GIS digital mapping of flood hazard in Jeddah–Makkah region from morphometric analysis

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Abstract

Floods are considered to be one of the natural disasters that seriously affect people's lives and property every year. Although, delineation and determination of hydrologic basins and their morphometric parameters are difficult morphological tasks, GIS-based approach simplifies the investigation of various morphometric factors and helps to explore the correlation between the drainage morphometry and landform properties. The present study is aimed to investigate the spatial distribution of drainage basins around Jeddah–Makkah region and its surrounding areas (nearly 40,247 km^2) using GIS spatial analysis. The morphometric parameters of these drainage basins and their channel systems were estimated and calculated. The computed morphometric parameters are categorized into the following three main groups: linear, aerial, and relief features. The documentation of these parameters was, then, used to evaluate and construct flood hazard map of the region. Flood hazard map assesses five classes with varying degrees (very low, low, moderate, high, and very high) of flood hazard zones. Such hydrological hazard is mostly due to the basin's area and its highest relief ratio, relative relief, and ruggedness factor. The flood hazard map shows that the city of Jeddah is in a moderate to high flood hazard zone, but most of the areas surrounding it are in moderate flood hazard zone. This indicates that during heavy rainfalls, flash flood could be generated in these areas which can be severely affecting the city. In addition, this study shows a remarkable correlation between theoretical concepts, data sets, and field observations, predominantly highlighting the role of geology and geomorphology in influencing the basin morphometry and identity.

Introduction

A disaster is defined as a sudden change with devastating impact or a natural catastrophe that causes great damage or loss of life. Disasters can be unnatural, such as fire and environmental pollution, or natural, such as landslides, floods, earthquakes, and volcanic eruption. The geological hazard is caused by different processes, such as the following: (a) internal geological processes, either below the earth's crust or at the oceanic floors (e.g., volcanoes, earthquakes), and (b)

external geological processes, such as geomorphologic activity that happens above the earth's surface (e.g., floods, landslides). Among these natural hazards is flooding which is one of the main natural disasters that affect people's lives and property every year (Wang 1999; Dilley et al. 2005). Many parts of the Kingdom of Saudi Arabia, such as the western and central regions, are prone to floods especially during the heavy rainfalls (Al-Bassam et al. 2014).

The western region of Saudi Arabia is bounded by the Hijaz Mountains to the east and the Red Sea to the west. Hence, the topography of this region and the lithology of the rocks and soil may increase the chances of the occurrences of geological hazard. In addition, and due to the rapid urban development and steady growth of population in the Kingdom, some of these areas are vulnerable to geological hazard. Although the western coastal areas of Saudi Arabia have low average rainfall, a rainstorm in the nearby mountains can generate flash floods which may damage properties, loss of human lives, and cause financial damages. Examples of floods from western (e.g., Jeddah Makkah, Taif, Medinah,

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and Allith), northern (e.g., Arar and Tabuk), and central parts (e.g., Hail) of Saudi Arabia are shown in Fig. 1.

In arid and semi-arid regions, such as Saudi Arabia, flash floods are very common. During the last decade, the city of Jeddah witnessed a consistent effect of flash floods (e.g., 2009, 2010~2011, and 2017). In 2009, multiple casualties were reported during this flood which was considered to be one of the worst floods that hit the region in over 25 years as the city received more than 9 cm of rain within a span of 4 h. In 2011, the city, again, received a rainfall of 11 cm within a span of 3 h. Authorities had to undertake extensive relief operations. Most of the families in the affected neighborhoods were rendered homeless, and basic facilities were out of reach in these localities.

The occurrence of flooding depends on several factors, such as the morphometric parameters of the drainage basins, regional geology, and floodplain settings (Subyani and Al-Dakheel 2009). Despite extensive studies in the field of flooding, the evaluation of drainage basins' hydrological features is still essential due to their influence in water management. Jones (1999) stated that the morphometric parameters, including shape, length, area, and slope, represent the land topographic expression that affects the pattern of the catchment's stream flow during concentration time. The geomorphic characteristics of a drainage basin represent a significant function in controlling the basin's hydrology (Jain and Sinha 2003; Okoko and Olujjinmi 2003; Ifabiyi 2004). Furthermore, the quantitative morphometric analysis of the channel network helps to understand the geo-hydrological behavior of the drainage basin (Easterbrook 1993; Soni 2017; Bisht et al. 2018).

In order to evaluate flooding, streamflow, which represents the watershed geomorphology, is essential to be determined

(Morisawa 1959). Watershed morphometric analysis involves the measurements of channel network of linear, aerial, and gradient features that represent a quantitative description of the drainage system (Strahler 1964; Nautiyal 1994; Soni et al. 2013; Tripathi et al. 2013; Soni 2017; Bisht et al. 2018). Evaluating the surface water hydrology and geomorphology are essential to understand the evolution of basin morphology, flood characteristics, and sediment yield (Jolly 1982; Ogunkoya et al. 1984; Anyadike and Phil-Eze 1989; Jenson 1991; Breilinger et al. 1993). In addition, the morphometric parameters at the watershed scale commonly provide valuable information concerning its formation and development since all the hydrologic and geomorphic processes occur within the watershed (Singh and Singh 1997; Mahtab et al. 2003; Pareta and Pareta 2012; Romshoo et al. 2012; Dar et al. 2013; Vandana 2013).

Geographic information system (GIS) and remote sensing (RS) data and tools are commonly used in studying and evaluating the morphometric parameters of the channel systems within any drainage basin (e.g., Srivastava and Mitra 1995; Agarwal 1998; Nag 1998; Moussa 2003; Vittala et al. 2004; Kouli et al. 2007; Al Saud 2010; Dawod et al. 2011; Geena and Ballukraya 2011; Al-Ghamdi et al. 2012; Chavan and Gadge 2013; Soni et al. 2013; Tripathi et al. 2013; Basihy et al. 2017; Soni 2017; Bisht et al. 2018). This study aims to investigate the spatial distribution of the main drainage basins around the Jeddah–Makkah region and its surroundings using RS data and GIS spatial analysis. The morphometric parameters of these drainage basins and their channel systems were estimated and calculated. In addition, the documentation of these parameters was, then, used to evaluate and construct flood hazard map of the region. Furthermore, the quantitative data of these morphometric parameters were also used to
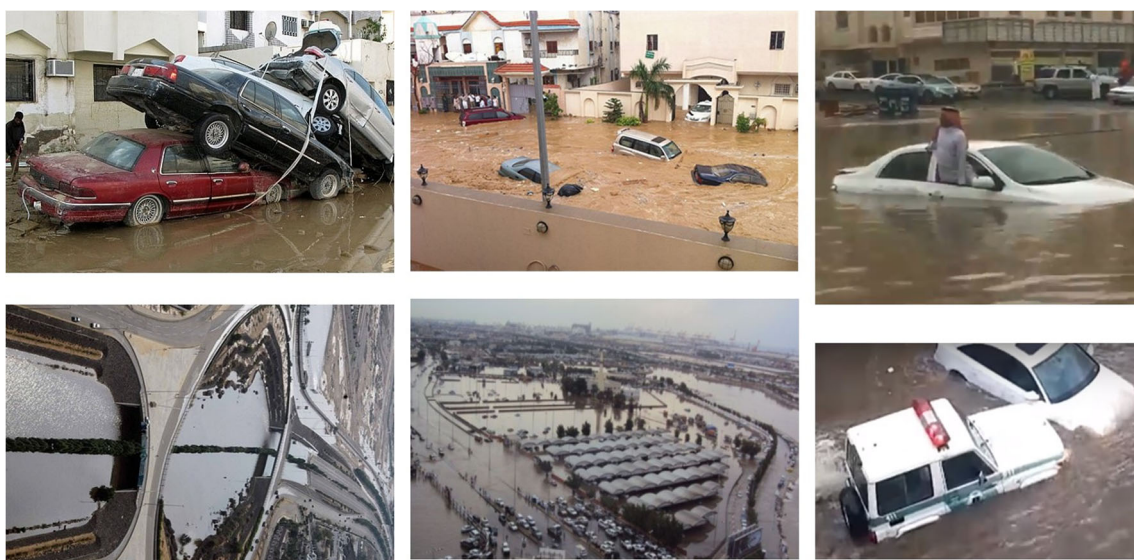
Fig. 1 This shows the damages of floods caused by heavy rains that lashed the western (e.g., Jeddah Makkah, Taif, Medinah, and Allith), northern (e.g., Arar and Tabuk), and central parts (e.g., Hail) of Saudi Arabia at the years 2009, 2010, 2011, and 2017

establish the relationship between these parameters and to develop empirical relationships where these relationships are seen to exist.

Study area

The study area is located at the central western part of the Arabian Shield extending from the mountains of Hijaz in the east to the Red Sea coastal plains in the west (Fig. 2a,b). It covers an area of nearly 40,247 km^2 between latitudes 20°50′ and 22°50′ north and longitudes 38°50′ and 40°59′ 59″ east. The study area is characterized by several basins (eight) that drain westwards into the Red Sea. The topography of the area is characterized by steep mountain slopes with an elevation of about 2600 m (above sea level) at the Hijaz mountain to a minimum of about 0~2 m at the Red Sea coast. The Jeddah–Makkah region extends westwards from the Red Sea coastal plains across Tihamat Al-Hijaz and the Hijaz Mountains to the Tertiary volcanic fields known as Harrat Rahat (Ramsay 1986; Sahl 1987; Moor and Al-Rehaili 1989; Bradi et al. 2010). The area is underlain by Late Proterozoic metavolcanic, metasedimentary, and plutonic rocks, Tertiary sedimentary rocks, and basalt lava flows, covered with Quaternary surficial deposits (Ramsay 1986).

Data and methodology

The data used in this study is consisted of the Global DEM with 30 m resolution (called ASTER GDEM) which has been obtained from the Advanced Spaceborne Thermal Emission and Reflection Radiometer (https://gdex.cr.usgs.gov/gdex/). The ASTER GDEM is a joint product developed and made available by the Ministry of Economy, Trade, and Industry (METI) of Japan and the United States National Aeronautics and Space Administration (NASA). In addition, the recent Landsat (Landsat 8) imagery which is acquired in 2013 and topographic maps (with scale 1:50,000) provided by the Aerial Survey Department, Ministry of Petroleum and Mineral Resources, KSA, were also used. These data were used to extract the elevation and the slope and to delineate the stream network and watershed boundaries. Figure 2c shows the steps that were taken to determine the hydrologic features of the drainage basins, such as watershed boundaries and stream networks (ESRI 2009). Furthermore, several field visits to different channels/wadis were conducted to verify and validate the results.

