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A GIS morphometric analysis of hydrological catchments within Makkah Metropolitan area, Saudi Arabia

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ABSTRACT

Spatial information technologies, particularly the Geographical Information Systems (GIS), represent efficient tools in determination of drainage basin morphometric properties for water resources management and environmental planning. GIS and a high-resolution Digital Elevation Model (DEM) have been utilized for the morphometric analysis of six basins exist within Makkah metropolitan area, southwest Saudi Arabia. Several morphometric parameters have been computed and analyzed,such as total relief, relative relief, relief ratio, ruggedness number, texture ratio, elongation ratio, circularity ratio, form factor ratio, drainage density, stream frequency, sinuosity factor, and bifurcation ratio. Impacts of morphometric parameters on flash flood characteristics have been also investigated. It has been found that the catchment no. 3 has the least time of concentration, the highest runoff depth. Such hydrological hazards are mainly due to the basin's small area and its highest relief ratio, relative relief, and ruggedness factor. Hence, it is concluded that this specific catchment might be considered as the most hazardous area in Makkah city in terms of flash flood impacts. Therefore, it is recommended that the attained results be utilized in water resources management and environmental planning in Makkah city.

Keywords: GIS, DEM, morphometry, water resources, Saudi Arabia.

1. Introduction

The hydrological and physical characteristic description of a watershed constitutes an essential task for hydrologic and water resource management projects. Delineation of hydrologic basins and determination of their morphometric parameters has been considered as regular geomorphologic tasks. Spatial information technologies, particularly Geographic Information Systems (GIS) and remote sensing (RS), have proved to be efficient tools in delineation of drainage pattern and water resources planning. GIS has been widely used in several geomorphologic, morphometric, flood management, and environmental applications (e.g. Dawod and Mohamed, 2009, El Bastawesy et al., 2010, Rao, et al., 2010, Dawod and Mohamed, 2008, and Dongquan et al., 2009). In Kingdom of Saudi Arabia (KSA), several morphometric and hydrological investigations have been carried out using different datasets and methodologies. Dawod et al. (2011) has developed a GIS-based flood management approach, including delineation of catchments, for Makkah metropolitan area. Dawod and Koshak (2011) utilized GIS to develop unit hydrographs for flood and water resources management within Makkah city. Also, Al Suad (2009) has applied topographic maps, IKONOS and ASTER remote sensed images, and GIS to delineate more than 20 sub-basin in wadi Auranh, southwest KSA. Elaji (2010) also utilized a number of GIS software along with

ASTER Digital Elevation Model (DEM) to construct a morphometric and hydrologic databases for Yalamlam basin. Moreover, Al-Ghamdi (2004) has utilized IRS and LandSat-5 remote sensing images to extract drainage networks in Nomaan mountainous area, southwest KSA. In addition, Shehata and Koshak (2007) have constructed a 3D GIS to understand and analyze the locations, types, and sizes of the possible natural risks in Mina, near Makkah city.

2. Study Area

Makkah city is located in the south-west part of KSA, about 80 Km east of the Red Sea (Fig. 1). It extends from $39^{o}\ 35^{'}$ E to $40^{o}\ 02^{'}$ E, and from $21^{o}\ 09^{'}$ N to $21^{o}\ 37^{'}$ N. The area of the metropolitan region (the study area) equals 1593 square kilometers approximately. The topography of Makkah is complex in nature, and several mountainous areas exist inside its metropolitan extent.

