstorms is common in arid Jordan, and often has induced immense damage to life and infrastructures. The current study presents a flash flood assessment for Wadi Rajil (northern Jordan) and Wadi Wuheida (southern Jordan) watersheds using ASTER DEM, GIS, and geomorphic field observation. A total of 23 morphometric parameters of paramount relation to flash flood risk estimation were extracted and calculated using ASTER DEM, GIS, and mathematical formulae developed for this purpose. Two methods were employed to assess flash floods and to generate flooding risk susceptibility maps. The first method is El-Shamy's approach, and the second is the morphometric hazard degree assessment method. Consequently, sub-basins with high and extreme flooding susceptibility were demarcated and displayed spatially using GIS. The maps so produced are meant to help planners and decision makers to devise appropriate plans to mitigate harmful flooding impacts, and to deal with flooding hazards.

Keywords

Flash Flood, ASTER DEM, Morphometry, Arid Watersheds,
El-Shamy's Approach, Jordan

1. Introduction

Morphometric analyses of drainage basins based on geoinformatics techniques and field collected data, are essential tools for flash floods hazard assessment. Relevant evaluation parameters can be employed to predict the hydrological behavior of the catchment, and geomorphic processes produced by exceptionally heavy rainstorms, and the resultant flash floods, including erosion type, rate, and sediment yield [1]. Hydromorphic explanation can be refined regarding the

conditions of flash floods generation, their destructive impacts, initiation of landslides and gully erosion, and the provision of abundant sediment supply. When field data are incorporated with remote sensing and GIS, it will provide precise information on morphometric properties of sub-basins and flash floods, and can be employed to assess areas prone to flash flooding, estimating flooding risk, and delineating the most susceptibility zones for flooding hazard. Rapid generated flows are frequently assigned to "flash floods" which are defined as "sudden floods with high peak discharges, produced by severe thunder storms that are generally of limited areal extent" [2] [3] [4]. Although flood hazards are most common in humid regions, they are equally characteristic events in arid and semiarid regions in the form of flash floods [5]. Climatic conditions gene-rating flash floods are common in arid Jordan, and they are initiated due to heavy rainstorms accompanied by high amount of precipitation falling in a short period of time. Thunder storms which produce flash floods are a localized process that takes place over the inland watersheds ranging in area from few ki-lometers to several hundred square km. Flashfloods in arid Jordan are extremely dangerous and of disruptive nature. They frequently cause extensive property damage, loss of life, and slope instability due to severe gully erosion and slump-ing. Other factors encouraging flash floods in Jordan are the morphological and ecological setting of arid watersheds (*i.e.*, the presence of long steep slopes, drai-nage networks, poor vegetation cover, low or negligible infiltration, and high velocity flows). In addition, human interventions render arid watershed highly vulnerable to flash flooding [6]. Past experience in arid coastal cities such as Aqaba and Eilat on the Gulf of Aqaba [7] [8] [9] [10] [11], Gulf of Suez, Red Sea and Sinai Peninsula [12] [13] [14] reveals that flash floods are classified as the most recurrent disaster recorded over the last three decades in the Middle East including Jordan. Available records of flash floods indicate that arid cities such as Aqaba, Ma'an, and Wadi Musa-Petra have been exposed to several flash floods of low magnitude (5 - 7 year return periods), medium magnitude (20 - 25 year return periods), and high magnitude (50 year return periods) [15] [16] [17] [18] [19] and caused immense damage to life and infrastructure. Moreover, un-predictable flash floods occasionally have caused serious problems to road net-works located in mountain valleys (*i.e.*, the Aqaba-Amman highway, Wadi Yu-tum, 15 km north of Aqaba), or on the desert plains (*i.e.*, the Amman-Aqaba highway west of Ma'an, the lower Wadi Wuheida), or the roads in Qa'a Azraq (lower WadiRajil). As an alternative to costly prolonged field monitoring of wa-tersheds to assess flood hazards, remote sensing and GIS techniques combined with hydro-morphometric analysis of watersheds provide a rapid, low cost and efficient tool to map and determine areas vulnerable to flood hazards and level of risk. Based on available free access ASTER and SRTM DEM's of reasonable resolution, it is possible to extract and calculate morphometric basic, linear, areal, shape, and relief parameters [20]-[26]. In the present research, two arid watersheds: Wadi Rajil (northern Jordan) and Wadi Wuheida (southern Jordan) were investigated using topographic, geological maps, air photos, field inspec-

tion, and ASTER DEM. Morphometric characterization and description of the hydrological pattern were conducted for both watersheds. The aim is also to generate flood hazards susceptibility maps based on El-Shamy's approach [27], and the morphometric hazard degree assessment method [28] [29] [30], in order to predict and demarcate the most hazardous sub-basins in terms of flooding, and the sub-basins which are expected to endanger Ma'an city, the Amman-Aqaba highway and Qa'a Azraq. The flood hazard maps produced were intended to help the planners understand the spatial distribution of flood hazard conditions, thus enabling them to prepare appropriate mitigation measures to reduce the negative impacts of flash floods. This research is also meant to improve the level of awareness among planners regarding flood geomorphology [31], and the essential role of morphometric analysis/information in the planning process [32] [33] [34] [35]. Moreover, attention is focused on providing advice for future planning on how to avoid destructive flood hazards in remote and data scarce areas. Appropriate measures for planning adjustment towards flooding hazards and management are recommended to help decision makers mitigate flash floods through the construction of flood prevention structures (*i.e.*, surface water harvesting systems, and groundwater artificial recharge). The recommended measures are flexible to the extent that these can be carried out by local administrative officials and the residents.

2. Study Area

Wadi Wuheida is an ephemeral stream which covers an area of 245 km^2 (**Figure 1**). It is located 35˚26' to 35˚41'E; and 30˚00' to 31˚14'N, and extends between
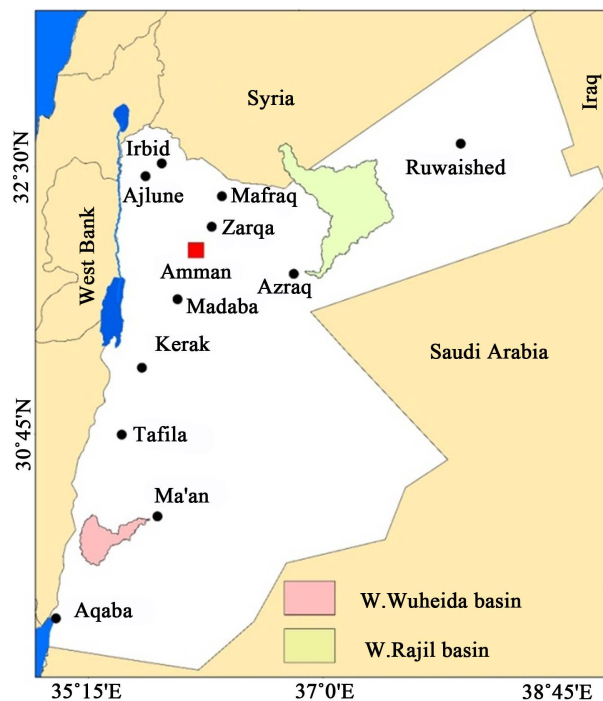

Figure 1. The study watersheds.

the crest line (rim), runs across Ra En Naqb escarpment and Sharah mountains in the west to the bridge of Ma'an on the Aqaba-Amman highway in the east, and discharges in El-Jafr depression. Wadi Wuheida and its tributaries drain part of Ras En Naqb escarpment (west of Ras En Naqb town), and part of Sharah mountains at a maximum average elevation of approximately 1719 m (a.s.l). The watershed rolls through steep to moderate and gentle-flat slopes across carbonate rocks of Upper Cretaceous age [36] towards El-Jafr depression in the east at an elevation of 1115 m (a.s.l) (Figure 2(a)). The watershed has a mushroom-like shape. The upper catchment is elongated north-south with an axis of 23 km, where as the long axis of the wadi is about 27 km and extendsin a west-east direction. A prominent slope variation exists across the catchment (0° - 5°
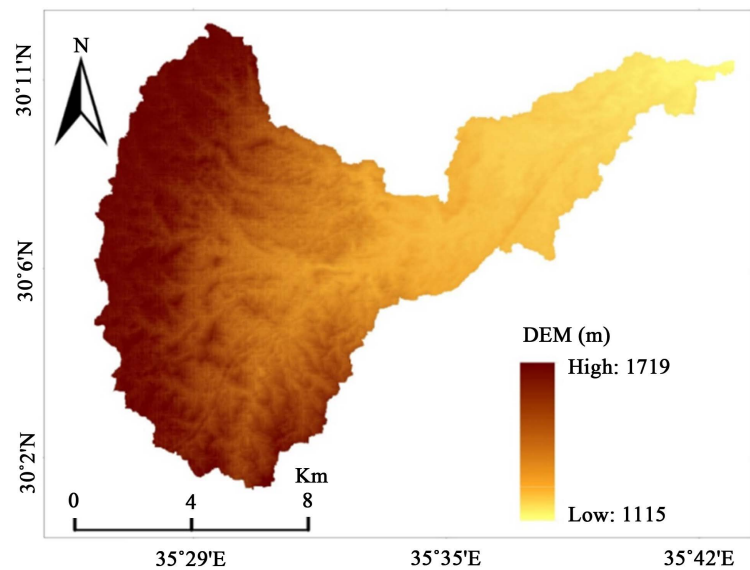
(a)
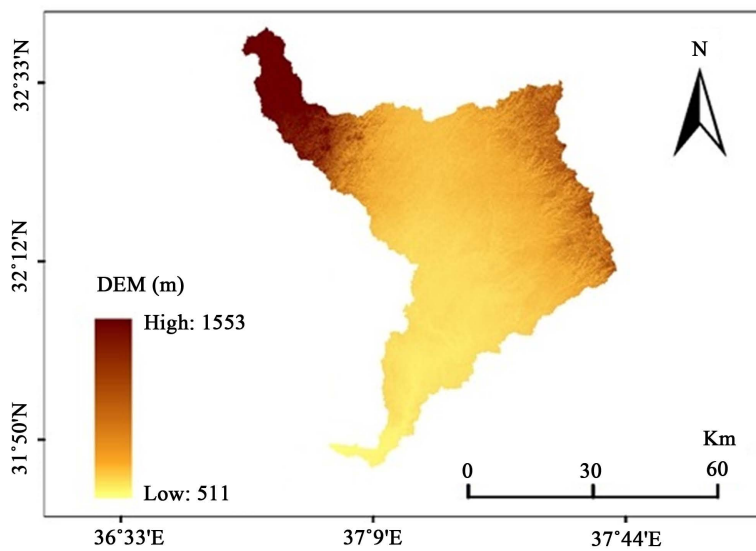
(b)

Figure 2. DEM of W. Wuheida (a) and DEM of W. Rajil (b).

to >25˚). Higher slope categories dominated the upper reaches (15˚ - 20˚, 20˚ - 25˚, and >25˚). Whereas, slope categories of 0˚ - 5˚, 5˚ - 10˚ and 10˚ - 15˚ dominated the lower catchment (Figure 3(a)). The north-south elongation of the upper watershed locates it within the track of depressions which run either from west to east (frontal storms) or from southwest to northeast (Red Sea trough storms). The mushroom shape of the upper catchment comprises 56% of the total area of the watershed. Thus, it provides a larger headwater area, which consists of highlands of elevations > 1400 m and receives a higher annual rainfall approaching 160 mm. In this regard, topographic characteristics of the watershed combined with the higher rainfall and slopes encourage high runoff potential. The catchment is classified as sixth order basin and of dendritic drainage pattern (Figure 4(a)). The Wuheida watershed-Ma'an-and El Jafr area is part of the Arabian Surface (the Oligocene peneplain) which has developed in the Eocene sediments [37].