Different GIS extension tools, such as the Hydrology Tool (e.g., ArcHdro 10.3 and ArcSWAT 2012.10.9) in the Spatial Analyst extension in ArcGIS 10.3, were used to determine the water path from upstream to downstream. The hydrology tool has a set of dialogs to delineate watersheds and to define stream networks. The stream networks are digitally created and processed to map the drainage basins and to quantitatively determine some of the main morphometric parameters. In addition, the flow direction and slope were also determined.

Based on the data and methods described previously, some of the main morphometric parameters were determined. These morphometric parameters were divided into three categories according to their orientation in space. They are linear (1-dimension), aerial (2-dimension), and relief (3-dimension) features. The three categories of the morphometric features and their related factors were calculated to delineate the watershed area based on a mathematical formula. These categories are as follows:

i)   *Linear features*, such as stream order (U), number of stream (N_u), stream length (L_u), mean stream length (L_{sm}), stream length ratio (R_L), bifurcation ratio (R_b), and mean bifurcation ratio (R_{bm}), were determined using different techniques provided by several authors, such as Horton (1945), Schumm (1956), Strahler (1957 and 1964), and Melton (1958).

ii) *Areal features*, such as basin area (A), basin perimeter (P), basin length (L_b), drainage density (D_d), drainage frequency (F_s), drainage texture (T), elongation ratio (R_e), circularity ratio (R_c), form factor (F_f), infiltration number (I_f), length of overland flow (L_g), and sinuosity index (S_l), were calculated based on methodologies provided by Horton (1932, 1945), Miller (1953), Schumm (1956), Chorley et al. (1957), Strahler (1964 and 1968), Faniran (1968), and Gravelius (1914).

iii) *Relief features*, such as basin relief (R), slope (S), relief ratio (R_r), dissection index (D_{is}), constant of channel maintenance (C), and ruggedness number (R_n), were determined based on the methodologies provided by Horton (1932, 1945), Schumm (1954, 1956, 1963), Hardely and Schumm (1961), Strahler (1964), Sreedevi et al. (2005), and Mesa (2006).

The documentation of some of these morphometric parameters was, then, used to construct flood hazard map of the study area. There are various approaches to perform the overlay analysis (ESRI 2009). The evaluated data which are calculated and obtained from spatial data analysis are converted into raster format to produce various map layers that spatially represent various datasets contributing to the flood hazard evaluation. The flood hazard model assesses five classes with varying degrees (very low, low, moderate, high, and very high) of flood hazard zones, which are mapped using a GIS weighted sum tool. The weighted sum model, in which there is the integration of 7 thematic layers that have the equal magnitude of contribution, was used during the process of flood hazard determination (for more information, see Peuquet 1986; Malczewski 1999; Akther et al. 2009).

Fig. 2 **a** Location map (Landsat 8
Imagery) of the Jeddah–Makkah
region and its surrounding areas.
b Geological map of Jeddah–
Makkah region and its
surrounding areas. **c** A flowchart
showing the steps followed to
determine the hydrologic features
of the drainage basins (modified
from ESRI 2009)
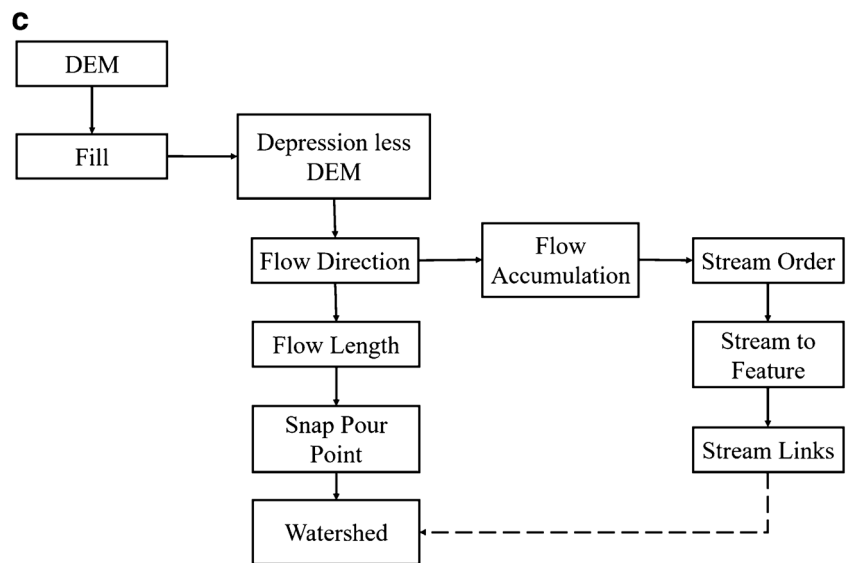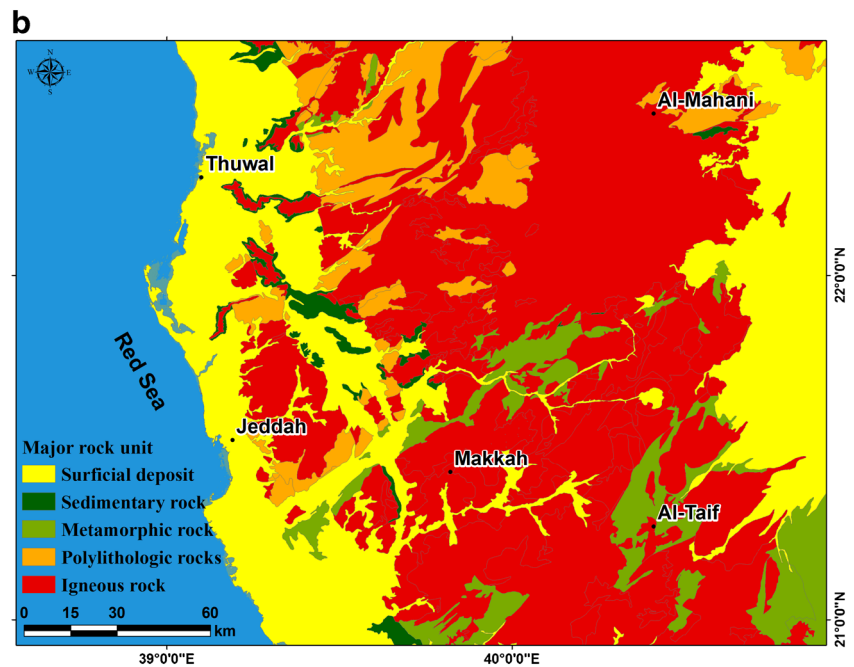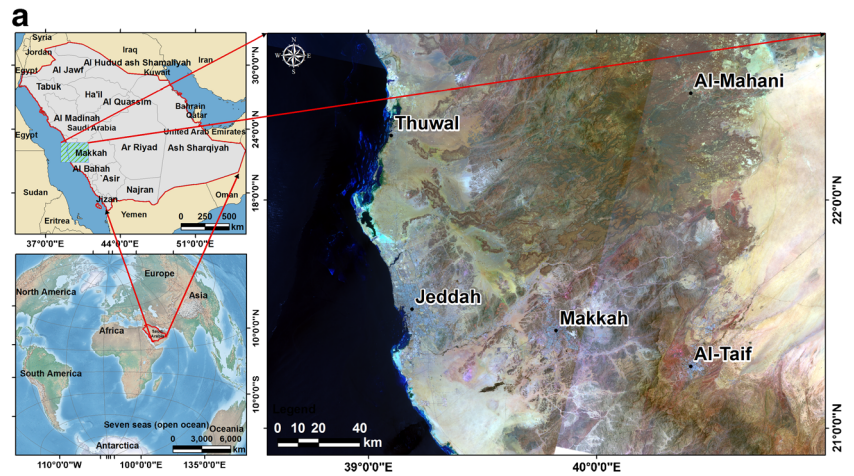
Data analysis and results

Linear features

One-dimensional (linear) features of the basins are related directly to the channel patterns of the drainage network (Hajam et al. 2013). Linear features represent streams' hierarchical location in the drainage network and present a measure of stream number, lengths of segments, and geometric homogeneity of the basin. Horton (1945), Strahler (1952, 1957), and Shreve (1967) proposed and amended the schemes of stream ordering which denotes the stream position and size in the basin. The basin order is commonly represented by the highest stream order (maximum order) that is available in the basin. The first step in basin analysis is to determine the stream order, where river size and basin size vary to a great extent with its order (Strahler and Strahler 1989). The calculations of the linear morphometric features of these basins, such as stream order (U), number of stream (N_u), stream length (L_u), mean stream length (L_{sm}), stream length ratio (R_L), bifurcation ratio (R_b), and mean bifurcation ratio (R_{bm}), are described in the subsequent texts.

Stream order (U)

Stream order is a technique of assigning a numeric order to links in a stream network (Gravelius 1914; Horton 1945; Strahler 1952; Schideggar 1970). It constitutes of a single outlet through which the drainage network of the basin transports water and sediments. Stream order is used for identifying and classifying the stream types based on their number of tributaries (Gravelius 1914; Horton 1945; Strahler 1952; Schideggar 1970). The stream ordering system used in this study is from Horton's (1945) method which was later modified by Strahler (1957). The Horton's method was chosen because of its clarity and simplicity. This technique assigns every headwater stream as an order of first (1st). At the confluence of two 1st order streams, it assigns the downstream reach as a second (2nd) order. Hence, the third (3rd) order is assigned to the confluence of two 2nd-order streams in a downstream reach, and so on (Fig. 3a; Table 1).

In this study, the drainage network of the eight major basins in the Jeddah–Makkah region and its surroundings is classified as fourth (4th)-order basins (Wadi Usfan, Wadi Nuuman, and Jeddah area), fifth (5th)-order basins (Wadi Thuwal, Wadi Khulays, and Wadi Malakan), and sixth (6th)-order basins (Wadi Fatma and Wadi Al-Mahani) (Fig. 3a,b; Tables 1 and 2). It has been recognized that there are some correlations between stream networks which are delineated from GDEM within the GIS environment and topographic maps (with scale 1:50,000).

Stream number (N_u)

Stream number (N_u) refers to the total number of streams in each order (Smith 1950). Based on the stream order (U) described previously, this study identified more than 2742 of 1st-order streams, 606 of 2nd-order streams, 129 of 3rd-order streams, 42 of 4th-order streams, 8 of 5th-order streams, and 2 of 6th-order streams (Table 1).