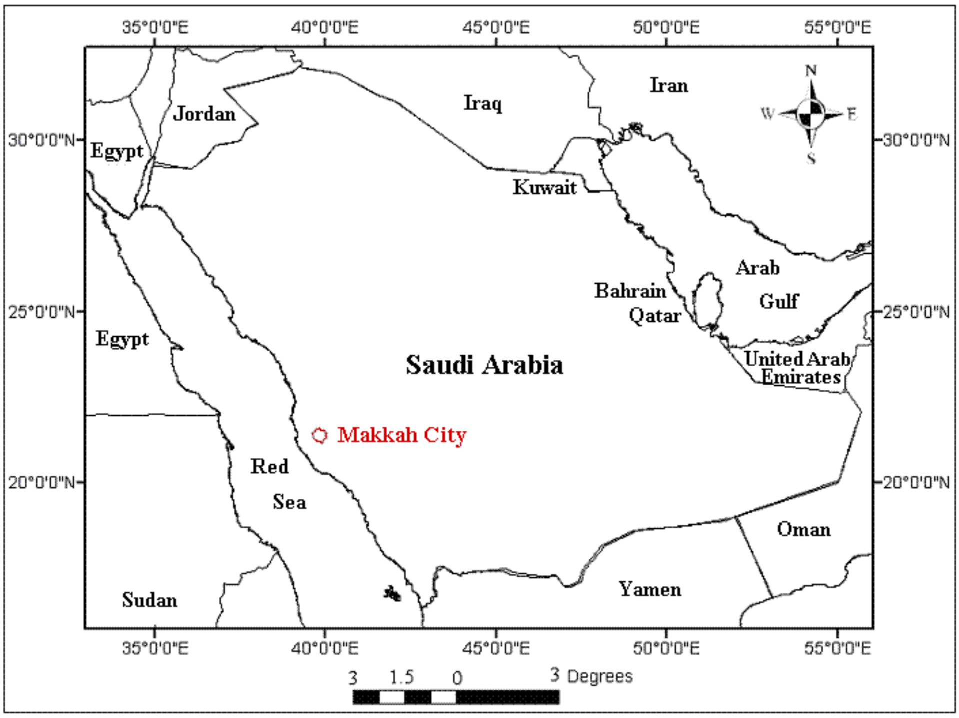

Figure 1: Study area map

The winter is considered as the main rainy season in Saudi Arabia. The annual rain over Makkah city, for a period extends from 1966 to 2009, varies from 3.8 mm to 318.5 mm, with an average of rainfall equals 101.2 mm (Dawod et al., 2011). Due to the complexity of Makkah's topography, flash floods occur periodically with significant variations in magnitude. Regarding the geology of Makkah metropolitan area, Precambrian volcanic rocks constitute the main geological features that define the general topography framework, particularly the mountainous structures, in this area. These rocks may be classified into several categories, but the most widespread types are: the precambrian layered rocks, e.g. unassigned amphibolites, tonalities, and diorite, that constitute about 65% of the area; and the Precambrian intrusive rocks that occupy approximately 20% of the area (Mirza and Barodi, 2004). The second main geological feature in Makkah is the quaternary deposits, e.g. sands and pebbles, exist in lower streams of the basins.

3. Morphometric Parameters

A number of common parameters are usually utilized in order to describe the morphometric and geomorphologic properties of a watershed. Such parameters can be grouped in four categories: topographic, areal, relief, and network properties. Although details can be found in several literature (e.g. Huggett, 2007, and Horton, 1945), table 1 presents mathematical formulas for computing morphometric parameters of a watershed.

3.1 Data and Methodology

The main utilized data piece is a Digital Elevation Model (DEM) for the study area. The acquired DEM produced by the by King Abdulaziz City of Sciences and Technology (KACST) with a horizontal spatial resolution equals 5 meters.

Table 1: Morphometric Parameter Mathematical Formulas

Parameter	Formula
Topographic properties	
Area of basin (km^2)	A
Perimeter of basin (km)	P
Maximum length: L_{max}	The maximum basin length
Relief properties	
Basin relief: ΔH	$\Delta H = H_{max} - H_{min}$
Relative relief: R_{hp}	$R_{hp} = \Delta H / P$
Relief ratio: R_h	$R_h = \Delta H / L_{max}$
Ruggedness number: N	$N = \Delta H . D$
Areal properties	
Texture ratio: T	$T = N_1 / P$
Elongation ratio: R_l	$R_l = 2 [\sqrt{(A / \prod)}] / L_u$
Circularity ratio: R_c	$R_c = 4 \prod A / P^2$
Form factor ratio: R_f	$R_f = A / L_b^2$
Network properties	
Drainage density (km/km^2): D	$D = L_u / A$
Stream frequency: F_s	$F_s = N_u / A$
Sinuosity Factor: S	$S = L_b / L_{min}$
Bifurcation Ratio: R_{b-m}	R_b = Number of streams of an order / number of streams of the next order. A mean value of this coefficient (R_{b-m}) is usually used for a watershed.
where: L_u = Total stream length of all orders, N_u = Total number of streams of all orders, N_1 = Total number of streams of 1^{st} order, L_b = Basin length (km), H_{max} = The elevation of the highest point in the basin , H_{min} = The elevation of the lowest point in the basin , L_{min} = shortest distance between spring and outlet, and $\prod = 22 / 7$	