(a)

(b)
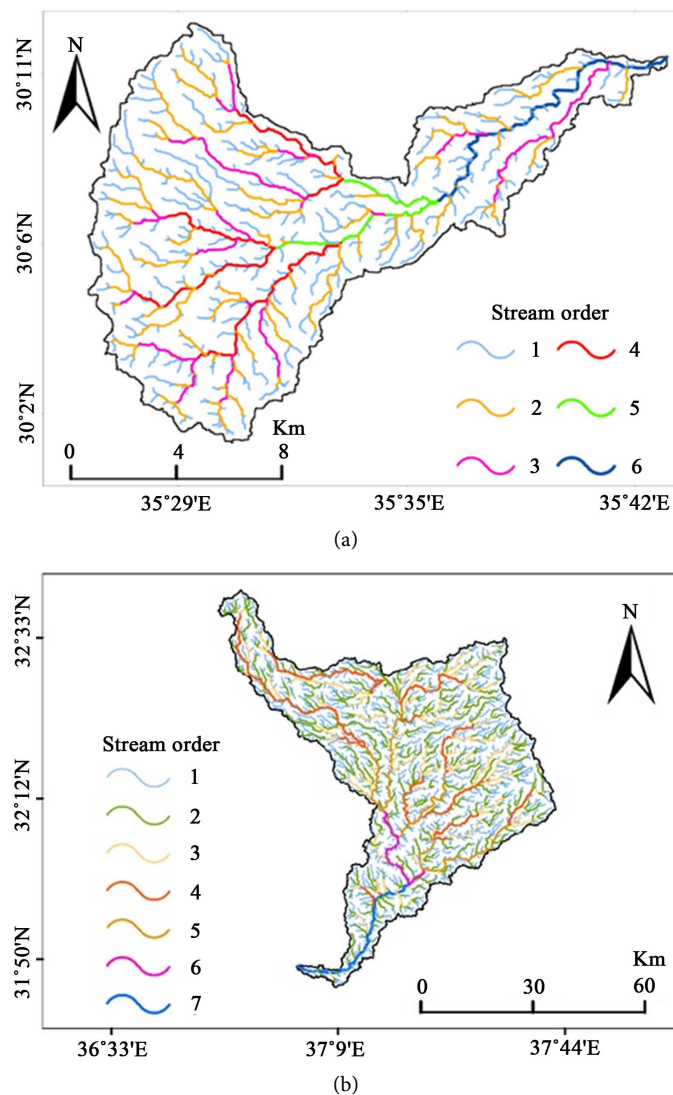
Figure 3. Drainage and stream order of W. Wuheida (a) and W. Rajil (b).
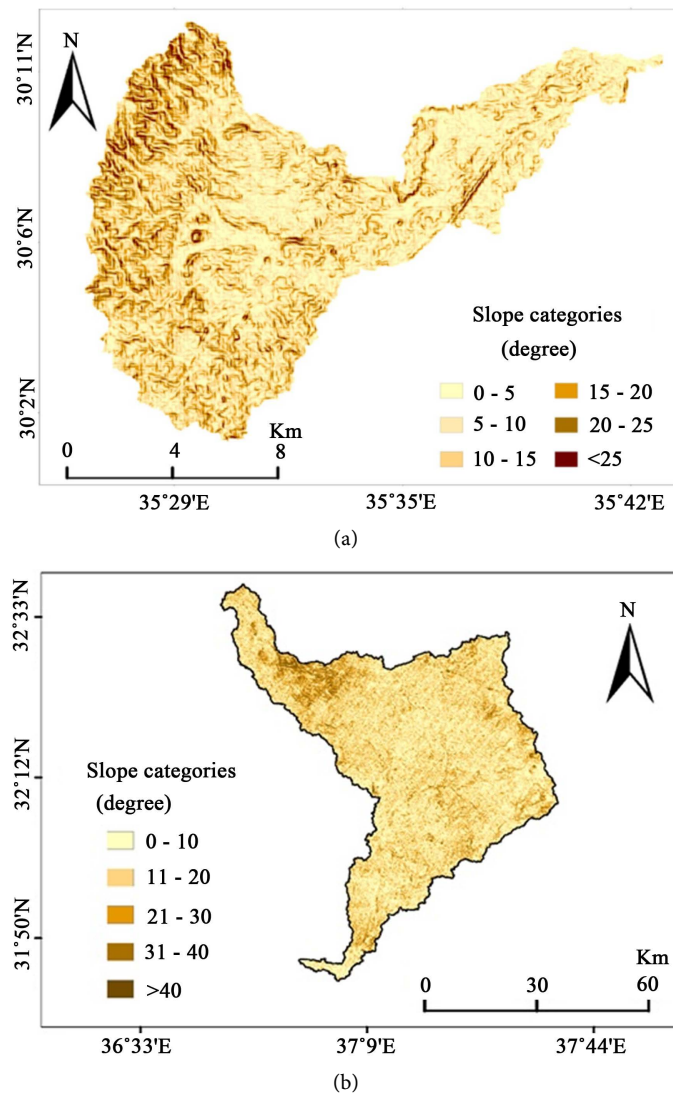
Figure 4. Slope categories of W. Wuheida (a) and W. Rajil (b).

Since early Miocene, and through Pliocene and Pleistocene, tectonic disturbances have affected the western and southwestern rims of these surfaces, thus giving rise to Ras En Naqb escarpment and Sharah mountains; uplifting of the eastern shoulder of the Rift; and basalt flows (Miocene to Pleistocene) to the south of El Jafr depression and the north eastern part of the Central Plateau including parts of Wadi Rajil catchment. Remnants of the Arabian Surface are still standing around Ma'an (including lower W. Wuheida), where a flat gentle stone Hamada surface formed and consists of wind-eroded chert residue, the flint-strewn "Hamada desert". The B^2/A^7 aquifer of Upper Cretaceous rocks constitutes the main aquifer in the catchment, and secure recharge at the headwater within the Asharah mountains and Ras En Naqb escarpment. Towards El-Jafr depression to the east, it becomes confined. The B^2 (the Amman formation) consists of limestone with chert inter bedded with phosphatic layers and marls. Further, A^7 (the Wadi Sir formation) is comprised of hard crystalline do-

lomitic limestone, chalky limestone with chert bands and nodules. Um Rijam-chert limestone formation (B^4) aquifer consists of limestone and chalky limestone [36] [38]. The B^4 aquifer receives limited water recharge during flash flooding [39]. The climate of Wadi Wuheida watershed is arid (BW). Rainfall amounts vary from 120 - 160 mm in the upper part, to 40 mm in Ma'an. Summer temperatures are hot and dry and winters are cold and relatively wet. Precipitation over the catchment is subjected to remarkable fluctuations. Relatively high precipitation in the upper catchment is affected by the orographic factor of Ras En Naqb and the Sharah Mts. Convective thunder storms which frequently occur in the fall (October-November) and spring (March-April) are influenced by the effect of the Red Sea trough and result in heavy rainfall events [40]. Several south-deepening Mediterranean depressions may affect southern Jordan from December to February. Snow may fall at high elevations (*i.e.*, Ras En Naqb and Asharah highlands), and freezing temperatures were recorded in January and February. Average monthly temperatures range from 30°C (summer maximum) to about 7° (winter minimum). Absolute average yearly maximum is approaching 43°C, and absolute yearly minimum may reach-8°C [41]. The low amount of rainfall results in poor vegetation cover, comprising of scattered acacia, tamarisk and cenapod, and some annual grasses. The land use/land cover is restricted to scattered and small patches of olive trees and woods in the highlands, and limited irrigated farming in El-Jafr and Ma'an.

Wadi Rajil watershed is located between 31°45' and 32°36'N and 36°45' and 37°43'E (Figure 1). The catchment has an area of 3085.87 km² with 7.6% (236.469 km²) of the total surface located in Syrian territory. The wadi is considered one of the major wadis entering the Azraq depression from the north. Wadi Rajil takes a NW-SE direction in the source area, then the direction changes from NE to SW, until it is terminated in the Azraq depression. The general shape of Wadi Rajil is trapezoidal, with its long axes generally oriented NE-SW direction. Terrain elevation ranges from 1553 m a.s.l at Salkhad in Syria, to 511 ma.s.l in Qa'a Azraq (Figure 2(b)). The entire Wadi Rajil watershed was found to be of seventh order (Figure 3(b)). Topographically, most of the catchment is nearly flat (0° - 2°), and undulating (2° - 10°) (Figure 4(b)). Wadi Rajil is part of the limestone plateau in east Jordan. 86.2% (2770.8 km²) of the total catchment area is covered by six basalt flows, tuff, and volcanic eruption that originated mainly in Jebel el Druz in Syria from the early Miocene to historical time.

The youngest deposits exist in the watershed, the gravel and sand are of fluvial origin. These deposits cover 3.07% of the total catchment area, while the outcropping formations of Eocene age [42] are: the Rijam and Wadi Shallala formation in the central and eastern part of the catchment. It occupies 10.7% of the total catchment area. 16 fourth-order sub basins were demarcated in W. Rajil (Figure 5(b)).

Heavy thunder storms occur in April and May, causing major floods and inundation in the lower catchment and Qa'a Azraq. Flooded water remains in the
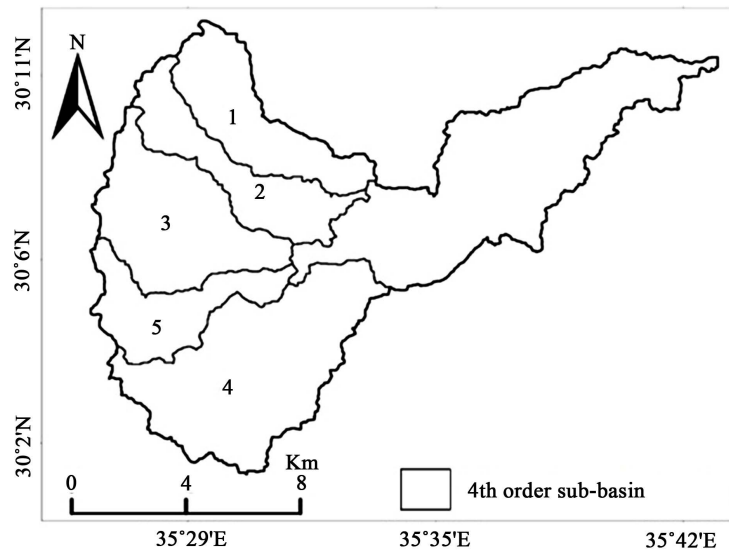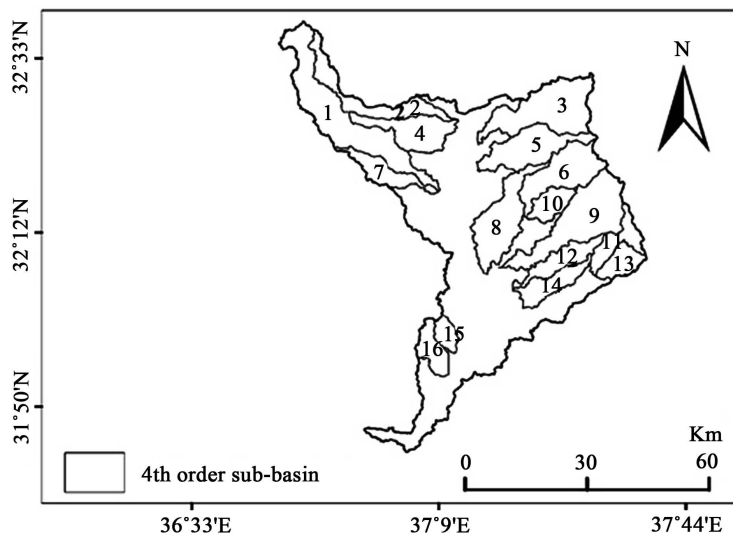
Figure 5. Fourth-order sub-bsins for W. Wuheida (a) and W. Rajil (b).