Stream length (L_u)

Stream length (L_u) is described as the total length of streams in each order (Strahler and Strahler 1989). Table 3 illustrates the length of specific stream segments (L_u) in each order in this study. The total stream length of the identified basins varies from 648.6 km for the Numman basin to 4719.6 km for the Al-Mahani basin (Tables 1 and 3).

Bifurcation ratio (R_b)

Horton (1945) defined bifurcation ratio (R_b) as an index of relief and dissection. Bifurcation ratio (R_b) is calculated by dividing the number of stream branches of one order (N_u) by the number of the next higher order (N_{u+1}).

$$R_b = \text{an order stream number } (N_u)/\text{next−order stream number } (N_{u+1})$$
(1)

For larger basins, the bifurcation ratio can be considered as the arithmetic mean of its ratios of the stream orders within the basin (Strahler and Strahler 1989). Generally, bifurcation ratios in homogenous lithology range between 3 and 5 (Horton 1945). A ratio of 10, however, may refer to elongated basins which are characterized by narrow and confined outcrops of soft and consolidated layers. Furthermore, bifurcation ratios (R_b) are also related to discharge rates where a low R_b value is considered as an indication of a high flood hazard (Jain and Sinha 2003).

In this study, the bifurcation ratio values range from 1.25 to 6.80 with an average of 4.78 (Table 1). This wide range of (R_b) is due to the variations in lithology and basin geometry. In addition, the bifurcation ratios of the 3rd-order to 4th-order streams which are mainly located in the hillslopes have an average of (3.44). These results may indicate moderate to high runoff. Furthermore, the discharge is attributed largely to the occurrence of less porous rocky hills marked with steep slopes.

As stated previously, several field trips were conducted to observe and confirm the classification described and to determine the role of the geomorphology of the area in influencing the basin morphometric parameters. Figure 3c shows the Wadi Fatma: (a) topographic elevation (masl) zones; (b) stream order map; (c) locations for field observations; (d) photograph for "FAT1B" location during field trips, and (e) flood hazard zones.
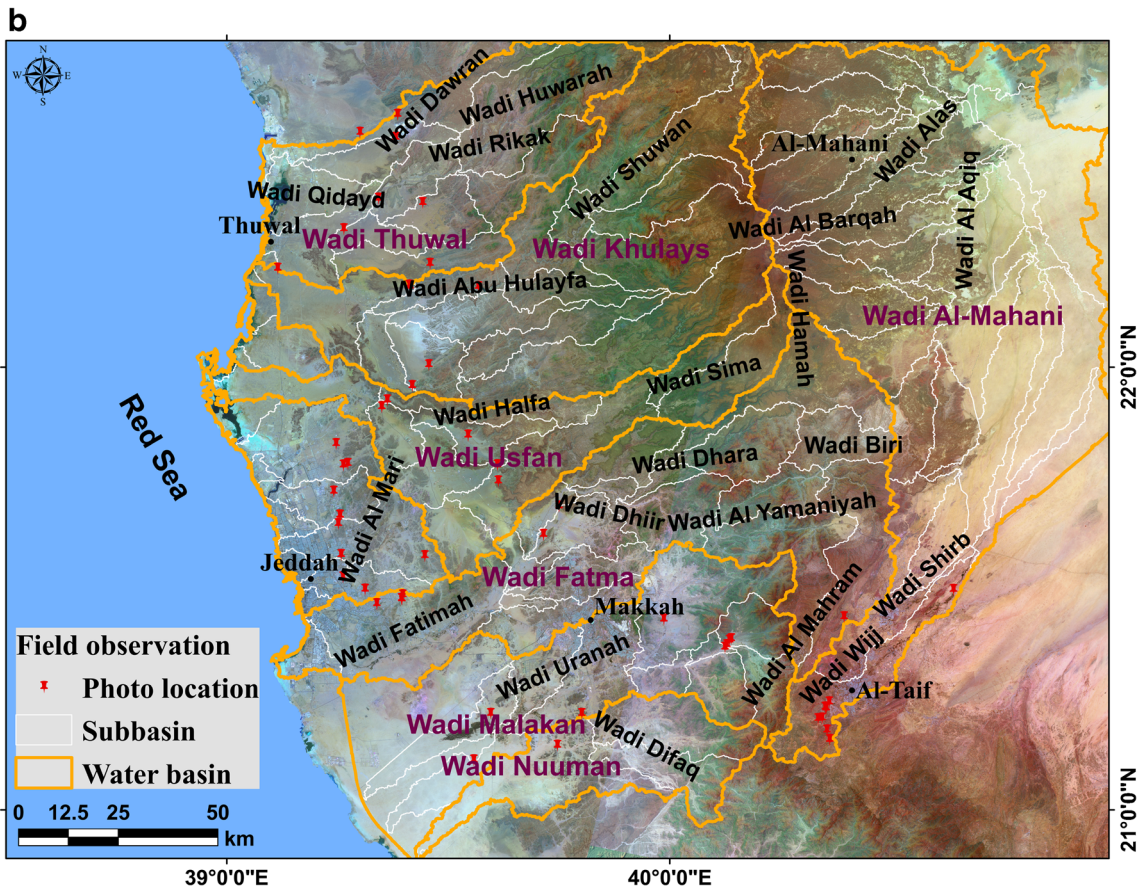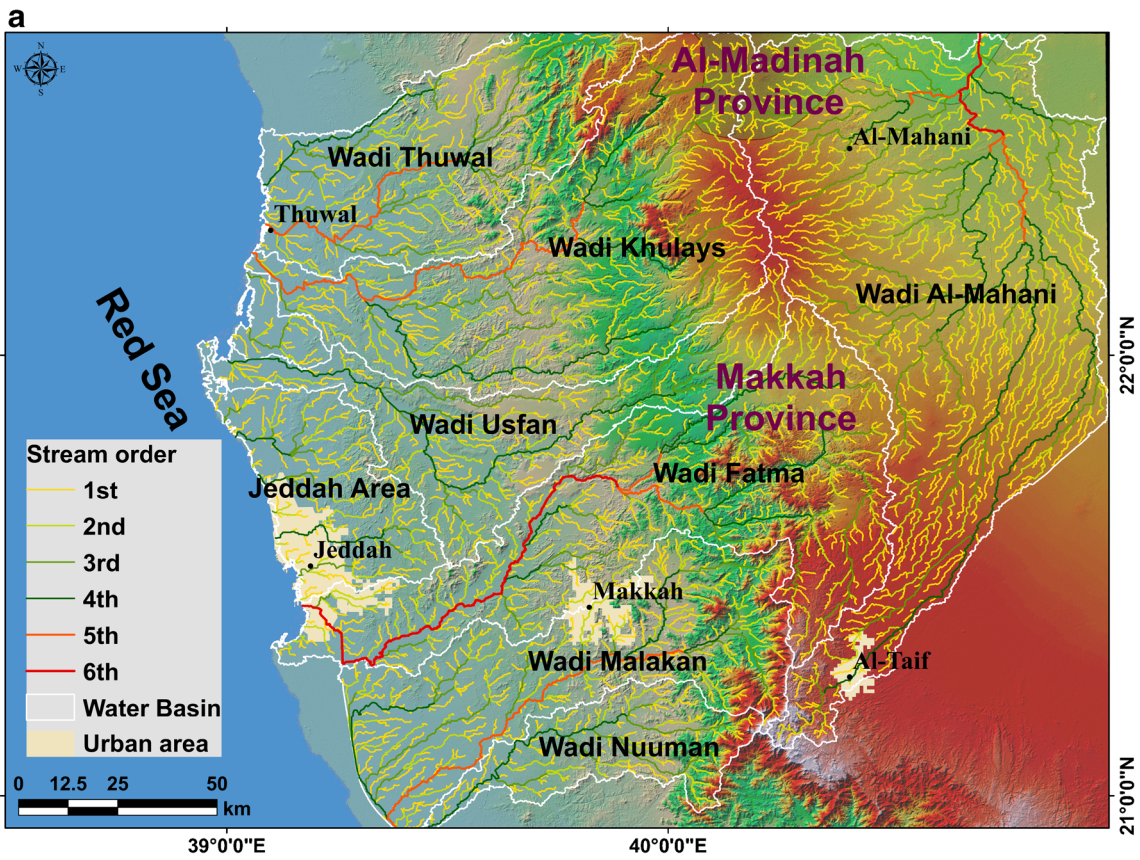
Fig. 3 **a** Stream order map of the Jeddah–Makkah region and its surrounding areas. **b** Sub-watershed map of the Jeddah–Makkah region and its surrounding areas. **c** Shows Wadi Fatma: (i) topographic elevation (masl) zones; (ii) stream order map; (iii) locations for field observations (through Nov. 2017); (iv) photograph for "FAT1B" location during "Nov. 2017" field observations; and (v) flood hazard zones

such as basin area (A), drainage density (D_d), drainage (stream) frequency (F_s), drainage texture (R_t), elongation ratio (R_e), circulatory ratio (R_c), form factor (F_f), infiltration number (I_f), length of overland flow (L_g), and sinuosity index (S_I).