A window covers Makkah metropolitan area (Fig. 2) has been provided through the Center of Excellence in Hajj and Omrah, Umm Al-Qura university. Mirza et al (2010) confirm that that national DEM is 3 times more accurate than published global ASTER and SRTM3 DEMs. From Fig. 2, it can noticed that the heights of Makkah metropolitan area range from 80 to 982 meters. In order to precisely determine morphometric parameters in Makkah metropolitan area, GIS technology has been utilized. The Arc GIS, Arc Hydro, and Tau DEM software have been applied in the current research to determine the morphometric parameters of Makkah city' basins. Additionally, some programming steps have been performed within the attribute tables to compute necessary morphometric quantities.

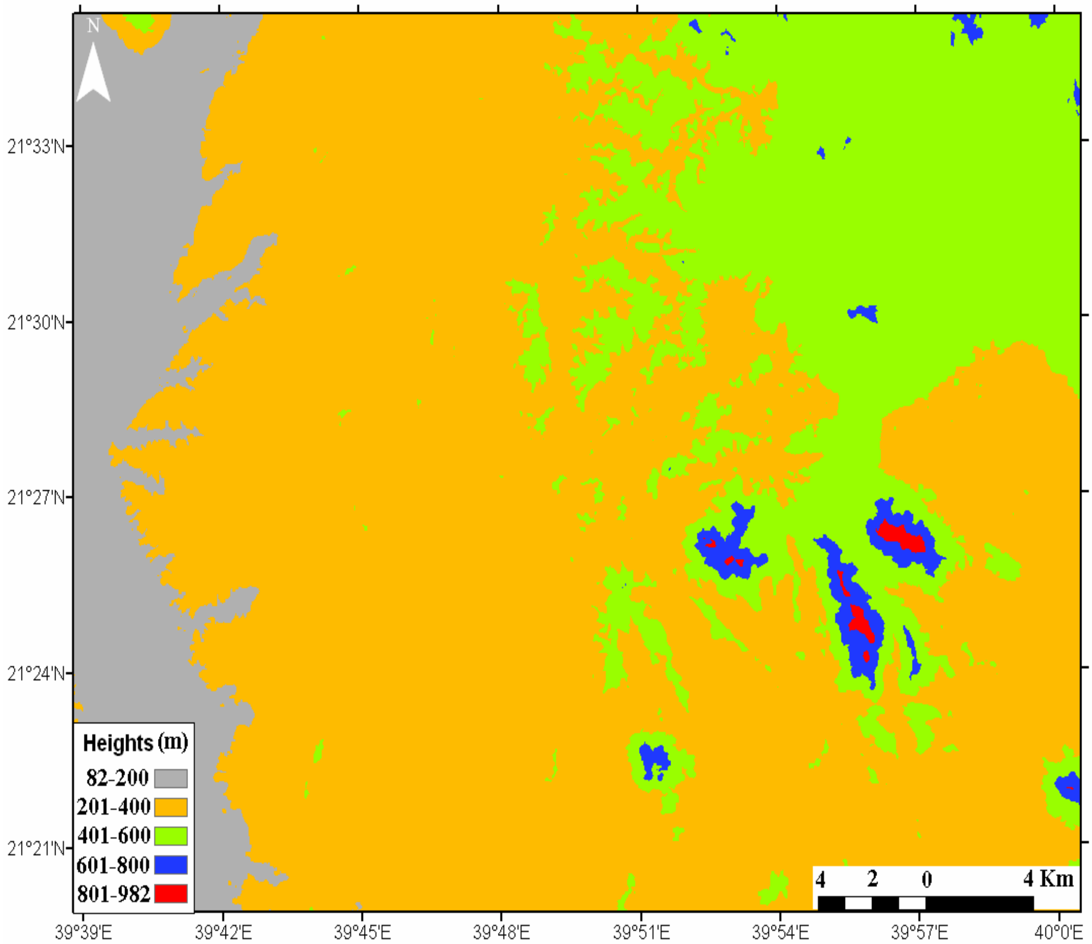

Figure 2: The National 5-m DEM for Makkah city

4. Results and Discussion

Utilization of the Arc GIS software, along with some other associated extensions, has resulted in delineating six watersheds within Makkah metropolitan area (Fig. 3). Four catchments are entirely located within the study