Qa'a for a few months before evaporation. The surface water potential of Wa-di Rajil can be utilized for groundwater artificial recharge, where the calculated flood volumes are: 0.95, 16.5, 36.9, and 61.5 MCM for 10, 25, 50, and 100 year return periods [43]. Such large amounts of water encourage surface water harvesting and groundwater recharge, thus, protecting Azraq town and the irrigated farms from flooding. Deep long trenches refilled with available basalt boulders and gravel have been suggested for artificial recharge in Wadi Rajil and for other comparable watersheds in the northern Badia of Jordan. Annual rainfall ranges between 50 mm (Azraq town) to 300 mm close to Salkhad in Syria. The average annual rainfall over Wadi Rajil is about 127 mm. Due to aridity, large seasonal and diurnal variation in temperature exist from a maximum 45° C in August to −6°C in January.

3. Materials and Methods

3.1. Data Source and Methods

Quantitative morphometric analysis of Wadi Rajil and Wadi Wuheida watersheds was performed using toposheets (1:50,000, and 20 m contour interval), ASTER DEM and Arc GIS (10.1) software packages. ASTER DEM is provided on line cost free to all researchers, and is available in Geo TiFF format and of 30 m spatial resolution. Recent investigation conducted on the Dead Sea (Jordan) to test the validity of ASTER DEM was compared with SRTM (the Shuttle Radar Topographic Mission) DEM, and referenced DEM constructed from a 1:25,000 scale topographic map [44]. It was concluded that the overall accuracy of the ASTER DEM is in line with the reported official accuracy specification [45]. The prepared topographic sheets were scanned, georeferenced, and converted to WGS1984, zone 36 N projection system using Arc GIS and the associated packages.

The two watersheds and the boundaries of the 21 fourth-order sub-basins were delineated initially using the topographic sheets. The ASTER DEM (v.2) was employed to demarcate watersheds and sub-basins boundaries, drainage networks using Arc Hydro tool (Figure 5). A total of 23 morphometric parameters were extracted and calculated using ASTER DEM, Arc GIS software, and the mathematical equations displayed in Table 1. The results of computation are illustrated in Tables 2-4. Different topographic features such as aspect, slope, and elevation were generated using the Spatial Analyst module. Basic parameters include: basin area (A) basin order (N_u), perimeter (P), basin length (L_b), number of streams (N_u), stream length (L_u), mean stream length (L_{sm}), length of main channel (L_m). Derived parameters are: bifurcation ratio (R_b), weighted mean bifurcation ratio (WMR$_b$), stream length ratio (R_L), sinuosity (SI), basin shapeindex (I_{sh}), length of overland flow (L_o), RHO coefficient (ρ), stream frequency (F_s), drainage density (D_d), drainage texture (D_t), basin relief (B_h), slope index (S_{In}%), relief ratio (R_r), ruggedness number (R_n). Whereas shape parameters are: elongation ratio (R_e), circularity ratio (R_c), and form factor ratio (R_f). The stream ordering for the entire Wadi Rajil and Wadi Wuheida was executed according to [24]. Thus, Wadi Rajil catchment was found to be of seventh-order, while Wadi Wuheida is found of sixth-order. Interpretation of parameter values was carried out according to the methods elaborated by [20], Strahler [21] [23] [24], Miller [46], and Schumm [25]. Efficient tools of GIS are capable of generating flood hazard, flood susceptibility, and sediment hazard maps, which illustrate flood-prone sub-basins. Risk and vulnerability maps help planners to assess the potential impact of floods [5], and to delimit the appropriate sites for future development; and to avoid sites exposed to flooding and sediment discharge. Based on the analysis of drainage, GIS afford devices which help not only to determine areas affected by floods, but to predict sites that are likely to be flooded in the future. Consequently, appropriate measures can be provided by planners to minimize the negative impact of floods and flooding effects.

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

	Morphometric Parameters	Formula/Definition	References
I	**Basic Parameters**		
1	Basin Area (A) (Km^2)	GIS Software Analysis	Schumm (1956)
2	Basin Perimeter (P) (Km)	GIS Software Analysis	Schumm (1956)
3	Basin Length (L_b)	GIS Software Analysis	Schumm (1956)
4	No. of streams (N_u)	Hierarchical Rank	Strahler (1952)
5	Stream Length (L_u) (Km)	$L_u = L_1 + L_2 + \cdots + L_n$	Strahler (1964)
6	Mean Stream Length (L_{sm}) (Km)	$L_{sm} = L_u/N_u$ (km)	Horton (1945)
II	**Derived Parameters**		
7	Bifurcation ratio (R_b)	$R_b = N_u/N_{u+1}$	Strahler (1964)
8	Weighted mean bifurcation ratio (WMR_b)	$WMR_b = \sum\left\{(R_b u/u+1)\times(N_u+N_u+1)\right\}\Big/\sum N$	Strahler (1953)
9	Stream Length ratio (R_L)	$R_L = L_u/L_{u-1}$	Strahler (1964)
10	Sinuosity (S_I)	$S_I = L_m/L_b$	Gregory and Walling (1973) [69]
11	Basin shape index (I_{sh}%)	$I_{sh}\% = 1.27 * A/L_b^2$	Haggett (1965) [70]
12	Length of overland flow (L_o)	$L_o = 1/2D_d$	Horton (1945)
13	RHO coefficient (ρ)	$\rho = R_L/R_b$	Horton (1945)
14	Stream frequency (F_s)	$F_s = N_u/A$	Horton (1932)
15	Drainage density (D_d) Km/Km^2	$D_d = L_u/A$	Horton (1932)
16	Drainage texture (D_t)	$D_t = N_u/P$	Horton (1945)
17	Basin relief (B_h) m	$B_h = H - h$	Strahler (1952)
18	Slope index (S_{In}%)	$S_{In}\% = (E/0.75L_m) \times 100$ ($E = E85 - E10$), E85 and E10 are the elevation of points at 85% and 10% of the main channel from its mouth). (L_m = The length of main channel from its mouth to water divide).	Majure and Soenksen (1991) [71]
19	Relief ratio (R_r)	$R_r = H/L_b$	Schumm (1956)
20	Ruggedness number (R_n)	$R_n = D \times (B_h/1000)$	Melton (1957)
III	**Shape Parameters**		
21	Elongation ratio (R_e)	$R_e = 1.128\sqrt{A/L_b}$	Schumm (1956)
22	Circularity ratio (R_c)	$R_c = 4\pi A/P^2$	Miller (1953)
23	Form factor ratio (R_f)	$R_f = A/L_b^2$	Horton (1932)

Table 2. Morphometric characteristics of W. Wuheida.

Par. no.	Morphometric Parameters		Stream Order					
			I	II	III	IV	V	VI
I	**Basic Parameters**							
1	Basin Area (A) (Km^2)	244.97						
2	Basin Perimeter (P) (Km)	135.33						
3	Basin Length (L_b)	30.06						
4	No. of streams (N_u)	490	387	76	19	5	2	1
5	Stream Length (L_u) (Km)	386.69	218.62	115.01	53.06	35.23	14.22	17.41
6	Mean Stream Length (L_{sm}) (Km)	2.98	0.56	1.51	2.79	7.05	7.11	17.41
II	**Derived Parameters**							
				II/I	III/II	IV/III	V/IV	VI/V
7	Bifurcation ratio (R_b)			5.09	4	3.8	2.5	2
8	Weighted mean bifurcation ratio (WMR_b)	3.8						
				II/I	III/II	IV/III	V/IV	VI/V
9	Stream Length ratio (R_L)	0.55		0.53	0.46	0.66	0.40	1.22
10	Sinuosity (S_l)	0.58						
11	Basin shape index (I_{sh})	0.34						
12	Length of overland flow (L_o)	0.79						
13	RHO coefficient (ρ)	0.16						
14	Stream frequency (F_s)	2.00						
15	Drainage density (D_d) Km/Km^2	1.58						
16	Drainage texture (D_t)	3.62						
17	Basin relief (B_h) m	604						
18	Slope index (S_{In}%)	0.08						
19	Relief ratio (R_r)	20.10						
20	Ruggedness number (R_n)	0.95						
III	**Shape Parameters**							
21	Elongation ratio (R_e)	0.59						
22	Circularity ratio (R_c)	0.17						
23	Form factor ratio (R_f)	0.27						

Table 3. Morphometric characteristics of W. Rajil.

Par. no.	Morphometric Parameter		Stream Order						
			I	II	III	IV	V	VI	VII
I	**Basic Parameter**								
1	Basin Area (A) (Km^2)	3085.87							
2	Basin Perimeter (P) (Km)	608.61							
3	Basin Length (L_b)	126.73							
4	No. of streams (N_u)	1994	1563	331	75	17	6	2	1
5	Stream Length (L_u) (Km)	3004.4	1697.6	869.74	437.06	254.59	136.78	31.86	45.37
6	Mean Stream Length (L_{sm}) (Km)	6.13	1.09	2.63	5.83	14.98	22.80	15.93	45.37
II	**Derived Parameters**								
				II/I	III/II	IV/III	V/IV	VI/V	V/VII
7	Bifurcation ratio (R_b)			4.72	4.4	4.4	2.8	3	2

Continued

			II/I	III/II	IV/III	V/IV	VI/V	V/VII
8	Weighted mean bifurcation ratio (WMR_b)	3.88						
9	Stream Length ratio (RL)	0.53	0.51	0.50	0.58	0.54	0.23	1.42
10	Sinuosity (S_I)	0.25						
11	Basin shape index (I_{sh})	0.24						
12	Length of overland flow (L_o)	0.49						
13	RHO coefficient (ρ)	0.14						
14	Stream frequency (F_s)	0.65						
15	Drainage density (D_d) Km/Km^2	0.97						
16	Drainage texture (D_t)	3.28						
17	Basin relief (B_h) m	604						
18	Slope index (S_{In}%)	0.02						
19	Relief ratio (R_r)	4.77						
20	Ruggedness number (R_n)	0.59						
III	**Shape Parameters**							
21	Elongation ratio (R_e)	0.49						
22	Circularity ratio (R_c)	0.10						
23	Form factor ratio (R_f)	0.19						

Table 4. Morphometric characteristics of the 21 sub-watersheds.