Aerial features

Two-dimensional (aerial) features are considered as vital factors in quantitative geomorphology. Table 4 shows the determined and calculated values of some of the aerial features

Basin area (A)

The size of the basin area influences the size of the hydrographic storm and the sizes of peak discharge and average runoff (Smart and Surkan 1967). Chorley et al. (1957) stated
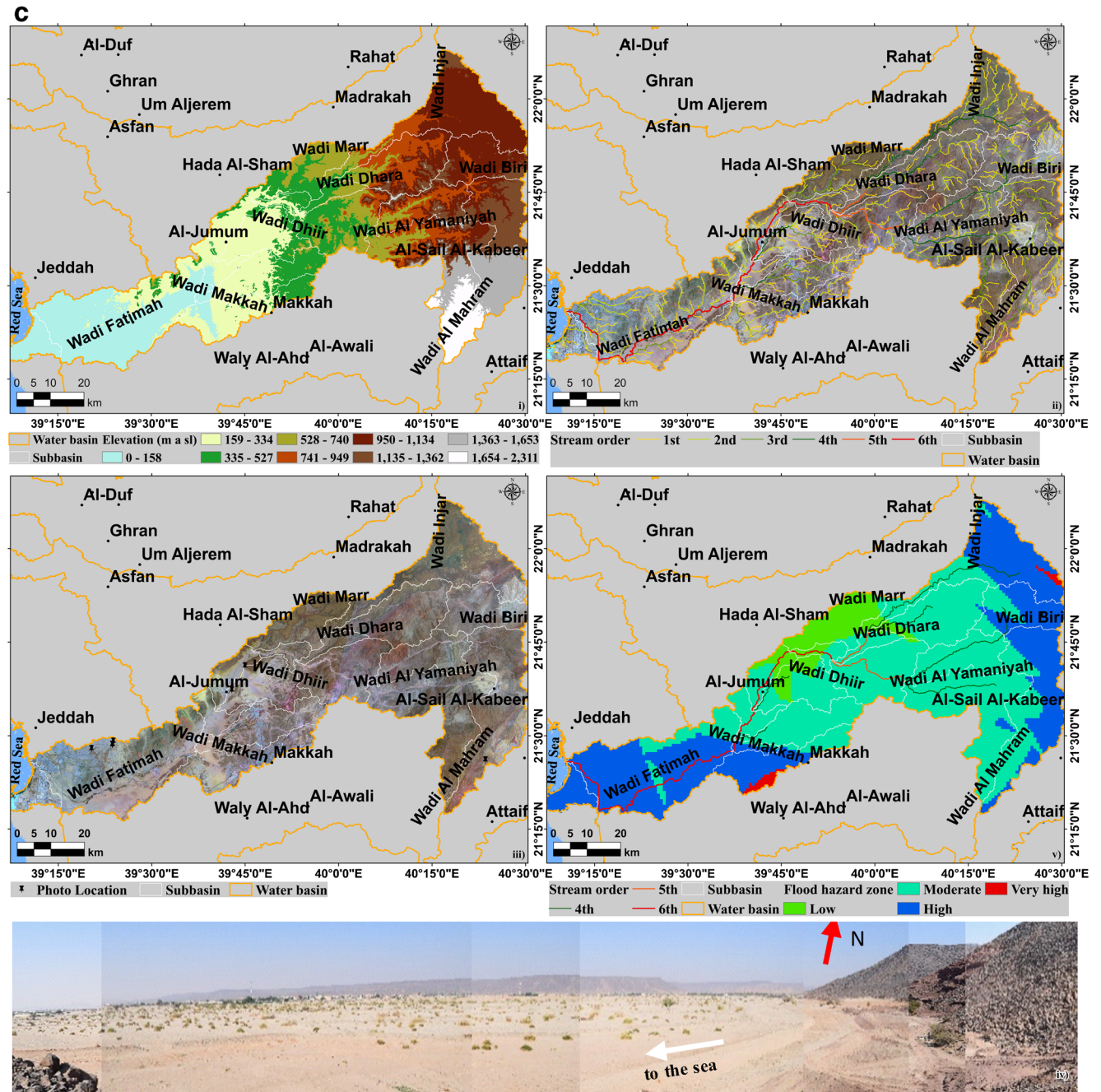

Fig. 3 (continued)

Table 1 Basins stream order determined for all eight basins

Basin	Stream order	1	2	3	4	5	6	Grand total	Bifurcation ratio					
									1\2	2\3	3\4	4\5	5\6	Mean
Thuwal	Count	263	62	13	3	1		342	4.24	4.77	4.33	3		4.09
	Length (km)	694.4	437.6	206.8	74.7	74.7		1488.2						
Khulays	Count	455	93	20	16	1		585	4.89	4.65	1.25	16		6.7
	Length (km)	1217.7	721.8	290.5	214.8	133.1		2577.9						
Usfan	Count	216	45	11	1			273	4.8	4.09	11			6.63
	Length (km)	620.4	318.5	183.6	155.8			1278.3						
Fatma	Count	481	116	20	6	2	1	626	4.15	5.8	3.33	3	2	3.66
	Length (km)	1204.8	601.6	269.6	192.2	46.4	133.4	2448						
Jeddah area	Count	159	39	12	3			213	4.08	3.25	4			3.78
	Length (km)	402	204.8	87.3	62.1			756.2						
Malakan	Count	331	74	16	4	1		426	4.47	4.63	4	4		4.27
	Length (km)	889.3	411.4	209.3	107.9	120.4		1738.3						
Nuuman	Count	138	34	5	1			178	4.06	6.8	5			5.29
	Length (km)	287.2	174.9	103.7	82.8			648.6						
Al-Mahani	Count	699	143	32	8	3	1	886	4.89	4.47	4	2.67	3	3.8
	Length (km)	2280.2	1247.1	664.5	428.7	59.1	40	4719.6						
Total	Count	2742	606	129	42	8	2	3529						
Sum	Length (km)	7596	4117.7	2015.3	1319	433.7	173.4	15,655.1						

that discharge per unit area is inversely related to basin size. The size of the basin areas within the study area varies from 1361.6 km² for the Numman basin to 8489.3 km² for the Al-Mahani basin, which indicates medium to large basin sizes (Table 3).

Drainage density (D_d)

Drainage density (D_d) is described as the length of stream channel per unit area (Horton 1945).

D_d is also defined as the quantitative ratio between the sums of all stream order lengths to the basin area (Horton 1932; Greenbaum 1989).

$$D_d = \text{total stream length of all orders } (L_u)/\text{basin area } (A) \quad (2)$$

In this study, ASTER DEM data was used to determine the D_d and to extract this spatial layer to be used in the flood hazard map. D_d is a characteristic of the topography which reflects the relation between the basin form attributes and the processes operating on the stream course (Gregory and walling 1973).

In addition, D_d is an indication of the infiltration and the time interval between precipitation and discharge.

Gresillon (1991) concluded that D_d decreases the span of infiltration, which, in turn, increases surface water runoff. When the density of surface water drainage is low, the infiltration rate is high, which, in turn, increases the groundwater recharge (Krishnamurthy et al. 2000). The high rate of precipitation runoff is represented by a high value of D_d. Alternatively, low D_d values may indicate that most of the rainfall infiltrates into the ground and consequently few channels are formed (Allen and Raes 1988). The low drainage density (D_d) values are indicative of permeable soil and low rainfall rates. In this study, D_d with low values is regarded as the high capability for groundwater potentiality (Fig. 3a).

According to Strahler (1952), D_d is divided into three categories, 3~4, 4~12, and > 12 (km/km²), implying low, medium, and high value, respectively. The drainage basins of the study area have medium values of D_d ranging from 0.453 km² for Wadi Fatma to 0.556 km² for Wadi Al-Mahani, indicating that not only soil is permeable but also rainfall rate is low in the study area (Table 4).

Table 2 Sub-watershed count for all eight basins

Basin name	Thuwal	Khulays	Usfan	Fatma	Jeddah area	Malakan	Nuuman	Al-Mahani	Total count
Sub-watershed count	11	15	10	17	9	13	3	39	117

Table 3　Summary of the calculated linear morphometric parameters for all eight basins

Basin	Area (km^2)	Perimeter (km)	Elevation (m)			Basin order	Stream count	Stream length (km)	Main stream length (km)	Shortest length (km)	Basin length (km)
			Min.	Max.	H						
Thuwal	3145.1	499.1	0	1554	1554	5	342	1488.1	152.3	121.2	99.2
Khulays	5289.3	593.4	0	1613	1613	5	585	2577.8	210.1	164.6	134.3
Usfan	2628.7	571.5	0	1443	1443	4	273	1278.3	215	178.9	170.8
Fatma	5237.9	691.9	1	2314	2313	6	626	2448	274.8	225.8	155.9
Jeddah area	1670.7	409	0	661	661	4	213	756.2	57.4	44.1	29.4
Malakan	3451.8	463	6	2599	2593	5	426	1738.3	170.3	129.3	108.6
Nuuman	1361.6	300.2	4	2600	2596	4	178	648.6	121.6	94.1	83.4
Al-Mahani	8489.3	754	892	2572	1680	6	886	4719.7	278.4	220	198.9
Total sum	31,274.4	4282.1					3529	15,655			

Drainage (stream) frequency (F_s)

Drainage (stream) frequency (F_s) is one of the factors that is related directly to the lithological characteristics. Drainage frequency (F_s) is defined as the streams number per unit area.

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

F_s depends on several factors, such as the relief, infiltration capacity, rock structure, nature and amount of rainfall, vegetation cover, and porous nature of the subsurface materials (Carlston 1963). Terrain dissection degree can be extracted from the stream frequency. Low stream frequency indicates a low degree of the terrain dissection. Moreover, low F_s values typically represent alluvial basins, whereas high values of F_s signify structure hills (Horton 1932).

There is a direct relationship between the drainage density (D_d) and the drainage frequency (F_s). Usually, slower flow occurs in a basin that has a low D_d and F_s; therefore, it is less likely to flood in basins with low to moderate drainage density and stream frequency (Carlston 1963). In this study, the stream frequency (F_s) varies between 0.104 streams/km^2 for Wadi Usfan and Al-Mahani and 0.131 streams/km^2 for Wadi

Nuuman, which indicates low relief and high infiltration capacity resulting in slower downstream runoff (Table 4).

Drainage texture (R_t)

Drainage texture (R_t), which is one of the main significant morphometric factors, is defined as the quantitative relationship between the total numbers of the 1st-order stream segments and perimeter of the basin (Jones 1999).

$$R_t = N_l/P \qquad (4)$$

R_t depends on several factors, such as rock and soil type, relief, infiltration capability, density and type of vegetation, climate, and stage of development (Kale and Gupta 2001). Based on the values of the drainage texture ratio, Smith (1950) proposed a new classification of the drainage texture (R_t) as follows: (a) very coarse (< 2); (b) coarse (2~4); (c) moderate (4~6); (d) fine (6~8); and (e) very fine (> 8). In addition, values of > 15 can be classified as ultra-fine texture for land with rough topography. Sherief (2008) concluded that basins with a comparable setting of geology, hydrology, and

Table 4　Summary of the calculated aerial morphometric parameters for all eight basins

Parameter	Thuwal	Khulays	Usfan	Fatima	Jeddah area	Malakan	Nuuman	Al-Mahani
Basin area (km^2)	3145.1	5289.3	2628.7	5237.9	1670.7	3451.8	1361.6	8489.3
Drainage density	0.473	0.487	0.486	0.453	0.467	0.504	0.476	0.556
Drainage frequency	0.109	0.111	0.104	0.127	0.12	0.123	0.131	0.104
Drainage texture	0.527	0.767	0.378	0.389	0.695	0.715	0.46	0.927
Elongation ratio	0.043	0.032	0.045	0.061	0.033	0.038	0.064	0.022
Circularity ratio	0.159	0.189	0.101	0.125	0.137	0.202	0.19	0.188
Form factor	0.32	0.293	0.09	1.933	0.216	0.293	0.196	0.215
Overland flow	1.057	1.026	1.028	1.105	1.07	0.993	1.05	0.899
Infiltration number	0.0515	0.0539	0.0505	0.0577	0.0559	0.0622	0.0623	0.058
Sinuosity factor	1.257	1.276	1.202	1.302	1.217	1.317	1.292	1.265

structure shall have identical texture ratio. In this study, the texture ratio values for the eight basins within study area vary from 0.378 for Wadi Usfan and 0.927 for Wadi Al-Mahani (Table 4). This indicates that these basins are identified as coarse textures which reflect the topographic complexity of the area.