area, while basins C5 and C6 represent sub-basins that exits within Makkah metropolitan extent but belong to some large basins surround Makkah city. Table 2 presents the topographic properties of these watersheds. Basin areas range from 74.3 to 360.6 square kilometers, while the basin perimeters vary from 50.2 to 134.9 kilometer. The maximum length of stream, which is a significant morphometric parameter, varies from 16.5 to 48.6 kilometer.

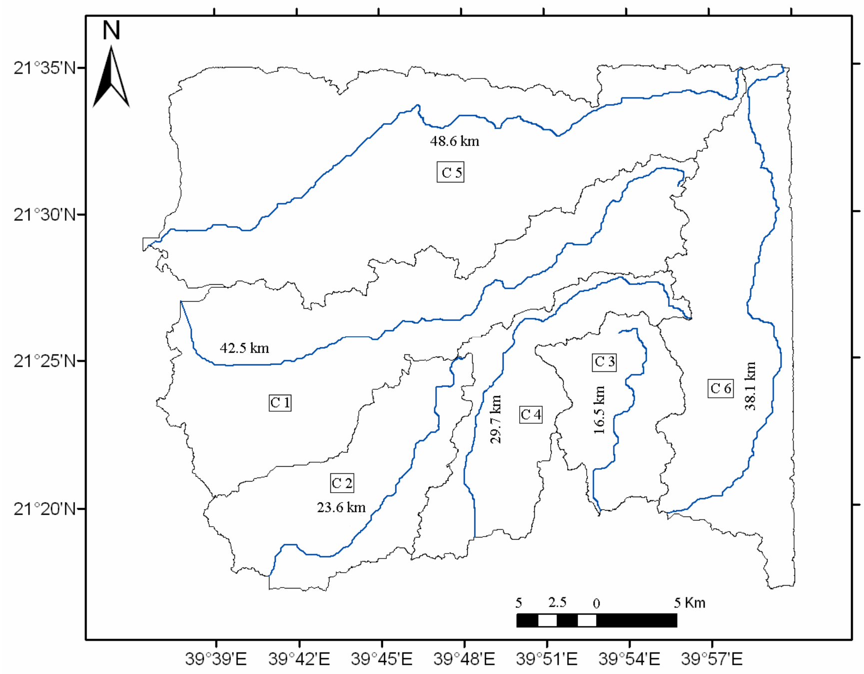

Figure 3: Watersheds and their main streams

Table 2: Statistics of topographic properties

Item	C1	C2	C3	C4	C5	C6
Basin Area (km^2)	252.7	122.3	74.3	109.9	360.6	200.2
Basin Premier (km)	134.6	69.1	50.2	89.1	134.9	102.0
Length of Main Stream (km)	42.5	23.6	16.5	29.7	48.6	38.1

Concerning the relief properties of the study area' watersheds, Table 3 presents the accomplished results. The total relief varies from 333 meters to 769 meters, while the relief ration, in m/km, range between 12.6 and 40.4. Additionally, the relative relief ranges from 4.0 to 13.3 meters, while the ruggedness value vary from 33.7 to 104.3.