Basin	Sub-basin	Morphometric parameter																							
		A	P	L_b	N_u	L_u	L_{sm}	R_b	WMR_b	R_L	S_I	ISH	L_o	ρ	F_s	D_d	D_t	B_h	S_{In}%	R_r	R_n	R_e	R_c	R_f
Wadi Rajil	1	280.33	203.37	32.45	179	331.61	17.91	5.47	4.65	1.00	0.22	0.34	0.59	0.18	0.64	1.18	0.88	843	1.26	25.98	1.00	0.58	0.09	0.27
	2	119.12	148.41	19.96	71	134.11	11.71	4.24	4.55	1.45	0.35	0.38	0.56	0.34	0.60	1.13	0.48	790	1.05	39.59	0.89	0.62	0.07	0.30
	3	210.83	133.01	27.60	144	225.30	9.04	4.88	4.48	0.69	0.26	0.35	0.53	0.14	0.68	1.08	1.08	290	0.20	10.51	0.31	0.59	0.15	0.28
	4	116.91	93.19	19.74	63	134.20	6.59	4.06	5.35	0.57	0.36	0.38	0.57	0.14	0.54	1.15	0.68	498	0.04	25.22	0.57	0.62	0.17	0.30
	5	142.64	108.90	22.11	95	163.41	5.73	4.92	4.99	0.49	0.32	0.37	0.57	0.10	0.67	1.15	0.87	320	0.04	14.48	0.37	0.61	0.15	0.29
	6	145.92	103.18	22.39	78	170.44	7.64	3.96	4.34	0.64	0.32	0.37	0.58	0.16	0.53	1.17	0.76	333	0.19	14.87	0.39	0.61	0.17	0.29
	7	70.30	90.23	14.79	41	90.56	4.86	3.44	4.75	0.60	0.48	0.41	0.64	0.17	0.58	1.29	0.45	434	0.11	29.34	0.56	0.64	0.11	0.32
	8	161.06	123.50	23.69	105	186.90	6.51	4.34	4.17	0.59	0.30	0.36	0.58	0.14	0.65	1.16	0.85	204	0.06	8.61	0.24	0.60	0.13	0.29
	9	226.85	139.58	28.77	130	252.71	9.11	4.70	4.79	0.58	0.25	0.35	0.56	0.12	0.57	1.11	0.93	376	0.22	13.07	0.42	0.59	0.15	0.27
	10	53.57	52.93	12.67	39	61.76	2.65	3.21	3.89	0.47	0.56	0.42	0.58	0.15	0.73	1.15	0.74	148	0.01	11.68	0.17	0.65	0.24	0.33
	11	73.51	90.73	15.17	48	66.05	4.39	3.39	4.14	1.42	0.47	0.41	0.45	0.42	0.65	0.90	0.53	248	0.23	16.35	0.22	0.64	0.11	0.32
	12	65.70	81.77	14.23	50	79.93	6.26	3.57	3.87	0.84	0.50	0.41	0.61	0.24	0.76	1.22	0.61	261	0.16	18.34	0.32	0.64	0.12	0.32
	13	53.47	49.15	12.66	46	60.72	1.36	4.21	3.59	0.50	0.56	0.42	0.57	0.12	0.86	1.14	0.94	185	0.01	14.61	0.21	0.65	0.28	0.33
	14	71.55	78.13	14.94	50	79.35	3.65	3.74	5.18	0.52	0.47	0.41	0.55	0.14	0.70	1.11	0.64	187	0.03	12.52	0.21	0.64	0.15	0.32
	15	31.20	35.11	9.32	19	55.34	3.62	2.61	3.30	0.60	0.76	0.46	0.89	0.23	0.61	1.77	0.54	89	0.01	9.55	0.16	0.68	0.32	0.36
	16	55.52	52.73	12.93	45	66.23	3.69	3.40	4.25	1.37	0.55	0.42	0.60	0.40	0.81	1.19	0.85	91	0.04	7.04	0.11	0.65	0.25	0.33
Wadi Wuheida	1	27.50	38.40	8.68	53	49.89	2.78	3.48	4.09	0.74	0.82	0.46	0.91	0.21	1.93	1.81	1.38	413	0.20	47.59	0.75	0.68	0.23	0.37
	2	24.98	45.32	8.22	42	44.28	2.34	3.50	4.89	0.52	0.26	0.47	0.89	0.15	1.68	1.77	0.93	385	0.18	46.85	0.68	0.69	0.15	0.37
	3	38.03	40.44	10.43	66	70.23	2.69	3.87	5.23	0.58	0.60	0.44	0.92	0.15	1.74	1.85	1.63	346	0.27	33.16	0.64	0.67	0.29	0.35
	4	21.43	39.06	7.53	42	43.64	4.43	3.50	4.89	3.94	1.95	0.48	1.02	1.12	1.96	2.04	1.08	319	0.14	42.35	0.65	0.69	0.18	0.38
	5	59.22	54.72	13.42	135	108.37	3.99	4.74	4.62	0.61	0.85	0.42	0.92	0.13	2.28	1.83	2.47	336	0.15	25.04	0.61	0.65	0.25	0.33

3.2. Flash Flood Analysis Methods

Quantitative analysis of drainage basin morphometry using remote sensing and GIS techniques has been employed recently to assess the probability of flash flood hazard. Various methods were employed in this regard. The most common is the morphometric assessment method which comprises:

1) El-Shamy's approach [27]

2) The morphometric ranking method [47]

3) Wahid's flash flood rating method [48] and the

4) Morphometric hazard degree assessment method [28] [29] [30]

5) Morphometric analysis of drainage basin and curve number (CN) method to evaluate flash flood hazard [3] [49].

In the present research, two different morphometric analysis methods have been adopted to evaluate the hazard degree of flash floods, and to generate flooding susceptibility maps. These methods are: El-Shamy's approach for assessing flooding hazard probability [5] [27]. The second method is the "morphometric hazard degree assessment" [28] [29] [30] [50]. The second method is a semi-quantitative measure which determined flash flood hazard based on eleven morphometric parameters.

El-Shamy [27] employed three morphometric parameters to assess the hazard potential of flash floods for different sub-basins. These are: drainage density (D_d), stream frequency (F_s), and bifurcation ratio (R_b). He elaborated two different morphometric relationships to determine the flood hazard degree for a catchment or sub-basin; bifurcation ratio (R_b) versus drainage density (D_d), and bifurcation ratio versus stream frequency (F_s). The empirical diagram established by El-Shamy [27] was divided into three zones. The first zone (A) is characterized by high susceptibility for flash flooding and low possibility for groundwater recharge. The second zone (B) is characterized by moderate susceptibility for flash floods, and moderate possibility for groundwater recharge. The third zone (C) is characterized by low susceptibility for flash floods and high possibility for groundwater recharge. The data from the diagram represent bifurcation ratio (R_b) vs. stream frequency (F_s), and the diagram illustrates that bifurcation ratio (R_b) vs. drainage density (D_d) are used to determine the overall hazard degree. If a sub-basin is plotted in zone B of the first diagram (moderate susceptibility of flash floods), and located in zone C of the second diagram (low susceptibility for flash floods), the overall hazard degree for this sub-basin will be low possibility for flash floods which represents the more "conservative" situation [5].

The morphometric hazard degree assessment method employed eleven morphometric parameters with a direct effect on flash floods [30]. Eight parameters are characterized with a direct proportional relationship with the degree of risk, whereas three parameters have an inverse proportional relationship with the degree of risk (Table 5). A hazard scale number was designed, starting with (1) representing the lowest hazard up to (5) indicating the highest hazard, and has

Table 5. Effective morphometric parameters based on the kind of relationship with the degree of risk.

Relationship with hazard	
Direct proportional relationship	Inverse proportional relationship
1) Area (A) 2) Drainage density (D_d) 3) Stream frequency (F_s) 4) Basin shape index (S_f) 5) Relief ratio (R_r) 6) Ruggedness number (R_n) 7) Slope index (S_{In}%) 8) Drainage texture ratio (T_t)	1) Mean bifurcation ratio (R_b) 2) Length overland flow (L_o) 3) Sinuosity (S_l)

been assigned to all parameters. The distributions of the hazard degrees for the sub-basins of Wadi Rajil and Wadi Wuheida have been calculated in order to:

1) Determine the minimum and maximum values for each morphometric parameter for all sub-basins of Wadi Rajil and Wadi Wuheida,

2) Assess the actual hazard degree for all the parameters which are located between the minimum and maximum values, depending on a test to extract the empirical relation between the relative hazard degree of a sub-basin with respect to flash floods and the morphometric parameters, and

3) The equal spacing or simple linear interpolation between data points procedure was chosen [51].

For parameters which show a direct proportional relationship to the degree of risk, the hazard degree was calculated using the following equation [28] [29]:

$$\text{Hazard degree} = \frac{4(X - X_{\min})}{X_{\max} - X_{\min}} + 1 \tag{1}$$

Likewise, for parameters which show an inverse proportional relationship to degree of risk, the hazard degree is calculated using the following equation:

$$\text{Hazard degree} = \frac{4(X - X_{\max})}{X_{\min} - X_{\max}} + 1 \tag{2}$$

where X is the value of the morphometric parameters to be assessed for the hazard degree for each sub-basin, $X_{\min}$ and $X_{\max}$ are the minimum and maximum values of the morphometric parameters of the two basins and all sub-basins respectively. The summation of the hazard degree (1 + 2) for each sub-basin represents the final flood hazard of these sub-basins.

An integration of the results was carried out using the morphometric hazard degree assessment method, and El-Shamy's model. Such a procedure was performed through superimposition of flood risk maps generated through the application of the two estimation methods. The product enables us to recognize the common sub-basins falling under each category of flooding risk; and to identify the most risk-prone sub-basins with reference to flash flooding. It also, allows the possibility to demarcate the most vulnerable sub-basins against flooding.

4. Morphometric Analysis of Watersheds

Quantitative analysis was conducted for W. Rajil and W. Wuheida catchments and the 21 fourth-order sub-catchments connected to both watersheds, in order to evaluate the morphometric properties of the drainage networks, based on twenty-five morphometric descriptors classified as: basic, derived, and shape parameters. These variables are utilized to characterize the two arid watersheds, and to improve our understanding of arid watershed development in relation to essential controlling factors, *i.e.*, geology (lithology and structure), tectonic and geomorphic processes, and rejuvenation. The results of morphometric analysis for the two watersheds (Table 2 and Table 3) and the 21 sub-basins are illustrated in Table 4. The drainage pattern is dendritic to sub-dendritic and sub-trellis in the southern part of W. Wuheida, whereas, it is trellis to sub-trellis in the southwestern and northeastern parts of W. Rajil, then changing to sub-dendritic in the northwestern part of the watershed. Referring to the ratio between basin area (A), and perimeter (P), the ratio is found 5.071:1 for W. Rajil, and 1.810:1 for W. Wuheida. Such figures indicate that the borderline of W. Rajil is a highly irregular water divide compared to W. Wuheida which is a slightly irregular water divide. The noticeable difference in the ratios between (A) and (P), has been verified by a striking differences in stream frequency (F_s) and drainage density (D_d) values. Although the number of streams and the area (A) of W. Wuheida are smaller compared to W. Rajil, the drainage network of W. Wuheida is more developed and integrated. Conversely, 86.2% of Wadi Rajil is covered by six basalt flows ranging in age from Oligocene to Pleistocene [52]; thus, the drainage network of W. Rajil was impeded from becoming integrated due to the progression of volcanic eruptions.

4.1. Basic Morphometric Parameters

The basic morphometric parameters computed for W. Rajil and W. Wuheida and the 21 sub-basins comprising basin area (A), basin perimeter (P), basin length (L_b), stream length (L_u), mean stream length (L_{sm}), and length of main channel (L_m).

4.1.1. Basin Area (A), Basin Length (L_b), and Basin Perimeter (P)

The area of a drainage basin is an essential morphometric parameter for hydrological data processing, analysis and interpretation. Larger basins and sub-basins with high local relief generally have greater discharge, thus directly influencing runoff and peaks magnitude. For this reason, basin area is an important component in hydrological processes [53]. In this regard, Chorley *et al.* [54] argued that the maximum discharge of flood per unit area is inversely related to the area of the drainage basin. The total drainage area for W. Rajil is 3085.87 km^2, and for W. Wuheida is 245 km^2; for the 21 sub-basins, it varies from 21.4 to 280.33 km^2. The basin length represents the maximum length of the watershed and sub-watersheds measured parallel to the main drainage line. The length of Wadi Rajil basin is 126.73 km and Wadi Wuheida 30 km, while the lengths of the

sub-basins range from 7.53 to 28.77 km. The perimeter of W. Rajil is 608.61 km, and W. Wuheida is 135.33 km. The perimeters of the sub-basins vary from 35.11 to 203.37 km (Table 4). Sub-watershed no.15 of W. Rajil, represents the shortest one, whereas, sub-basinno.10 of the same watershed has the longest perimeter. Equally, sub-watershed no.1 is the longest, but with the highest perimeter. With reference to the area, sub-basin no. 1 of W. Rajil is the largest, and sub-basin no. 4 of W. Wuheida is the smallest.