Elongation ratio (R_e)

Elongation ratio (R_e) is defined as the quantitative relationship between the ratio of the diameter of a circle of the same area as the basin to the maximum basin length (Schumm 1956).

$$R_e = 2*\sqrt{(A/\pi)}/L_u \tag{5}$$

With a highly elongated shape, R_e value is equal to zero, whereas it is considered to be in circular shape when the R_e is equal to 1. This indicates that the elongation ratio with higher values reflects a more circular shape of the basin and vice versa. Strahler and Strahler (1989) explained that R_e with variable values from 0.6 to 1.0 indicates that there is a major variation in the basin's geological structure solidity. In addition, they classified the basins into elongated (< 0.7), less elongated ($0.7\sim0.8$), oval ($0.8\sim0.9$), and circular (> 0.9) in shape. In this study, R_e ranges from 0.032 and 0.064 which indicates that the eight basins have elongated shapes with significant differences in their relief and hardness.

Circularity ratio (R_c)

Similar to the elongation ratio (R_e), the circularity ratio (R_c) is defined as the quantitative relationship between the basin area and the area of the circle having a circumference equal to the perimeter of the basin (Miller 1953; Gregory and Walling 1973).

$$R_c = 4\pi A/P^2 \tag{6}$$

When the value of R_c is equal to 1, the basin is defined as a circular basin, whereas the elongated basins have R_c value of 0. The higher values of R_c indicate more circularity of the basin shape and vice versa. The low values of R_c ratio reflect the influence of the structure on the drainage development (Horton 1932). In this study, R_c values range from 0.101 to 0.202, which indicates that the eight basins far-off the circularity and the lineaments and the fracture traces affect the drainage pattern (Table 4).

Form factor (R_f)

The form factor (R_f) is the numerical guide that is used to represent various basin shapes (Horton 1932). It is defined as the ratio of basin area to the square of the basin length.

$$R_f = \text{basin area}/(\text{basin length})^2 \tag{7}$$

R_f is expressed by a numerical value ranging from 0.1 to 0.8. Smaller values of R_f indicate more elongated basin shapes. Furthermore, low peak flows of longer duration can be interpreted from low values of R_f, whereas the high peak flows of shorter duration occur within basins that have high values of R_f. In this study and due to the elongated alluvial basins, the R_f has low values (Table 4). The values of R_f varies from 0.090 to 1.933 which indicates that the area has low peak flow and long duration with elongated shape basins.

Infiltration number (I_f)

Infiltration number (I_f) is defined as the result of multiplying the drainage density (D_d) by drequency (F_s) (Okoko and Olujjinmi 2003)

$$I_f = D_d * F_s \tag{8}$$

The lower values of I_f are expected with higher infiltration, lower runoff, porous lithology, and lower relief. In this study, I_f is calculated and it ranges between 0.0505 and 0.0623, which indicates that the basins have high porosity and high infiltration but low runoff and low relief.

Length of overland flow (L_g)

Length of overland flow (L_g) is defined as the distance of the water that flows until it reaches a definite channel. Horton (1945) and Ifabiyi (2004) stated that L_g can be calculated as half of the reciprocal of drainage density (D_d).

$$L_g = (1/D_d)/2 \tag{9}$$

L_g has a great effect on water quantity which is necessary to go above a certain threshold of erosion (Ifabiyi 2004). The smaller the L_g value is, the faster surface runoff can enter the stream. In a homogeneous area, less rainfall is necessary to provide a significant volume of surface runoff to stream discharge when the value of overland flow is small. In this study, the values of L_g range from 0.899 to 1.105 km which indicates high valued erosion threshold with slow surface runoff entering the streams (Table 4). This represents a good drainage pattern.

Sinuosity index (S_I)

Sinuosity (S_I) is an important parameter to describe the overall map-view style (e.g., meandering, braided, and straight) of a fluvial system (e.g., Leopold and Wolman 1957; Schumm 1977; Rust 1978). S_I is calculated by dividing the channel length (La) by meander wavelength for discrete segments of the channel. The overall sinuosity of a channel is calculated by dividing the length

along the channel course via the total length of the channel axis (valley length).

$$S_I = \text{channel length/valley length} \qquad (10)$$

Schumm ([1977](#)) found a strong empirical relationship between the S_I and grain size of sediment transported by the fluvial system. He suggested that fluvial channel systems that have S_I of 1–1.3 are bedload-dominated systems, the systems with S_I of 1.4–2 are mixed-load systems, and systems with $S_I > 2.0$ are suspended-load-dominated systems. In the case of single-channel fluvial systems, Leopold and Wolman ([1957](#)) used an S_I value of 1.5 to categorize channels as either low sinuosity ($S_I < 1.5$) or high sinuosity ($S_I > 1.5$). In this study, the calculated sinuosity values for all channels vary between 1.2 and 1.3 which indicates that all these channels are low-sinuous bedload-dominated systems (Table 4). The field visits to these channel systems confirm this interpretation.

Relief feature

The three-dimensional relief features of the drainage basins include area, volume, and altitude of the vertical dimension of landforms. The main objective of studying the relief features is to investigate the different geo-hydrological characteristics. A number of relief factors, such as basin relief (H), slope (S), relief ratio (R_h), dissection index (D_I), constant of channel maintenance (C), and ruggedness number (R_n), were determined (Table 5). Although, calculations of these parameters are complicated, they are effective in quantitatively depicting sequential stages of landscape evolution (Rodrique-Itrube and Valdes [1979](#)).

Basin relief (*H*)

Basin relief (H) is defined as the distinction between the highest and lowest elevations of a wadi/channel.

$$H = \text{highest elevation } (h_2) - \text{lowest elevation } (h_1) \qquad (11)$$

H is a significant factor in understanding the geomorphic processes and landform characteristics. High H values reflect high gravity of water flow, low permeable rocks, and high runoff, whereas the moderate H indicates steep to the moderate ground slope. In addition, a low value of relief ratio indicates that the discharge capabilities of the watershed are low and the probabilities of groundwater potentiality are high. In this study, basin relief (H) values vary from 1443 to 2600 m which indicates low to moderate relief for all the eight basins (Table 5).

Slope

Land surface slope has often played a very important role in land use planning, especially in hilly terrain areas. Surface slope calculation is described as the maximum rate of change in elevation from every cell to its neighbors. The slope is one of the effective aspects to evaluate flash floods, where the flow velocity increases as the slope increases.

A slope map, unlike conventional topographic contour map, does not represent the elevation of an area but rather shows the inclination of the ground surface to the horizontal. To create a slope map for this study, the raster slope layer was made with the GRID module in ArcInfo using the slope command. This command fits an inclined plane at each cell center to represent the maximum rate of change of elevation in respect to the surrounding 3×3 cell block. Figure 4 shows a slope map for the study area. It presents useful information about the numerical value of the slope of the land surface which varies from 0 to around 60° whereas it varies from 0 to nearly 37° for the slope of the studied basin areas.

Relief ratio (*R_h*)

Relief ratio (R_h) measures the drainage basin's steepness and is considered to be an indicator of the intensity of erosional process that operates on the basin's slope (Schumm [1956](#)). R_h is a quantitative height–length ratio, which can be calculated as the ratio between the total basin relief (H) and the maximum basin length.

$$R_h = \text{basin relief/maximum basin length} \qquad (12)$$

The basin with higher relief and steepness shows higher values of R_h. This indicates higher erosion power, high sediment yield, and high flood peak in the catchment area. Furthermore, R_h with low value is primarily a result of the resistant of the basin basement rocks and low-degree slope. In this study, R_h values vary from 0.006 to 0.021, which indicates that the catchment area has low to moderate relief with lower erosion and flood peak (Table 5).

Dissection index (*D_I*)

Dissection index (D_I) is an important parameter of the drainage basin which shows the scale of dissection or vertical erosion and expounds the step of terrain or landscape development in any given physiographic region or basin (Thornbury [1969](#); Sarma et al. [2013](#)). On average, the D_I values range between "0" and "1." A D_I value of "0" indicates lack of vertical dissection/erosion and, hence, dominance of flat surface, whereas a D_I value of "1" indicates the presence of vertical cliffs which it might be at vertical escarpment of hill slope or at a shoreline. In this study, D_I values of all eight basins range from 0.653 to 1, which indicates that these basins are significantly dissected (Table 5).

Table 5   Summary of the calculated relief morphometric parameters for all eight basins

Parameter	Thuwal	Khulays	Usfan	Fatma	Jeddah area	Malakan	Nuuman	Al-Mahani
h1	0	0	0	1	0	6	4	892
h2	1554	1613	1443	2314	661	2599	2600	2572
Basin relief	1554	1613	1443	2313	661	2593	2596	1680
Relative relief	3.114	2.718	2.525	3.343	1.616	5.6	8.648	2.228
Relief ratio	0.01	0.008	0.007	0.008	0.012	0.015	0.021	0.006
Dissection index	1	1	1	1	1	0.998	0.998	0.653
Constant of channel maintenance	3.247	3.173	3.315	3.928	3.527	3.244	3.371	2.791
Ruggedness number	0.735	0.786	0.702	0.299	1.081	1.306	1.237	0.934

Constant of channel maintenance (C)

Constant of channel maintenance (C) is defined as the ratio between the area of a drainage basin and total length of all channels (Schumm 1977). It is also equal to the drainage density. This parameter describes the units' necessity of watershed surface to bear one unit of channel length. Morisawa (1959) calculated this parameter as the inverse of the D_d and concluded that higher value of C reveals sturdy lithology control, with a highly porous surface. In addition, the alluvial basin of plain and piedmont zone shows higher values.

$$C = 1/D_d \quad (13)$$

In this study, C values range from 2.791 to 3.93 km which indicates that there is a strong lithology control on the studied basins (Table 5).