Table 3: Statistics of relief properties

Item	C1	C2	C3	C4	C5	C6
Total Relief (m)	546	333	667	769	632	714
Relief ratio (m/km)	12.6	14.1	40.4	25.9	13.0	18.7
Relative relief (m)	4.0	4.8	13.3	8.6	4.7	7.0
Ruggedness value	33.7	38.1	104.3	66.4	33.8	51.1

It has been found that catchment no. 3 has the maximum relief ratio, relative relief, and ruggedness factor even though it does not have the maximum height difference (total relief). That might be due to the smallest basin area of that catchment (only 74.3 square kilometers as seen in Table 2). Hence, that catchment can be considered the most topographical-complex basin in the study area, which will result in more steep morphometric characteristics as will be seen later on. Table 4 presents the attained results of the aerial properties of the catchments within Makkah metropolitan area. The circularity ratio is the ratio of the basin area to the area of a circle has the same circumference. It is influenced by the length and frequency of streams, geological structures, land use, and the slope of the watershed. Catchment no. 3 has the highest circularity ratio (0.37) and catchment no. 2 has a closer value (0.32). It can be seen from Fig. 2 that these two basins are the closer to a circular shape. Again, catchment no. 3 has the highest circularity ratio even though it is the smallest watershed, which is considered as a hazardous indication since it means that the flash floods could reach great volume over a small area. On the other hand, the elongation ratio represents how close a basin to a rectangular shape. From table 4, it can be seen that two basins have rectangular ratio grater than 0.5, while the other four have elongation ratios less than 0.4. Hence, the six catchments in Makkah metropolitan area are far from a complete rectangular shape (see Fig. 2). Moreover, the form factor ratio is another indication of the basin circularity. Its value is always less than 0.785, for a perfectly circular basin (Horton, 1945). The attained form factor ratios for the study area vary from 0.12 to 0.27, which also means that six basins don't represent a circular shape. Additionally, the texture ratio of the six basins vary from 3.46 to 7.86, which indicates that it may be classified as a medium texture. It is known that the basins have similar geological, structural, and hydrological conditions will nearly have the same category of texture ratio (Sherief, 2008). It is concluded that the complex topography of the study area plays a major factor affecting the aerial characteristics of those watersheds.

Table 4: Statistics of aerial properties

Item	C1	C2	C3	C4	C5	C6
Texture ratio: T	5.69	5.58	4.20	3.46	7.86	5.98
Elongation ratio: R_l	0.42	0.53	0.59	0.40	0.44	0.42
Circularity ratio: R_c	0.18	0.32	0.37	0.17	0.25	0.24
Form factor ratio: R_f	0.14	0.22	0.27	0.12	0.15	0.14

The network properties are considered the major morphometric characteristics of watersheds. Stream order is used to denote the hierarchical relationship between stream segments and allows drainage basins to be classified according to size. Several stream-ordering systems exist, the most commonly used being those devised by Arthur N. Strahler and by Ronald L. Shreve. In Strahler's ordering system (which is used in the current research), a stream segment with no tributaries that flows from the stream source is denoted as a first-order segment.

A second order segment is created by joining two first-order segments, a third-order segment by joining two second order segments, and so on. It has been found that the maximum stream order in the six watersheds, in the study area, equals 5 for the four small sub-basins (No. C2, C3, C4, and C6) and reaches order 6 in the other two sub-basins (C1 and C5), which have the maximum basin areas (Table 5). Figure 4 depicts the stream order spatial variations in Makkah metropolitan area. Analyzing the variations of streams' length, Table 6 concludes that there is an inversely proportional relationship between stream lengths and stream orders.

Table 5: Statistics of basin stream orders

Catchment	C1	C2	C3	C4	C5	C6
No. of streams of Order 1	766	386	211	308	1059	610
No. of streams of Order 2	257	109	65	85	318	171
No. of streams of Order 3	45	23	13	25	53	40
No. of streams of Order 4	10	4	4	5	14	9
No. of streams of Order 5	3	1	1	1	3	1
No. of streams of Order 6	1	NA	NA	NA	1	NA
Total No. of streams	1082	523	294	424	1448	831

Table 6: Statistics of basin stream lengths' percentage

Catchment	C1	C2	C3	C4	C5	C6
Order 1	51.0%	54.3%	50.4%	54.1%	53.0%	51.5%
Order 2	26.2%	23.4%	23.8%	24.6%	22.7%	23.2%
Order 3	12.3%	11.7%	14.9%	8.6%	12.3%	14.1%
Order 4	4.3%	6.3%	7.1%	11.6%	5.8%	7.4%
Order 5	5.4%	4.4%	3.8%	1.1%	4.7%	3.7%
Order 6	0.8%	N/A	N/A	N/A	1.5%	N/A