4.1.2. Stream Order (u) and Stream Number (N_u)

Stream ordering has been assigned based on the number and type of tributary junction. The two watersheds and the sub-basins were ranked according to the stream ordering system developed by Strahler [24]. Stream order represents a preparatory indicator of stream size, drainage area and discharge. The total number of streams in W. Rajil watershed is 1995, and the first order streams account for 78.3% of the total stream numbers. The total number of streams in W. Wuheida is 490, and the first order streams constitute 79% of the total streams. The details of stream characteristics validate Horton's [20] first law, or, the "law of stream number," which stated that the number of steams of different order in a given drainage basin tends to closely approximate an inverse geometric ratio [55]. W. Rajil consists of 16 sub-basins which are assigned as fourth-order basins, and W. Wuheida is composed of 5 sub-basins of the same order. Application of Strahler's ordering procedure through Arc GIS (10.1) reveals that W. Rajil is classified as seventh order; and W. Wuheida is sixth order.

4.1.3. Stream Length (L_u) and Mean Stream Length (L_{sm})

Stream length is calculated from the mouth of stream to drainage divide. L_u is a dimensional parameter utilized to understand the characteristics of the drainage network elements and its contributing basin surfaces [24]. L_u is an important variable employed to examine the hydrological characteristics of the drainage basin, *i.e.*, surface runoff and the hydrological properties of the underlying bedrock such as permeability. Streams of short length generally are characteristic of terrain with greater slopes and highly dissected with very fine textures. Longer stream lengths are often developed where the bedrocks are permeable. Details of stream length characteristics of W. Rajil and W. Wuheida support Horton's [20] "law of stream length" which states that "the average length of streams of each of the different orders in a drainage basin tends closely to approximate a direct geometric ratio". Variation in order and size of the tributary basins are largely attributed to morphological (relief and slope), structural, tectonic and geomorphic evolution of the drainage basin. The total stream length is generally high in the first order streams and decreases as the stream order increases. The total stream length of W. Rajil is 3004.4 km, and for W. Wuheida is 386.7 km, and the first order streams account for 56.5% of the total stream length of both watersheds. Mean stream length is calculated by dividing the total stream length of order (u) and number of stream segments of the same order (u). The mean

stream length for W. Rajil varies from 1.09 km for the first order streams to 45.37 km for the seventh-order stream (Table 3), whereas the mean stream length for W. Wuheida ranges from 0.56 km for the first order streams to 17.41 km for the sixth-order stream (Table 2). The L_{sm} value for any given order is greater than that of the lower order and less than that of its next higher order. For the 21 sub-basins, the L_{sm} values vary from 0.56 for the first-order streams, to 22.8 for the fourth-order streams.

4.2. Derived Morphometric Parameters

4.2.1. Bifurcation Ratio (R_b) and Weighted Mean Bifurcation Ratio (WMR$_b$)

The bifurcation ratio (R_b) refers to the ratio of the number of streams of a given order (N_u) to the number of streams in the next higher orde $(N_u + 1)$. Horton [20] elaborated R_b parameter as a morphological index of relief and dissection. For flat or rolling catchments, the R_b value is ≈ 2, while the value for dissected catchments approaches 4. To achieve a more illustrative bifurcation value, Strahler [56] employed a weighted mean bifurcation ratio (WMR_b) calculated according to the following equation:

$$WMR_b = \sum\left\{\left(R_b u/u+1\right)\times\left(N_u + N_u +1\right)\right\}\Big/\sum N$$

Later, Shumm [25] adopted this method to determine the mean bifurcation ratio (R_b) of a drainage basin at Perth Amboy, New Jersey, where the value is found to be 4.87. R_b values vary from 2 to 4.72, and the weighted mean bifurcation ratio (WMR_b) is 4.6 for W. Rajil (Table 3). Likewise, the R_b values range from 2 to 5, and the WMR_b value is 3.8 for W. Wuheida (Table 3 and Table 4). Higher values of R_b and WMR_b for W. Rajil indicate that the wadi is largely affected by progressive tectonic activity during the eruption of successive basalt flows. Whereas W. Wuheida experienced less structural distortions, and mainly affects the water divide area at Ras En Naqb. The trend of R_b values in W. Rajil from the second-order stream to seventh-order stream is relatively irregular due to the tectonic activity mentioned above. By contrast, the trend of R_b values in W. Wuheida decreases regularly from the second-order streams to the sixth-order stream due to the presence of homogeneous surface rock strata in Ras En Naqb in the south, and El-Jafr depression in the north.

4.2.2. Stream Length Ratio (R_L) and Sinuosity (S_l)

Stream length ratio (R_L) refers to the ratio between the individual lengths of steam in a given order and the total length of streams in the next order [20]. R_L parameter reveals a significant relationship with surface flow discharge and the erosional stage and geomorphic development of the drainage basin [53] [57]. As a result of morphological variation (*i.e.*, slope and relief) over a watershed, R_L values vary considerably. The R_L value for W. Rajil is 0.3, and for W. Wuheida is 0.55, whereas R_L values for the 21 sub-basins vary from 0.51 for the first-order streams to 0.66 for the fourth-order streams. Sinuosity (S_l) is defined as the ratio

of the maximum length of the main channel (L_m) to basin length (L_b) or,

$$S_I = L_m / L_b$$

Generally, S_I values range from 1 to 4. Streams having S_I value of 1.5 are described as sinuous. When S_I values exceed 1.5, streams are described as meandering [58]. Sinuosity (S_I) is considered a significant morphometric parameter which helps in interpreting the geomorphic evolution of a watershed.

4.2.3. Basin Shape Index (I_{sh}) and Slope Index (S_{In}%)

The basin slope index (I_{sh}) describes the relation between the basin area, and the length of the drainage basin. W. Rajil and W. Wuheida attain basin shape index values of 0.24 and 0.34 respectively. These values reveal an elongated drainage basin; thus a reasonable chance is available for groundwater recharge. Slope index (S_{In}%), or the slope of main channel of a given basin is considered to be of hydrological significance [59]. Steep channels occasionally have high surface runoff values, and low infiltration rates, which in turn accelerate soil erosion. Therefore, sediment load production tends to be high in arid watersheds, where slopes are overgrazed and barren [11] [60]. Slope index (S_{In}%) is also an indicator for the channel slope from which an assessment of the runoff volume can be estimated [30]. The two arid watersheds under consideration are characterized by medium to high relief, where the slope index (S_{In}%)values are 0.02 for W. Rajil, and 0.08 for W. Wuheida.

4.2.4. Length of Overland Flow (L_o) and RHO Coefficient (ρ)

RHO coefficient (ρ) is defined as the ratio between the length ratio (R_l) and the bifurcation ratio (R_b) [20]. ρ parameter is influenced by physical (geological, geomorphic, climatic and biologic) and anthropogenic factors [61]. The relationship between drainage density (D_d) and the geomorphic evolution of a drainage basin is determined by the RHO parameter. Consequently it helps to assess the storage capacity of the drainage network [20]. A high RHO value of a watershed is indicative of a high hydric storage during flooding; therefore, the erosion effect is decreased during the raised discharge [59]. The RHO values for W. Rajil and W. Wuheida are 0.14 and 0.16 respectively (Table 2 and Table 3). Whereas RHO values for the 21 sub-basins range from 0.10 to 0.42 (Table 4). Length of overland flow (L_o) is defined as the length of water over the ground before it gets concentrated into stream channels or permanent drainage channels [62]. The shorter the length of overland flow the quicker surface runoff will enter the stream. In the current study, the length of overland flow (L_o) for W. Rajil is 0.49 and for W. Wuheida is 0.79. Such values indicate that L_o for W. Rajil is shorter than W. Wuheida, due to variation in slope, lithology, land cover, rainfall intensity and infiltration capacity [53]. The slope index value for W. Rajil is 0.02 which is noticeably less than the slope index value of W. Wuheida (0.08). These values denote that surface water concentration in W. Wuheida is faster compared with W. Rajil. The larger value of average L_o is close to half the aver-

age of the distance between the stream channels. Thus, it is equal to approximately half of the D_d value [20]. The long-term evolution of a drainage basin and landforms development is also affected by L_o parameter. The L_o values for the 21 sub-basins vary from 0.45 to 1.02 (Table 4).

4.2.5. Stream Frequency (F_s), Drainage Density (D_d), and Drainage Texture (D_t)

Stream frequency (F_s) refers to the ratio of the total number of streams (N_u) of all orders in a basin and the basin area [20]. Stream frequency is affected by lithology and underlying materials; therefore, it is an expression of drainage texture of watersheds and sub-basins. The values of F_s are positively correlated with D_d values of the catchment. Consequently any increase in stream segments is associated with that of drainage density [63]. High F_s values indicate low impermeability and low infiltration rate of surface water; thus, increased runoff is noted. Such hydrological conditions make the watersheds and the sub-watershed more prone to flooding, surface erosion, and landslide activity. The F_s value for W. Rajil is relatively low (0.65), while F_s value for W. Wuheida is moderate (2.0) which denotes that fractured and weathered basalt covered most of W Rajil compared with more solid carbonate rocks exposed across W. Wuheida. The values of F_s for the 21 sub-basins range from 0.53 to 2.28. Drainage density (D_d) is defined as the total length of stream per unit area divided by the area of the watershed [20]. D_d value refers to the closeness of spacing of channels; therefore, it is a quantitative measure for relief dissection, runoff potential, and thus, in turn the drainage efficiency of watersheds. High D_d values denote high runoff and low infiltration rate due to the presence of impermeable underlying materials, spare vegetation, and hilly relief. Conversely, low drainage density implies low runoff, high infiltration and groundwater recharge. The achieved value of D_d for W. Rajil is 0.97 km / km^2 (Table 3), and for W. Wuheida 1.58 (Table 2). High D_d value for W. Wuheida implies a high potential runoff from large headwater area over the Ras En Nagb highlands, and consequently high flooding potential down the wadi [17]. D_d values for the 21 sub-basins range from 0.90 to 2.04 (Table 4). Drainage texture (D_t) represents the total number of stream segments of all orders per unit perimeter of the basin [20]. Drainage texture is controlled by: lithology, soil, relief, vegetation, infiltration-capacity and climate. D_t reflects the relative channel spacing within a drainage network. According to Smith [64], D_t tends to be coarse (2 - 4) in initial and early stages of the erosion cycle, and fine (6 - 8) in maturity stage. Barren soft rocks (*i.e.*, Lisan marl or the "Kata" in the Jordan Rift) produce a fine (6 - 8) and very fine (>8) texture although it is developed under arid climate. Whereas massive limestone rocks in northern Jordan produce a coarse texture though landforms were developed under a dry-Mediterranean (semi-humid) climate. The D_t value for W. Rajil is 3.28, and for W. Wuheida 3.62. These values imply that the texture of both catchments is coarse, while the D_t values for the 21 sub-basin range from 0.45 to 2.47.

4.2.6. Basin Relief (B_h), Relief Ratio (R_r) and Ruggedness Number (R_n)

Basin relief (B_h) or total relief is the elevation difference between the highest and lowest point in a given watershed [25]. B_h parameter significantly controls flooding patterns and sediment production by controlling stream gradient. Basin relief is a measure of the potential energy of drainage basins. Thus, it is essential to understand the denudational status of a catchment, drainage network development, overland flow, through flow, and the fluvial-erosional conditions of a catchment. Increase in B_h value caused high surface runoff, and low infiltration; thus increasing surface erosion and sediment production. The basin relief value of both W. Rajil and W. Wuheida is 604 m, and for the 21 sub-basins it varies from 89 m to 843 m. High soil erosion loss and sediment production, and high flooding potential is predictable for both watersheds. Schumm [25] elaborated relief ration (R_r) as a dimensionless height-length ratio between the basin relief (B_h) and basin length (L_b). The R_r variable allows comparison of the relative relief of any catchment regardless of the differences in scale of topography. R_r values normally increase with decreasing catchment areas. For example in the W. Wala catchment, southern Jordan, the R_r value is 15.1, whereas R_r values for 23 fourth-order sub-basins vary from 0.5 to 76.1. The basin relief values range from 96 m to 459 m [65]. Small relief ratio reveals the dominance of gentle slopes (3° - 5°) and the subdued topography across the watershed. R_r ratio and other relief morphometric parameters generally indicate the level of basin energy, erosion potential of processes operating over a catchment, and sediment transport efficiency [61]. The relief ratio for W. Rajil is 4.77, for W. Wuheida is 20.1, and for the 21 sub-basins it ranges from 7.04 to 47.59. Ruggedness number (R_n) is a dimensionless parameter representing the product of basin relief (B_h) and the drainage density [21] [24]. The R_n parameter has been elaborated to measure the flash flood potential of a drainage basin [66] and to illustrate the geometric characteristics of drainage basins [67]. High values of R_n obtain when both relief and drainage density are large. Present analysis shows that R_n for W. Rajil is 0.59, and for W. Wuheida is 0.95. Watersheds having high R_n values (>0.5) are highly susceptible to an increase in peak discharge, high soil erosion rates, and high sediment load production [55].