Ruggedness number (R_n)

Ruggedness number (R_n) is the product of maximum basin relief and drainage density within the drainage basin (Strahler 1968).

$$R_n = D_d \times (H/1000) \quad (14)$$

The high ruggedness values arise with long steeper slope basins while the low ruggedness values infer that the area has
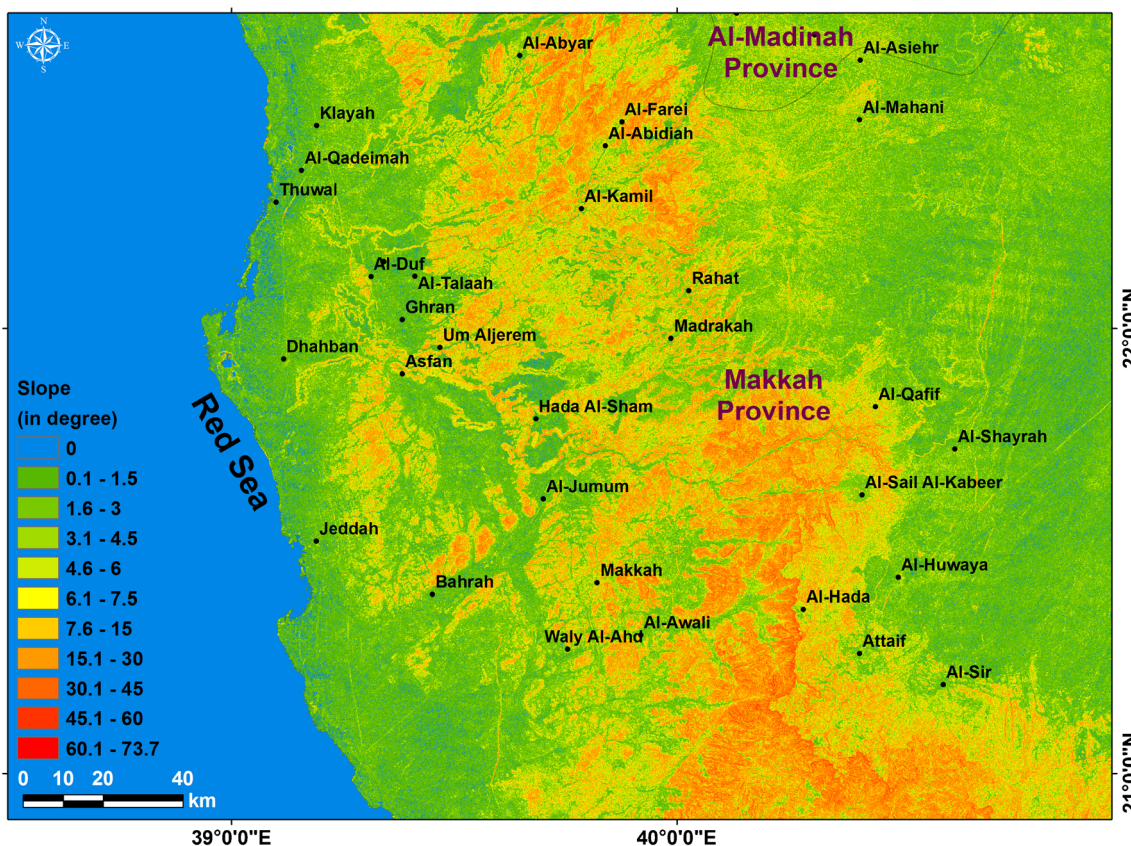
Fig. 4   Slope map of the study area

less soil erosion and less structure influence. In this study, the calculated values of ruggedness number (R_n) vary from 0.702 to 1.306, which indicates that the eight basins have submissive to sharp morphology and wildernesses topography (Table 5).

Discussion

Flood hazard map

In the present study, the flood hazard map for the Jeddah–Makkah region and its surrounding areas was obtained by using ArcGIS. The map was created based on the results of 7 morphometric parameters determined previously, which include the basin areas (A), drainage density (D_d), drainage frequency (F_s), drainage texture (R_t), mean bifurcation (R_b), relief ratio (R_h), and ruggedness (R_n) (Table 6). These parameters are spatially variable and geographically dependent, and they were selected due to their high influences on flooding during heavy rainfalls. Bajabaa et al. (2014) concluded that there is a strong relationship between flooding and different morphometric parameters, such as those described previously. For example, the mean bifurcation ratio (MR_b) has an inverse relationship with flash floods while basin area (A), drainage density (D_d), stream frequency (F_s), texture ratio (R_t), relief ratio (R_h), and ruggedness ratio (R_n) have a direct effect on flooding.

Each parameter was classified into five classes with varying degrees (very low, low, moderate, high, and very high) of flood hazard by using the quantile technique (Fig. 5). The purpose of using this technique is to get the same number of values for each class where the range of possible values is divided into unequal-sized intervals. These classes are ranked in respect to its significance for the objective of the flood hazard modeling (Fig. 5). This means that higher values of (A, D_d, F_s, R_t, R_h, and R_n) and lower value of mean (R_b) are considered to be higher flood hazard. This map is the result of the weighted sum of flood hazard model as shown in Fig. 6. It is well noted that the high flood hazard area (high and very high) is located within the south, west, and the northwest of the study area, whereas the lower flood hazard zone (very low and low) is found to be around the east of the study area. This

indicates that the city of Jeddah is located in a high flood hazard zone and during heavy rainfalls flash flood could be generated in these areas which can severely damage the city (Fig. 6). Although, the new construction of some water path around Jeddah can reduce the impact of these flood hazards, these particular basins are thought to be hazardous in terms of flash flood impacts.

Empirical relationships

Several morphometric parameters for all wadis/channels at the eight basins around the Jeddah–Makkah region were calculated and cross-plotted against each other to establish relationships. Wherever a relationship is seen to exist, an empirical equation is, then, developed to describe the relationship. For example, a cross-plot of the total stream length (L_u) versus the basin area (A) shows a regression line which indicates that a direct relationship exists as the stream length increases when the basin area increases (Fig. 7). This relationship allows for an empirical equation to be developed which describes the relationship between L_u and A ($L_u = (0.5576 \times A) - 222.78$).

One of the main important parameters that were calculated in this study is the bifurcation ratio (R_b). This parameter has an inverse relationship with flooding. Figure 8 shows the variation of the R_b for all the eight basins. Comparing this plot with the flood hazard maps (see Fig. 6), it is clearly seen that the basins (e.g., Fatima, Malakan, and Nuuman) with low R_b have high flood hazard, whereas the basins (e.g., Usfan and Khulays) with high R_b have low flood hazard. In addition, the higher value of R_b indicates that the drainage pattern was influenced by sturdy structural control, whereas the lower values of R_b indicate less-/or no structural disturbances. It has also been seen that higher R_b values are found between 3rd- and 4th-order, reflecting higher runoff and discharge attributive to the formation of less porous rock related to steep slopes.

When plotting stream order (U) against stream number (N_u) and stream length (L_u), it can be observed that the basin area increases formally with higher stream order which is in acquiescence to Schumm's (1956) law of basin area (Figs. 9 and 10). In addition, the plotted stream number (N_u) of every order against the stream order (U) of every basin indicates that the stream number (N_u) decreases with increasing stream order

Table 6 Summary of the morphometric parameters used to create the flood hazard map for the study area

Factor	Basin area	Drainage density	Drainage frequency	Drainage texture	Mean bifurcation ratio	Relief ratio	Ruggedness number
Class 1	< 2546.8	< 0.475	< 0.109	< 0.589	> 5.14	< 0.0075	< 0.796
Class 2	3741.7	0.483	0.111	0.608	5.14	0.0088	0.858
Class 3	5452.7	0.494	0.115	0.625	4.88	0.0100	0.866
Class 4	6620.4	0.522	0.122	0.664	4.77	0.0122	0.909
Class 5	> 6620.4	> 0.522	> 0.122	> 0.664	< 4.76	> 0.0122	> 0.909