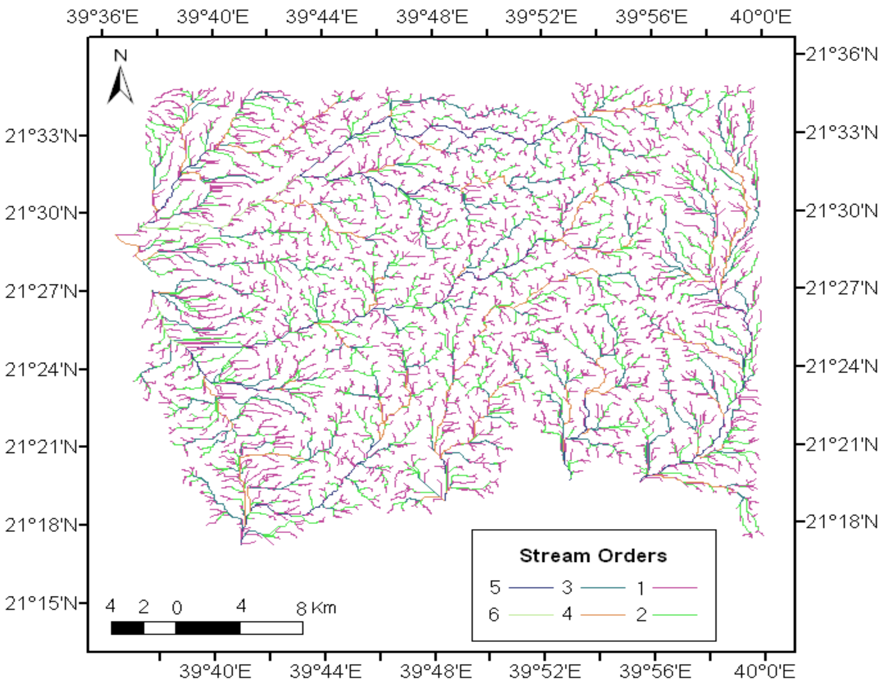

Figure 4: Stream orders of watersheds

Drainage density is a measure of how frequently streams occur on the land surface. It indicates the closeness of spacing between channels and is a measure of the total length of the stream segment of all orders per unit area. It reflects a balance between erosive forces and the resistance of the ground surface, and is therefore related closely to climate, lithology, and vegetation. Drainage densities can range from less than 5 km/km2 when slopes are gentle, rainfall low, and bedrock permeable, to much larger values of more than 500 km/km2 in upland areas where rocks are impermeable, slopes are steep, and rainfall totals are high (Huggett, 2007). Table 6 that the drainage density for Makkah's sub-basin range from 2.56 to 2.73 km/km^2. So, that can classified, in general, as a medium drainage density pattern. Moreover, the stream frequency for Makkah's sub-basin vary between 3.86 and 4.28 streams/km^2 (Table 7). Generally, the stream frequency has positive correlation with the drainage density of all sub-watersheds, suggesting increase in stream population with respect to increase in drainage density. Also, the sinuosity factor of the basins within Makkah metropolitan area range from 1.21 to 1.42. Thus, those streams can be classified as from transitional to regular streams, which is due to the steep slopes in the topography of the study area.

Another commonly used topological property is the bifurcation ratio, that is, the ratio between the number of stream segments of one order and the number of the next-highest order. A mean bifurcation ratio is usually used because the ratio values for different successive basins will vary slightly. With relatively homogeneous lithology, the bifurcation ratio is normally not more than five or less than three. However, a value of ten or more is possible in very elongated basins where there are narrow, alternating outcrops of soft and resistant strata. The values of mean bifurcation ratios, in the study area, slightly vary between 3.87 to 5.32 (Table 7). Similar results for some small sub-watersheds have been reported (Altın and Altın, 2011, and Javad et al., 2009).