4.3. Shape Morphometric Parameters

4.3.1. Elongation Ratio (R_e)

Elongation ratio (R_e) is defined as the ratio between the diameter of a circle having the same area as the basin (A), and the basin length (L_b) [25]. Strahler [24] reported that R_e ratio vary from 0.6 and 1.0 for a wide range of geomorphic environment. Values close to 1.0 are characteristic of watersheds with low relief. Whereas values in the range 0.6 - 0.8 are typical for catchments with high relief and steep slopes. Low values of R_e (<0.5) imply that drainage basins are more elongated, and at the youth-age stage of geomorphic evolution. When R_e values approach 1.0, the shape of the drainage basin approaches a circle [25]. A circular basin suggests an early mature-age stage of geomorphic evolution [53], and is

more efficient in runoff discharge than is an elongated one [68]. The R_e value of W. Rajil is 0.49 (Table 3), and for W. Wuheida is 0.59 (Table 2), which imply that these watersheds are more elongated, and elongated, respectively.

4.3.2. Circularity Ratio (R_c)

Circularity ratio (R_c) parameter is indicative of basins shape, and the rate of infiltration including the time needed for excess water to reach the basin outlet. R_c refers to the ratio of the basin area (A) and the area of a circle with the same perimeter (P) as the basin [24]. Low, medium, and high values of R_c denote young, mature, and old stages of the geomorphic cycle of the catchment. Drainage basins of different circularity ratio, ranging from 0.4 to 0.5, were considered by Miller [46] as strongly elongated, with homogeneous bedrock and regolith materials, and a uniform rate of infiltration. Consequently, the excess runoff takes a longer time to reach the basin outlet. More elongated or elongated shapes allow drainage basins to be slow in disposing water, which resulted in a broad and low-peaked hydrograph. Thus, reduction of water velocity can be attained through the construction of water harvesting structures, *i.e.*, dams and surface reservoirs [30]. The R_c value of W. Rajil is 0.10, and for W. Wuheida is 0.17, and for the 21 sub-basins, it ranges from 0.07 to 0.32 (Table 4).

4.3.3. Form Factor Ratio (R_f)

The form factor parameter has been elaborated by Horton [20] to forecast the flow intensity of a given watershed. It refers to the ratio between the area of basin (A) and the square of the basin length (L_b). R_f values vary from 0 for highly elongated shape, to 1 for a perfect circular shape of the basin. Catchments with low R_f value, tend to be elongated, which implies low peak flows for longer duration, and thus of less probability for the basin to flood. Furthermore, catchments with high R_f values experience high peak flow of short duration, where the floods will be stronger and have higher velocities associated with greater erosion and transport capacities. The R_f value for W. Rajil is 0.19 (Table 3), and for W. Wuheida is 0.24 (Table 2). The R_f values for the 21 sub-basins range from 0.24 to 0.38. These values indicate that both watersheds and the related sub-basins are more elongated and elongated in shape with low peak flows of longer duration.

5. Results and Discussion

Two approaches were employed to assess flash floods hazards and flooding risk for two arid watersheds in Jordan. W. Rajil Watershed in the north which is developed over the basalt "Harra", and W. Wuheida in the south, developed in the "Hamada" landscape. The potential hazard was analyzed, and sub-basins vulnerable to flooding, and expected to cause heavy damages to the local inhabitants, their livelihood, and infrastructure, were demarcated. Past experience reveals that Ma'an city and the surroundings, the Amman-Aqaba highway, Azraq town and Qa'a Azraq were exposed to recurrent severe floods of different magnitudes as a result of favorable climatic conditions introduced by the Red Sea Trough (RST), or the frontal con-

vective storms. In order to assess the hazardous effects of flash floods on the 16 forth-order sub-basins of W. Rajil, and five sub-basins related of W. Wuheida, fourteen hydro-morphometric parameters were utilized in the analysis. The two methods employed are: 1) El-Shamy's approach [27] for flooding hazard assessment (El-Shamy 1992) which is based on three morphometric parameters; and 2) The morphometric hazard degree assessment method [28] [29] [30]. The second method is considered a semi-quantitative measure determined on the bases of eleven morphometric parameters.

5.1. Flash Flood Risk Assessment: El-Shamy's Approach

Following El-Shamy's approach, the relationship between the Bifurcation ratio (R_b) versus Drainage density (D_d), and the bifurcation ratio versus Stream frequency (F_s), morphometric data for the sub-basins of W. Rajil (termed 1 - 16) and W. Wuheida (desighnated 1 - 5) were plotted in line with El-Shamy's diagram (**Figure 6(a)** and **Figure 6(b)**). With reference to W. Rajil, the estimation

(a)

(b)
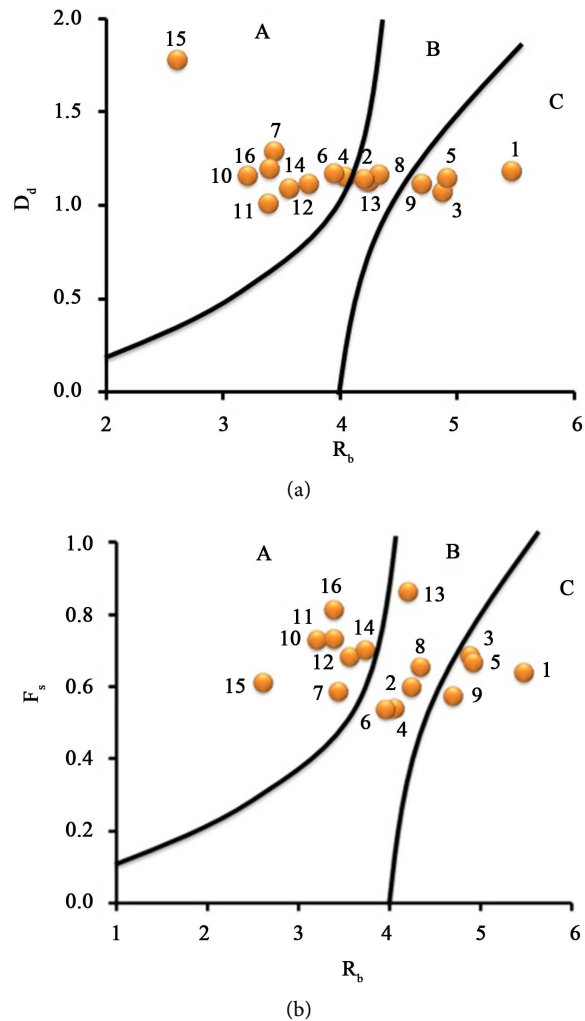
Figure 6. Flooding susceptibility of W. Rajil based on El-Shamy's approach, R_b vs. D_d (a) and R_b vs. F_s (b).

of flash flood risk based on the relation between R_b and D_d reveals that nine sub-basins (4, 6, 7, 10, 11, 12, 14, 15, and 16) are located in Zone *(A)* and represent high flooding susceptibility for flash floods. Three sub-basins (2, 8, and 13) are located in zone (B), which represent moderate susceptibility for flash floods, and four sub-basins (1, 3, 5 and 9)are located in zone (*C*), which represent low susceptibility for flash floods (**Figure 6(a)** and **Table 6(a)**). Additionally, and based on the relation between Bifurcation ratio versus Stream frequency, seven sub-basins (7, 10, 11, 12, 14, 15 and 16) are located in zone (*A*), which represents high susceptibility for flash floods, and five sub-basins (2, 4, 6, 8 and 13) are located in zone (B), which represents moderate susceptibility for

Table 6. Hazard degree analysis for W. Rajil (a) ad W. Wuheida (b) (based on El-Shamy's approach 1992).

(a)

Sub-basin no.	R_b	F_s	HD1	D_d	HD2	FHD
1	5.47	0.64	L	1.18	L	L
2	4.24	0.60	M	1.13	M	H
3	4.88	0.68	L	1.07	L	L
4	4.06	0.54	M	1.15	H	H
5	4.92	0.67	L	1.15	L	L
6	3.96	0.53	M	1.17	H	H
7	3.44	0.58	H	1.29	H	H
8	4.34	0.65	M	1.16	M	M
9	4.70	0.57	L	1.11	L	L
10	3.21	0.73	H	1.15	H	H
11	3.39	0.73	H	1.01	H	H
12	3.57	0.68	H	1.09	H	H
13	4.21	0.86	M	1.14	M	M
14	3.74	0.70	H	1.11	H	H
15	2.61	0.61	H	1.77	H	H
16	3.40	0.81	H	1.19	H	H

(b)

Sub-basin no.	R_b	F_s	HD1	D_d	HD2	FHD
1	3.48	1.93	H	1.81	H	H
2	3.50	1.68	H	1.77	H	H
3	3.87	1.74	M	1.85	M	M
4	3.50	1.96	H	2.04	H	H
5	4.74	2.28	M	1.83	M	M

R_b = Bifurcation Ratio, F_s = Stream Frequency, D_d = Drainage Density, HD1 = Hazard degree R_b vs. F_s, HD2 = Hazard degree R_b vs. D_d, and FHD = Final hazard degree from HD1 and HD2. L: low susceptibility for flash floods; M: moderate susceptibility for flash floods; and H: high susceptibility for flash floods.

flash floods. Finally, four sub-basins (1, 3, 5, and 9) are located in zone (C) which represents low susceptibility foe flash floods (**Figure 6(b)**). Through integration of the results achieved based on the relation between R_b vs. D_d and R_b vs. F_s, showed that sub-basins 1, 3, 5, and 9 are categorized under low possibility of flash floods in both relations (**Figure 7**). While sub-basins 2, 8, and 13 are grouped under moderate possibility of flash floods. Likewise, sub-basins 7, 10, 11, 12, 14, 15 and 16 are classified under high susceptibility for flash floods based on both relations, except for sub-basins 6 and 4.