Fig. 5 Five ranked classes of morphometric parameters used for modeling the flood hazard
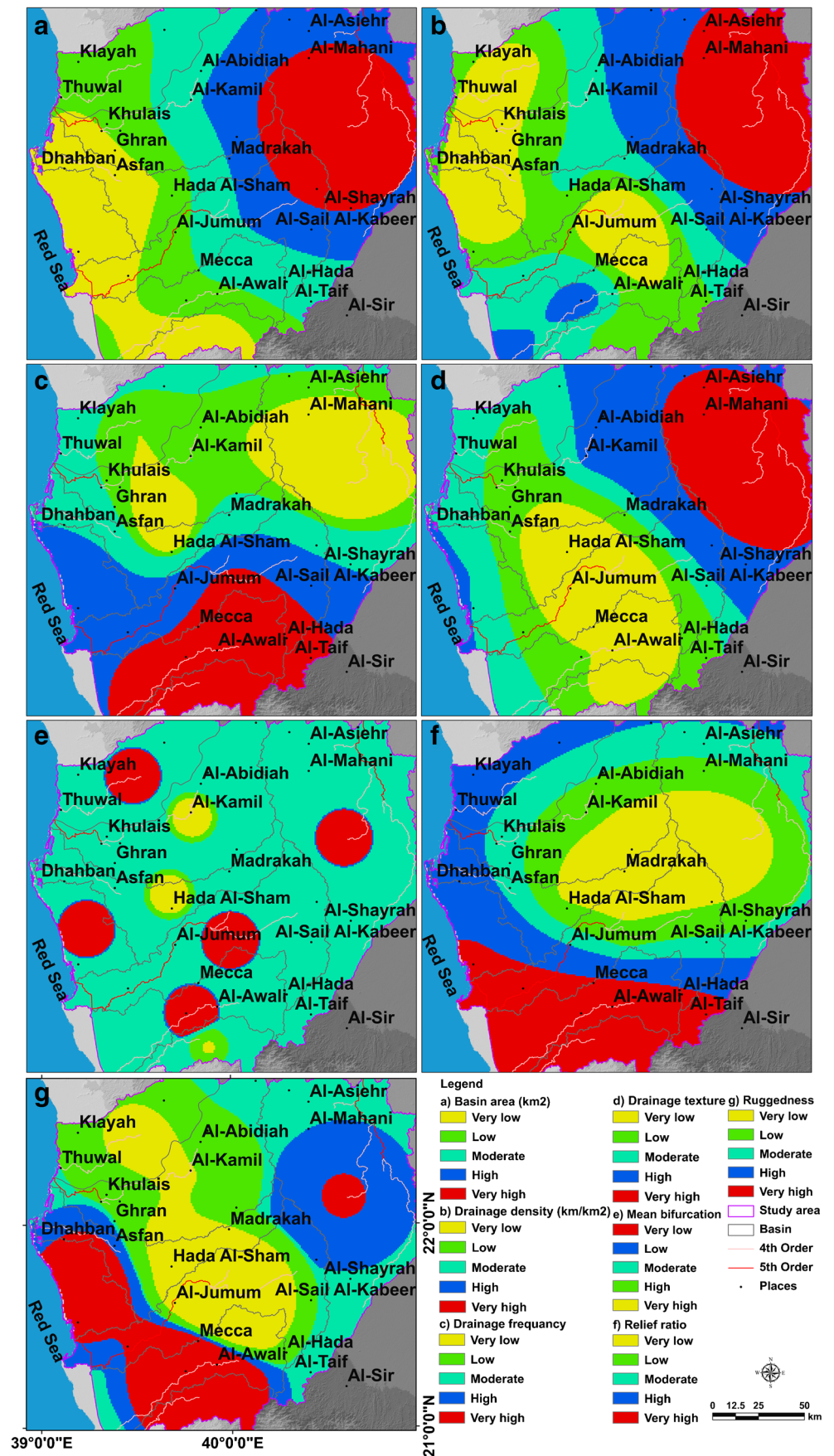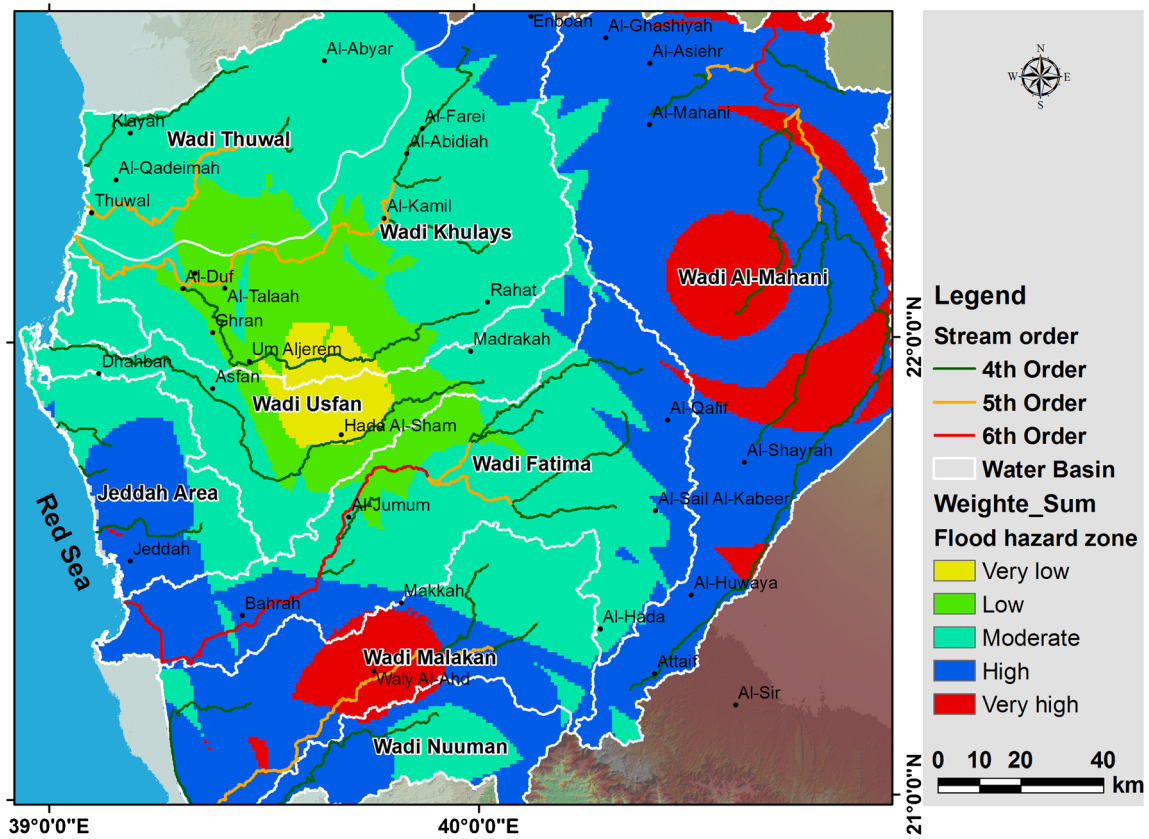
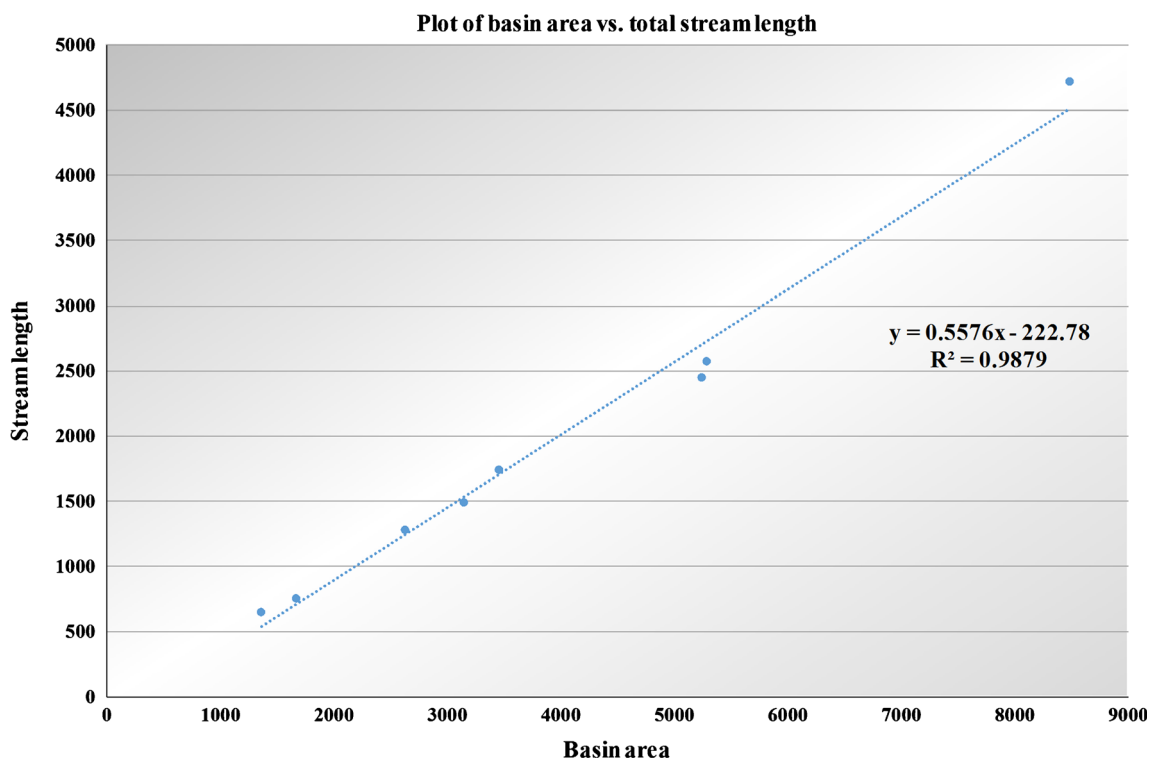**Fig. 6** Flood hazard map of the study area

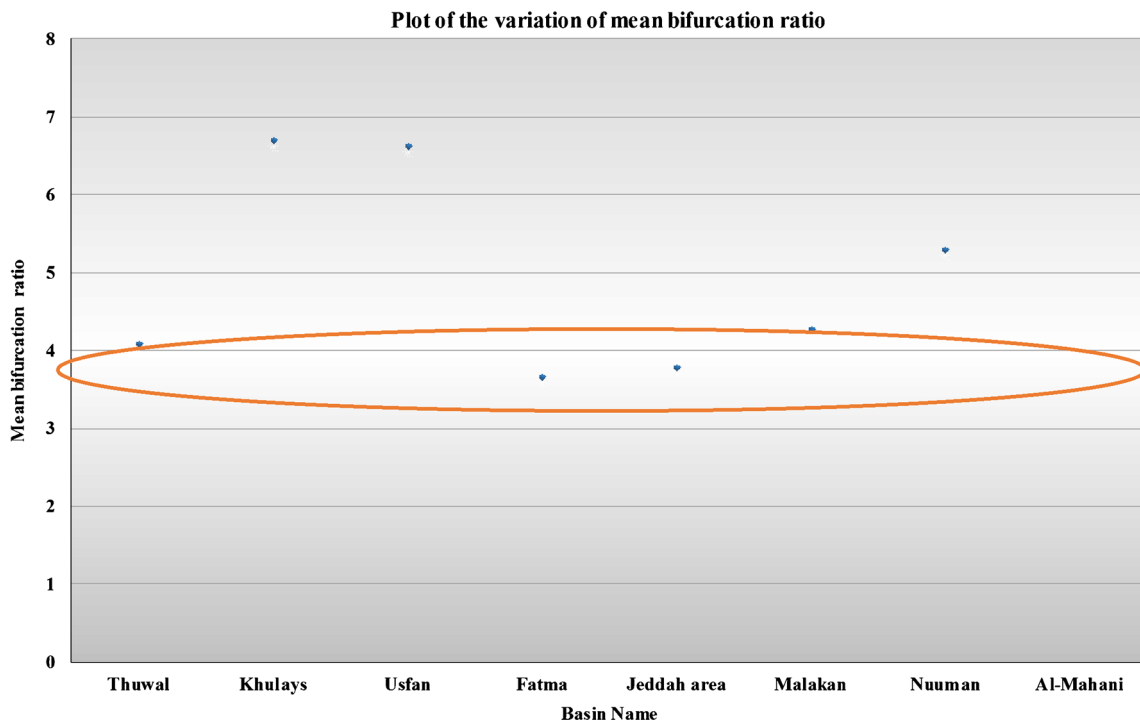**Fig. 7** Cross-plot of the basin area versus the total stream length

Fig. 8 Cross-plot of the mean of bifurcation ratio versus the major basins

(U) in acquiescence to Horton's (1945) law of beck numbers. Another validation to Horton's (1945) law is that when the stream length (L_u) of every order is plotted against stream order (U), it shows a direct geometric sequence. This functional relationship yields a group of points positioned primarily in a line and indicates that the basin evolution follows the erosion laws with constant weathering-erosion characteristics.