Table 7: Statistics of network properties

Item	C1	C2	C3	C4	C5	C6
Drainage density: D (km/km^2)	2.67	2.71	2.58	2.56	2.59	2.73
Stream frequency: F_s (stream/km)	4.28	4.28	3.96	3.86	4.02	4.15
Sinuosity Factor: S	1.26	1.21	1.26	1.42	1.25	1.30
Bifurcation Ratio: R_{b-m}	3.90	4.51	3.87	4.26	4.16	5.32

A correlation analysis has been performed between the main morphometric parameters of the six sub-basins. The results (Table 8) showed that the basin area, with a positive correlation equals 0.999, is the most effective element that influences the sum of stream lengths of all orders. Moreover, the basin width and length also resulted in high positive correlation values, 0.95 and 0.91 respectively. On the other hand, the total relief, or height difference, has a non-significant negative impact, -0.02, to the sum of stream lengths of all orders. Similar results have been reported by Subyani et al. (2010) for major basins in western Saudi Arabia.

Table 8: Correlation between main morphometric parameters

Item	$\sum L_n$	A	ΔH	L	W
$\sum L_n$	1				
A	0.999	1			
ΔH	-0.02	-0.01	1		
L	0.91	0.92	-0.22	1	
W	0.95	0.94	0.14	0.74	1
where: $\sum L_n$ = sum of stream length of all orders, A = basin area, ΔH = total relief, L = length of main stream of the basin, and W = basin width.					

In order to study the relationship between the morphometric properties of watersheds and their hydrological impacts, Table 9 summarizes some flood hazard factors. The time of concentration is the time elapsed of a water drop to travel from the farthest point of a basin to its outlet. The catchment no. 3 has the least time of concentration (1.73 hours), the highest runoff depth (178.8 mm). Such hydrological vulnerabilities are mainly due to the basin's small area and its highest relief ratio, relative relief, and ruggedness factor. Again, that catchment might be considered as the most hazardous area in Makkah city in terms of flash flood impacts.

Table 9: Flood characteristics in Makkah city

Item	C1	C2	C3	C4	C5	C6
Time of concentration (hours)	5.69	3.76	1.73	2.63	6.72	4.17
Runoff depth (mm)	151.7	151.7	178.8	166.7	151.7	148.8

After Dawod et al., 2011

5. Conclusions

Delineation of hydrologic basins and determination of their morphometric parameters are standard geomorphologic tasks. GIS has been utilized to compute several morphometric parameters for six basins within Makkah city, southwest Saudi Arabia, for water resources management and environmental planning. The accomplished results show that the basins' areas range from 74.3 to 360.6 square kilometers, while the maximum length of stream varies from 16.5 to 48.6 kilometer. Additionally, the total relief varies from 333 meters to 769 meters, while the relief ration range between 12.6 and 40.4 m/km. In addition, the relative relief ranges from 4.0 to 13.3 meters, while the ruggedness value vary from 33.7 to 104.3. It has been found that catchment no. 3 has the maximum relief ratio, relative relief, and ruggedness factor even though it does not have the maximum height difference (total relief). That might be due to the smallest basin area of that catchment (only 74.3 square kilometers. Hence, that catchment can be considered the most topographical-complex basin in the study area, which will result in more steep morphometric characteristics.

Also, it has been found that the maximum stream order in the six watersheds, in the study area, equals 5 for the four small sub-basins and reaches order 6 in the other two sub-basins The correlation results showed that the basin area is the most effective element that influences the sum of stream lengths of all orders. The drainage density for Makkah's sub-basin range from 2.56 to 2.73 km/km^2. So, that can classified, in general, as a medium drainage density pattern. Dawod et al. (2011) have found out that the catchment no. 3 has the least time of concentration, the highest runoff depth. Such hydrological hazards are mainly due to the basin's small area and its highest relief ratio, relative relief, and ruggedness factor. Again, it is concluded that this particular catchment may be regarded as the most hazardous area in Makkah city in terms of flash flood impacts. Therefore, it is recommended that the attained results be utilized in hydrological, water resources, and environmental management in Makkah city, Saudi Arabia.

Acknowledgements

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