With respect to W. Wuheida and based on the relation between Bifurcation ratio (R_b) vs. Drainage density (D_d), it is found that two sub-basins (3 and 5) are located in zone (B) which represents moderate susceptibility for flash floods, and three sub-basins (1, 2, and 4) are located in zone (A) which represents high possibility for flash floods (**Figure 8(a)**, **Table 6(b)**). None of the sub-basins were categorized in zone (C) of low flooding susceptibility for flash floods. Based on the relation between Bifurcation ratio vs. stream frequency, three sub-basins (2, 3 and 5) are located in zone (B) which represents moderate susceptibility for flash floods, and sub-basins (1 and 4) are located in zone (A) which represents high susceptibility for flash floods (**Figure 8(b)**, **Table 6(b)**). Again through integration of the results based on the relation between R_b vs. D_d and R_b vs. F_s, sub-basins 3 and 5 are grouped under the category of moderate susceptibility for flash floods, based on both relations (**Figure 9**). In parallel, sub-basins 1, 2 and 4 are ranked under the category of high susceptibility for flash floods. None of the sub-basins are ranked in the category of low susceptibility for flash floods (**Figure 9**) It is evident that similar and consistent results were achieved regarding
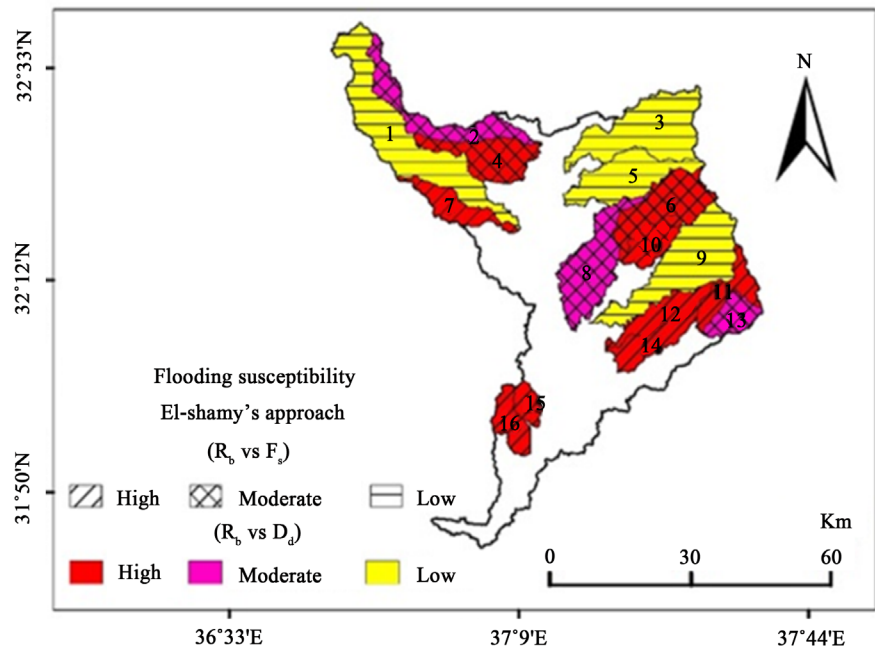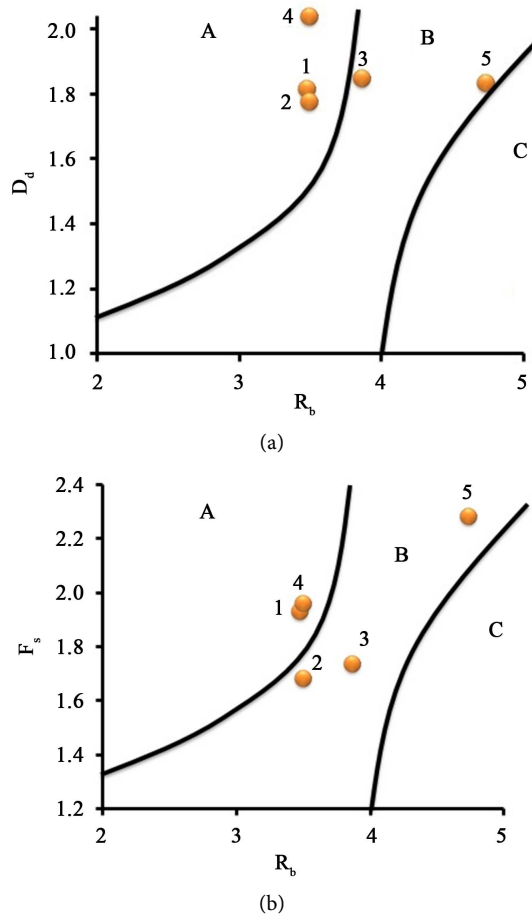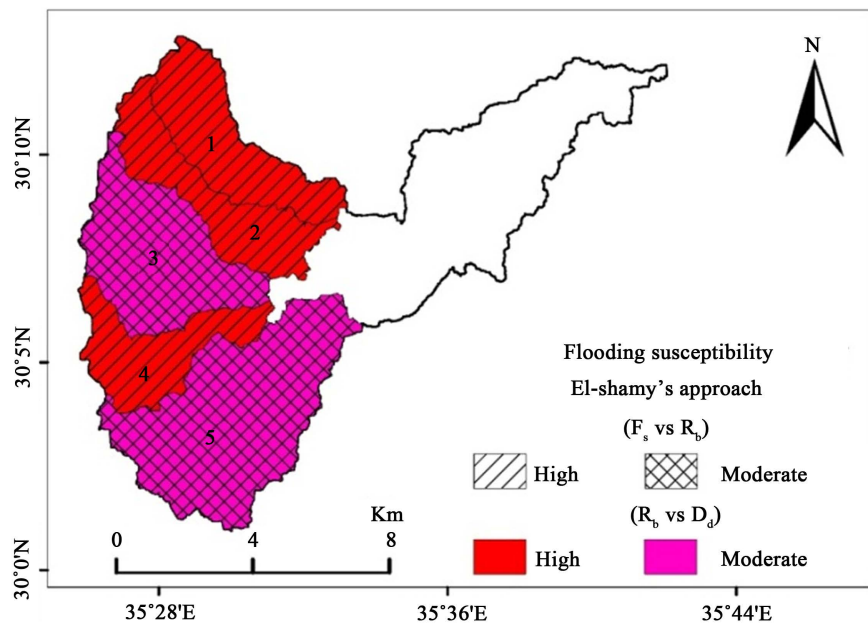

Figure 7. Flooding susceptibility of W. Rajil based on El-Shamy's approach (R_b vs. D_d layer superimposed on R_b vs. F_s layer).

Figure 8. Flooding susceptibility of W. Wuheida based on El-Shamy's approach, R_b vs. D_d (a) and R_b vs. F_s (b).

Figure 9. Flooding susceptibility of W. Wuheida based on El-Shamy's approach (R_b vs. D_d) layer superimposed on (R_b vs. F_s) layer.

flash flood susceptibility by use of El-Shamy's approach as clarified through sub-basins categorized under zone (*A*) and zone (*C*) for W. Rajil, and zone (*B*) and zone (*A*) for W. Wuheida.

5.2. The Morphometric Hazard Degree for Flash Floods Assessment Method

The Morphometric Hazard Degree assessment method was employed to perform the required morphometric analysis, to estimate the flash flood hazard and the degree of risk for the sub-basins of W. Rajil and W. Wuheida, Table 7 and Table 8 display the results of this method for both watersheds, as expressed by ranking score for the different eleven morphometric parameters based on the relation with hazard whether proportional or inverse. To compile the flood risk map using GIS, the summation of hazard degree values for the sub-basins was grouped into five categories of susceptibility for flash floods as follows:

    1) Low flooding susceptibility   19 - 23.9
    2) Moderate flooding susceptibility   24 - 27.9
    3) High flooding susceptibility   28 - 31.9
    4) Very high flooding susceptibility   32 - 35.9
   5) Extreme flooding susceptibility   36 - 39.9

Table 7. Hazard degrees of the effective parameters of the studied 16 sub-basins of W. Rajil.

Relation with hazard	The effective morphometric parameters	The minimum and maximum values of the parameter in all sub-basins		The value of the morphometric parameters to be assessed for each sub-basin															
				Hazard degrees of the effective parameters (X)															
		X_{min}	X_{max}	Sub Basin 1	Sub Basin 2	Sub Basin 3	Sub Basin 4	Sub Basin 5	Sub Basin 6	Sub Basin 7	Sub Basin 8	Sub Basin 9	Sub Basin 10	Sub Basin 11	Sub Basin 12	Sub Basin 13	Sub Basin 14	Sub Basin 15	Sub Basin 16
Proportional	Basin area (A) (Km^2)	24.98	226.85	2.87	1.00	4.68	2.82	3.33	3.40	1.90	3.70	5.00	0.43	1.96	1.81	1.56	0.92	0.12	0.61
	Drainage density (D)	0.90	1.29	3.92	3.33	2.75	3.56	3.54	3.77	5.00	3.69	3.21	3.61	1.00	4.26	3.44	2.16	8.99	3.02
	Stream frequency (F_s)	0.53	0.86	2.28	1.75	2.82	1.05	2.61	1.00	1.60	2.44	1.47	3.38	2.45	3.78	5.00	2.02	0.91	3.39
	Basin shape index (I_{sh})	0.34	0.46	1.00	2.42	1.45	2.45	2.11	2.07	3.38	1.90	1.34	3.90	3.51	3.30	3.91	2.35	4.00	2.83
	Relief ratio (R_r)	7.04	39.59	3.33	5.00	1.43	3.23	1.91	1.96	3.74	1.19	1.74	1.57	2.14	2.39	1.93	0.67	0.31	0.00
	Ruggedness number (R_n)	0.11	1.00	5.00	4.51	1.91	3.08	2.16	2.26	3.03	1.58	2.40	1.28	1.51	1.94	1.46	0.44	0.22	0.00
	Slope index (S_{in}%)	0.01	1.26	5.00	4.33	1.63	1.11	1.10	1.59	1.34	1.19	1.68	1.00	1.70	1.50	1.00	0.64	0.00	0.11
	Drainage texture (D_t)	0.45	1.08	3.71	1.15	5.00	2.41	3.66	2.92	1.00	3.52	4.04	2.80	1.48	2.00	4.07	1.18	0.55	2.54
Inverse	Weighted mean bifurcation ratio (WMR_b)	3.30	5.35	2.37	2.57	2.70	1.00	1.70	2.97	2.17	3.30	2.09	3.85	3.36	3.88	4.43	1.33	5.00	3.15
	Length of overland flow (L_o)	0.45	0.89	3.70	3.96	4.22	3.86	3.87	3.77	3.22	3.80	4.02	3.84	5.00	3.55	2.92	4.04	1.00	3.65
	Sinuosity (S_l)	0.22	0.76	5.00	2.94	4.72	3.96	2.38	4.28	3.07	4.40	4.79	2.48	3.16	2.94	1.48	2.80	1.00	2.57
	Summation of hazard degree			36.39	31.79	31.32	29.10	27.73	27.96	29.63	28.37	30.47	26.76	25.94	29.40	27.86	19.16	22.11	20.86
	Classification of the sub-basins hazard degree			Extreme hazard	High hazard	High hazard	High hazard	Medium hazard	Medium hazard	High hazard	High hazard	High hazard	Medium hazard	Medium hazard	High hazard	Medium hazard	Low hazard	Low hazard	Low hazard

Table 8. Hazard degrees of the effective parameters of the studied 5 sub-basins of W. Wuhida.