Furthermore, the basin shape essentially governs the water rate that is supplied to the main channel. Elongation ratio (R_e), circulatory ratio (R_c), and form factor (R_f) are parameters used for characterizing drainage basin shape that is a critical parameter for the hydrological evaluation. Elongation ratio's value ranges from zero in extremely elongated shape to 1.0 which is circular. According to Strahler (1964), values near to 1.0 are a
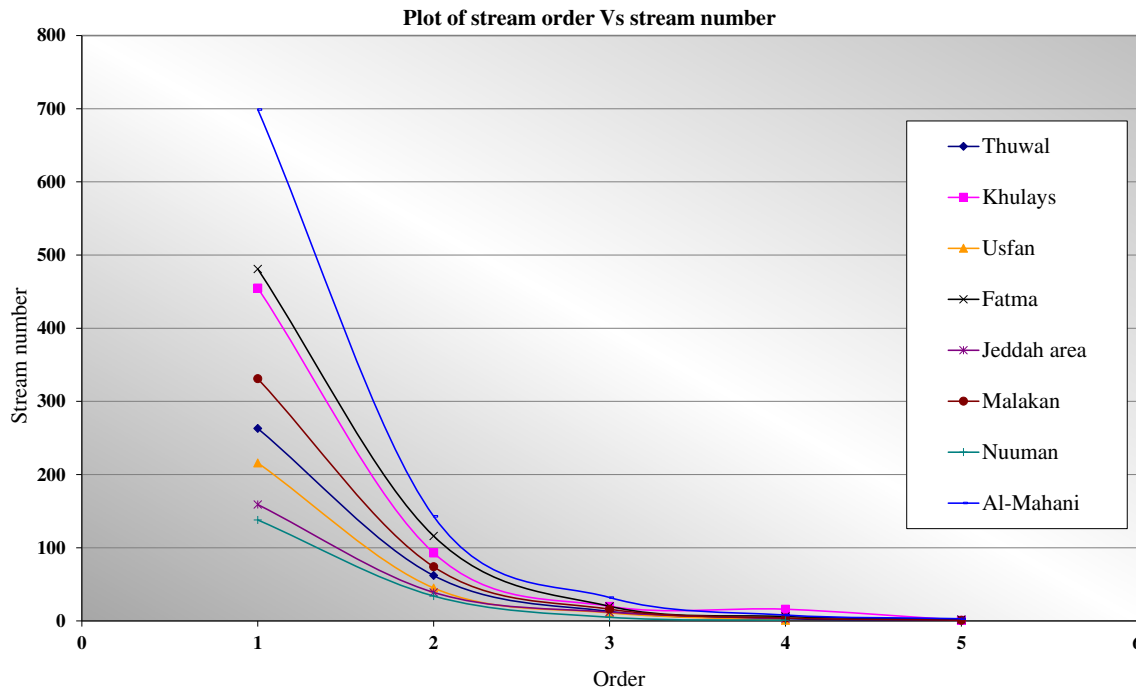

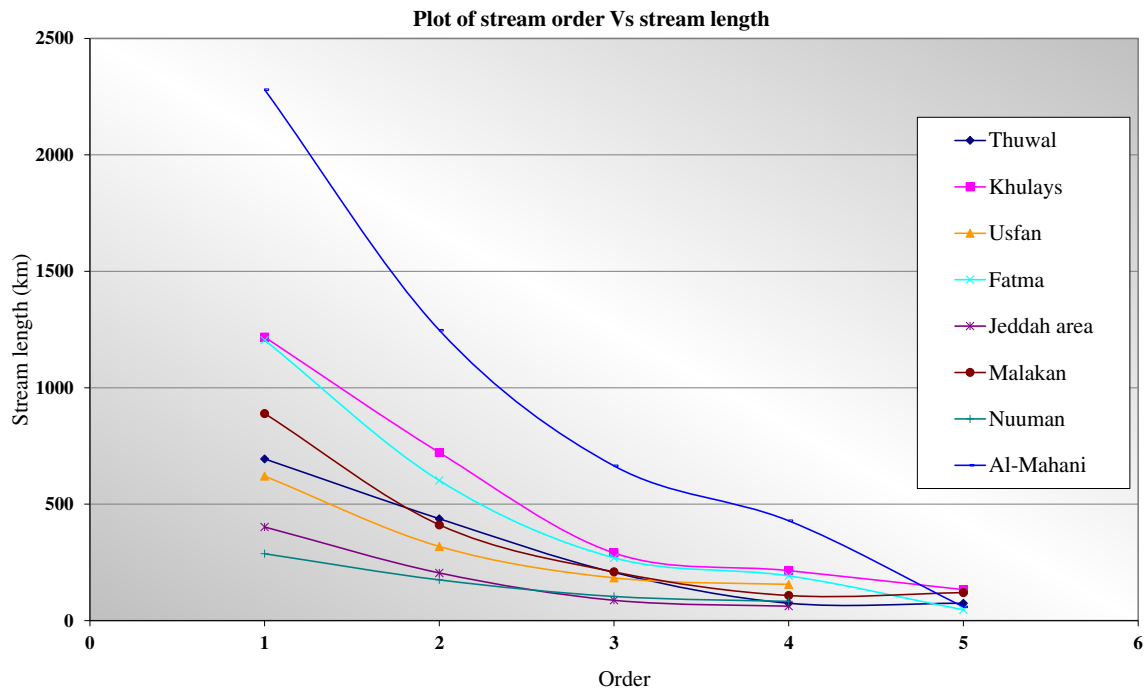**Fig. 9** Cross-plot of the stream order versus the stream number

Fig. 10 Cross-plot of the stream order versus the stream length

sign of very low relief regions whereas those of 0.6 to 0.8 are typically related to high relief and steep ground slope. Moreover, efficient in run-off discharge is achieved with the circular basin than the elongated one (Singh and Singh 1997). Naturally, all basins have an inclination to become elongated to acquire the mature stage. When the basin at its development is exposed to the impact of sturdy tectonics, the circularity ratio presents lower values (Singh and Singh 1997). So, the structural control on drainage basin is perhaps liable for the low values of circularity ratio. In addition, high peak flows with shorter duration take place when the basins have high R_f while the lower peak flows of longer duration occur in the elongated drainage basins that have low R_f. In this study, mutual relationship between these factors can be assessed from
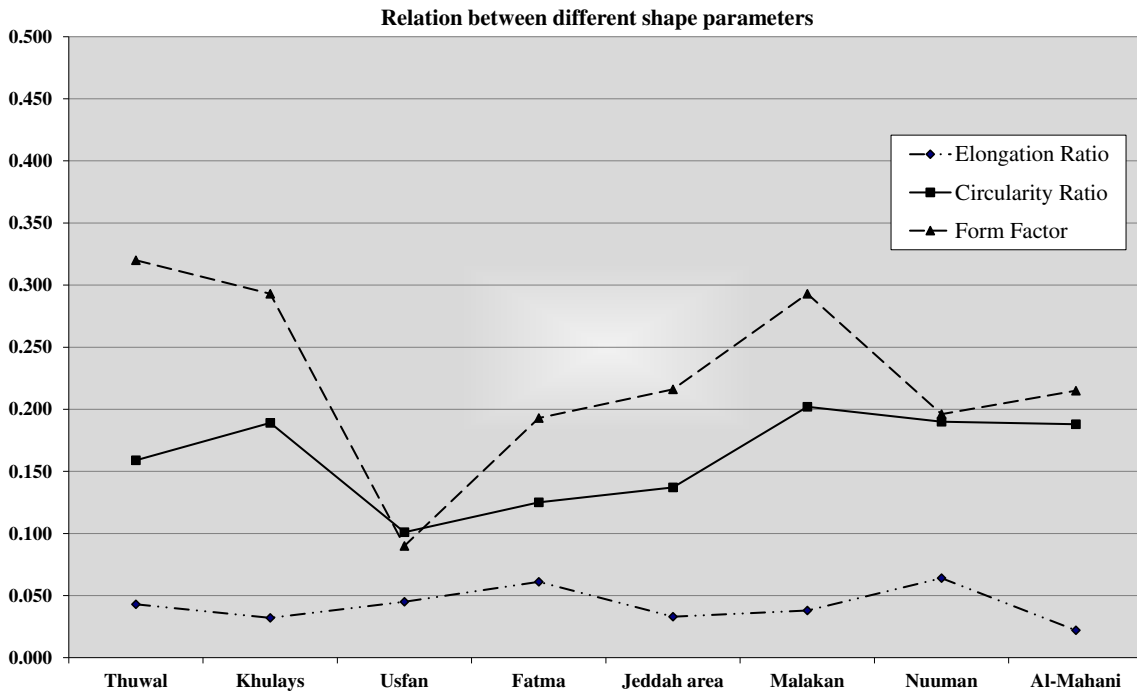

Fig. 11 Cross-plot of elongation ration, circularity ration, and form factor versus the major basins

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the graphical representation illustrated in Fig. 11. This plot indicates a direct relationship between R_f and R_c; however, an inverse relationship between these two factors and the R_e is recognized. The complexity of these relations may be due to structural control on the basins.

Conclusions

Although, the average rainfall in the coastal areas of western Saudi Arabia is low, rainstorms on the nearby mountains can generate flash floods, such as those that occurred in 2009, 2010~2011, and 2017. This study is aimed to investigate the spatial distribution of the eight drainage basins in the Jeddah–Makkah region and its surroundings to map the flood hazard using RS data and GIS. GIS-based approach simplifies investigation of various morphometric parameters and helps to develop relationship between the drainage morphometry and landforms properties. Several of the main morphometric parameters have been determined to help achieve the goal of this study. These morphometric parameters were divided into the following three main categories: (a) linear, (b) aerial, and (c) relief features.

The results of these calculated and estimated parameters were used to construct the flood hazard map of the study area. The flood hazard map assesses five classes with varying degrees (very low, low, moderate, high, and very high) of flood hazard zones. Such hydrological hazards are mostly due to the basin's area and its highest relief ratio, relative relief, and ruggedness factor. The flood hazard map shows that the Jeddah area is in moderate to high flood hazard zone but most of the areas surrounding it are in moderate flood hazard zone. Therefore, during heavy rainfalls flash flood could be generated in these areas which can severely damage Jeddah City. Although the new construction of some water path around Jeddah can reduce the impact of these flood hazards, these particular basins are thought to be the hazardous in terms of flash flood impacts. Finally, this study shows a remarkable correlation between theoretical concepts, data sets, and field observations, especially the role of geology and geomorphology in influencing the basin morphometry and identity.

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