Relation with hazard	The effective	The minimum and maximum values of the parameter in all sub-basins	The value of the morphometric parameters to be assessed for each sub-basin						
			Hazard degrees of the effective parameters (X)						
Morphometric parameters			X_{min}	X_{max}	Sub Basin 1	Sub Basin 2	Sub Basin 3	Sub Basin 4	Sub Basin 5
Proportional	Basin area (A) (Km^2)		21.43	59.22	1.64	1.38	2.76	1.00	5.00
	Drainage density (D)		1.77	2.04	1.64	1.00	2.13	5.00	1.87
	Stream frequency (F_s)		1.68	2.28	2.65	1.01	1.37	2.86	5.00
	Basin shape index (I_{sh})		0.42	0.48	3.97	4.36	2.68	5.00	1.00
	Relief ratio (R_r)		25.04	47.59	5.00	4.87	2.44	4.07	1.00
	Ruggedness number (R_n)		0.61	0.75	5.00	3.01	1.72	2.03	1.00
	Slope index (S_{In}%)		0.14	0.27	2.72	2.15	5.00	1.00	1.18
	Drainage texture (D_t)		0.93	2.47	2.18	1.00	2.83	1.39	5.00
Inverse	Weighted mean bifurcation ratio (WMR_b)		4.09	5.23	5.00	2.20	1.00	2.20	3.14
	Length of overland flow (L_o)		0.89	1.02	4.36	5.00	3.87	1.00	4.13
	Sinuosity (S_I)		0.26	1.95	3.68	5.00	4.20	1.00	3.62
Summation of hazard degree					37.85	30.97	29.99	26.55	31.94
Classification of the sub-basins hazard degree					Extreme hazard	High hazard	High hazard	Moderate hazard	High hazard

With respect to the sixteen sub-basins of W. Rajil watershed, sub-basins nos. 14, 15, and 16 (18.75% of the total) have the lowest overall values, therefore representing the category of low flooding susceptibility (Table 7 and Figure 10). Sub-basins nos. 13, 11, 10, 6, and 5 (37.5% of the total) have intermediate score values, thus characterized by moderate flooding susceptibility. Conversely, sub-basins nos. 12, 9, 8, 7, 4, 3, and 2 (43.75% of the total) have high overall score values, and thus represent relatively dangerous sub-basins with high flooding susceptibility. Additionally, sub-basin no. 1 has the highest overall score value, thus, representing the most dangerous sub-basins with extreme flooding susceptibility (Figure 10). None of the sub-basins of W. Rajil is classified as of very high flooding susceptibility. It can be concluded that 50% of W. Rajil sub-basins are expected to suffer high and extreme flooding susceptibility. It can also be deduced that 81.25% of W. Rajil sub-basins are expected to experience moderate, high, and extreme susceptibility to flooding. Such results reveal that the main hazardous sub-basins are located on the northwest and eastern parts of the watershed, and directly threaten the lower part leading to Qa'a Azraq, Azraq town, wetland reserve, Azraq-Safawi and the Azraq-Qrayyat (to Saudi Arabia), major roads seriously threatened by expected flooding. Thus, the protection of the town, agricultural areas, and, the major roads from repetitive
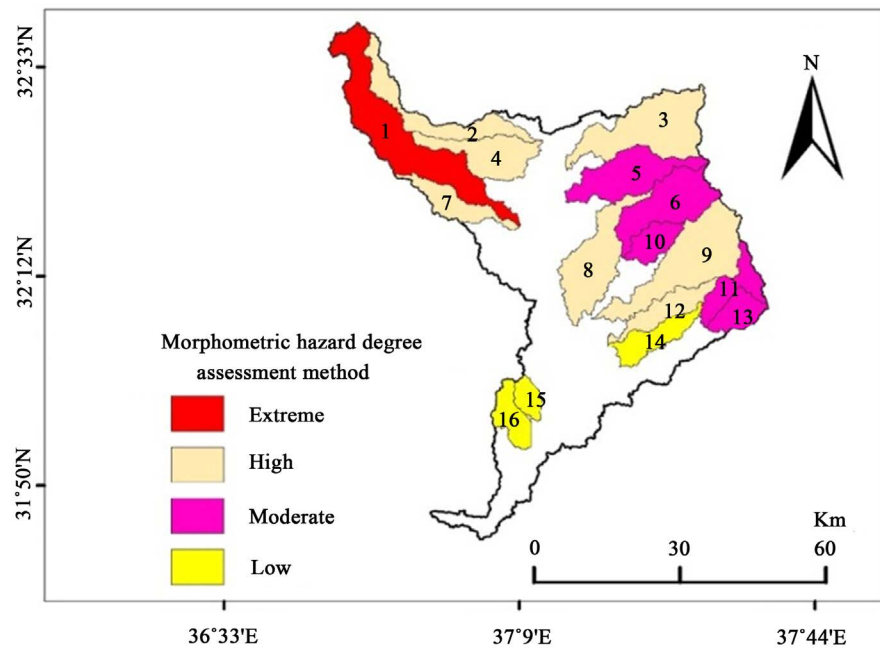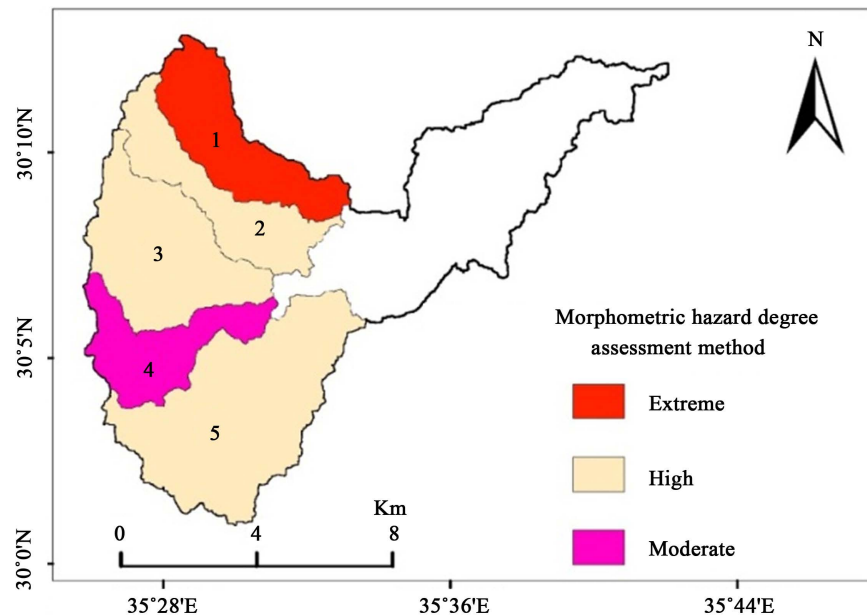
Figure 10. Sub-basins flooding hazard degree of W. Rajil based on the morphometric hazard degree assessment method.

flooding is essential to maintain future development of the Azraq area as a tourism and environmental conservation center.

With respect to the five sub-basins of W. Wuheida, the summation of the hazard degree scores for the sub-basins of the watershed, was grouped into five categories of susceptibility for flash floods such as the following:

1) Low flooding susceptibility   20 - 23.9
2) Moderate flooding susceptibility   24 - 27.9
3) High flooding susceptibility   28 - 31.9
4) Very high flooding susceptibility   32 - 35.9
5) Extreme flooding susceptibility   36 - 39.9

Accordingly, sub-basin no. 1 of W. Wuheida (20% of the total) has the highest overall score values: it thus, represents extreme flooding susceptibility (Table 8 and Figure 11). Whereas sub-basins nos. 2, 3, and 5 (60% of the total) have high score values and are thus, characterized by high flooding susceptibility. Alternatively, sub-basin no. 4 (20% of the total) has an intermediate score value, hence it represents moderate flooding susceptibility. It is obvious that 80% of Wadi Wuheida sub-basins are of extreme and high flooding susceptibility. Sub-basins nos. 1, 2, 3, and 5 are the most hazardous sub-basins, and are located within the headwaters of W. Wuheida in a mushroom-like shape (Figure 11). This zone is directly affected by the track of depressions which approach the catchment either from the west to east (frontal storms) or form southwest to northeast (Red Sea Trough storms). Furthermore, the mushroom shape provides a larger headwater area (56% of the total watershed area), which comprises the highest terrain in Ras En Naqb/Sharah highlands, with an average annual rainfall

Figure 11. Sub-basins flooding hazard degree of W. Wuheida based on the morphometric hazard degree assessment method.

approaching 160 mm, since this area receives the highest precipitation, and recorded repetitive destructive floods associated with high slopes yielding high runoff potential [17]. The extreme flood of W. Wuheida on 11 March 1966 (or Ma'an flood), and the major flood of 2 - 3 February 2006 resulted in high peak discharge, estimated at 540 m^3/s for WadiYutum south of Ras En Naqb [7] [8], and 270 to 320 m^3/s for W. Wuheida, north of Ras En Naqb/Sharah, during the 2006 flood [17].

Consequently, Ma'an city, El-Jafr playa, local inhabitants in the upper reaches of the watershed, and the Amman-Aqaba highway are seriously threatened by destructive flash floods. For this reason, flood control in the upper catchment is highly requisite to protect Ma'an city and other infrastructure facilities against flooding in order to maintain future development of the Ma'an-Ras En Naqb area.

6. Conclusions

In the present study, hydro-morphometric analysis, and GIS-based flood hazard and flood susceptibility mapping were carried out to display flood-prone areas in W. Rajil and W. Wuheida catchments. Flood risk analysis was conducted using two morphometric analysis methods within a GIS environment. These methods are 1): El-Shamy's approach; and 2): the morphometric hazard degree for flash flood assessment method. Sub-basins affected by floods of low, moderate, high, very high, or extreme flooding susceptibility can be demarcated. Consistent results were achieved on flash flood susceptibility utilizing El-Shamy's approach as illustrated through sub-basins categorized under zone (*A*) and zone (*C*) for W. Rajil; and zone (*A*) and zone (*B*) for W. Wuheida. In this regard, sub-basins nos.

1, 3, 5 and 9 of W. Rajil are ranked under low susceptibility for flash floods based on the relation between R_b vs. D_d, and R_b vs. F_s. Similarly, sub-basins nos. 7, 10, 11, 12, 14, 15, and 16 are categorized under high susceptibility for flash floods based on both previous relations (except sub-basins no.6 and 4). Reasonable results were obtained for W. Wuheida. Sub-basin no. 1 was ranked under an extreme susceptibility for flash floods, and sub-basin 4 was grouped under the class of moderate susceptibility for flash floods based on both relations between R_b vs. D_d, and R_b vs. F_s. The superimposition of the two thematic layers of El-Shamy's approach, R_b vs. F_s layer, and R_b vs. F_s layer for both W. Rajil showed that sub-basins 7, 10, 11, 12, 14, 15, and 16 (44% of the total) are grouped under high possibility of flash flood on both relations. With reference to W. Wuheida, sub-basins 1, 2, and 4 (75% of the total) are classified under the category of high susceptibility for flash floods. None of the sub-basins are ranked in the category of low susceptibility for flash floods. The results of the morphometric hazard degree for flash floods assessment method indicate that 50% of W. Rajil sub-basins are expected to suffer high and extreme flooding susceptibility. Thus, it is anticipated that 81.25% of W. Rajil sub-basins will likely experience moderate, high, and extreme susceptibility for flooding. Such results reveal that the main hazardous sub-basins are located on the northwestern and eastern part of the watershed, and directly threaten the lower part leading to Qa'a Azraq, the Azraq town, wetland reserve, Azraq-Safawi, and Azraq-Qrayyat (to Saudi Arabia), major roads seriously threatened by expected flooding. As far as W. Wuheida is concerned, 80% of sub-basins nos. 1, 2, 3, and 5 are of extreme and high flooding susceptibility. These sub-watersheds receive the highest rainfall (160 mm annually), and are characterized by moderate to relatively steep slopes. Thus, it yields high runoff potential. Repetitive destructive floods were recorded in W. Wuheida, and resulted in the destruction half of Ma'an town in 1966 due to high peak discharge. During the extreme flood, the estimated peak discharge of W. Yutum, south of Ras En Naqb was 540 m³/s. Similarly, the peak discharge of W. Wuheida during the major flood of February 2006 was estimated in the range of 270 to 320 m³/s. Based on the present results, it can be concluded that 81.25% of the sub-basins related to W. Rajil can be categorized under moderate, high, and extreme susceptibility for flash floods. In parallel, 80% of the sub-basins pertaining to W. Wuheida are grouped under high and extreme flooding susceptibility. Consequently, Ma'an city, the Amman-Aqaba highway, El-Jafr village, Qa'a Azraq, the Azraq town, wetland reserve, and major roads connecting Jordan with northern Saudi Arabia and western Iraq via Azraq are seriously exposed to flash floods. Thus, protection measures are highly requisite to protect Ma'an city, Azraq town, the Amman-Aqaba highway, other major roads, and infrastructure facilities against flooding, in order to maintain the future development of Ma'an and Azraq areas. Hydro-morphometric and GIS-based flood hazard and the generated flooding risk maps aim to help planners and decision makers to assess the potential impact of floods, and to avoid; areas exposed to harmful flash floods; and also to predict sites which are likely to

be flooded in the future. Decision makers can also act properly pre-disaster, during, and post-disaster; thus, precautionary measures can be prepared in order to minimize flooding effects. Post-disaster, the compiled GIS maps can also help decision makers to assess damage and losses caused by flooding. Therefore, flood protection measures can be usefully implemented to protect developed sites against flooding.

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