Morphometric analysis and prioritisation of watersheds for flood risk management in Wadi Easal Basin (WEB), Jordan, using geospatial technologies

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Abstract
Morphometric analysis and sub-watersheds prioritisation were carried out for the Wadi Easal Basin, Jordan, which is characterised by a high topographic diversity. The total ranking method was applied to prioritise the sub-watersheds in terms of susceptibility to flash flood. Results of morphometric analysis revealed that the study area is a fifth order drainage system with a dendritic drainage pattern and elongated shape. Prioritisation results showed that about 71% (15 out of 21 sub-watersheds) of sub-watersheds have high-very high susceptibility to flooding, which forms about 64% of the total area of the basin. The main underlying morphometric parameters behind this are the high drainage density, stream frequency, high basin relief, basin slope, ruggedness number, and circulatory ratio, and the low value of basin shape. Overall, the basin has a rugged topography with steep slopes and high relief. Since the basin is ungauged, and no information about its past hydrological behaviour is present, the results of this study can be used as guidance for competent authorities to initialize flood mitigation or artificial groundwater recharge measures.

KEYWORDS
flash flood, geospatial technology, Jordan, morphometric analysis, prioritisation

1 | INTRODUCTION

Flash floods are among the most catastrophic and dangerous natural hazards, since they are sudden and unpredictable, and lead to destruction in infrastructure, threat to human life and property (Taha, Elbarbary, Naguib, & El-Shamy, 2017; Toduse et al., 2020). Flash floods were ranked as first in terms of damages, exceeding those caused by earthquakes, volcanoes and landslides (Ali et al., 2020; Bui et al., 2020; Costache, Hong, & Pham, 2019). The number of flash floods has increased where globally more than 78 million people have been affected (more than 5,000 deaths annually) and losses in properties of about US$ 56 billion have been estimated (Grabs, 2010; Guha-Sapir, Hoyois, Wallemacq, & Below, 2017; Karamouz & Fereshtehpour, 2019; Modrick & Georgakakos, 2015; WMO, 2016). Moreover, it is predicted that floods in conjunction with other hazards, could produce by 2030, annual losses up to US$415 billion at the global level (UNISDR, 2015). Due to their convective origin, flash floods occur locally in watersheds of areas less than 1,000 km² with a complex orography, and short response times of few hours or minutes, and thus there are minimum possibilities for prediction (Destro
et al., 2018; Marchi, Borgia, Preciso, & Gaume, 2010). Rainfall intensity and duration, rainfall characteristics, water evaporation and infiltration, drainage characteristics, environmental conditions, and anthropogenic processes are the most important factors that influence the severity of flooding (Azmeri & Vadiya, 2016; Jodar-Abellán, Valdes-Abellán, Pla, & Gomariz-Castillo, 2019; Youssef, Pradhan, & Hassan, 2011). Demarcating areas susceptible to flash floods is essential to save human life and his possessions (Ali et al., 2020; Borrelli et al., 2017). Watershed management aims at controlling damaging runoff and utilising it for beneficial uses, combating erosion, and enhancing groundwater storage (Ratna Reddy, Saharawat, & George, 2017; Sebastian, Jayaraman, & Chandrasekhar, 1995). Watershed management implies optimal climate change adaptation which involves water resources management under climate change scenarios (Worku, Teferi, Bantider, & Dile, 2020).

Development of land and water conservation measures necessitates morphometric analysis and prioritisation of sub-watersheds within a basin (Aher, Adinarayana, & Gorantiwar, 2014). Morphometric analysis has been extensively used for the purpose of prioritisation and assessment of watersheds susceptibility to natural hazards such as flash floods and erosion (Abuzied, Yuan, Ibrahim, Kaiser, & Saleem, 2016; Alam, Ahmed, & Sammonds, 2020; Ameri, Pourghasemi, & Cerda, 2018; Asfaw & Workineh, 2019; Charizopoulos, Mourtzios, Psilovikos, Psilovikos, & Karamotsou, 2019; Hussein, Abdelkareem, Hussein, & Askalany, 2019; Kannan, Venkateswaran, Vijay Prabhum, & Sankar, 2018; Shivhare et al., 2018; Taha et al., 2017). These studies have used the classic works of Horton (1945; 1932), Smith (1950), Strahler (1952), Miller (1953), and Schumm (1956) as a guidance. Morphometry is defined as the quantitative analysis of the earth’s surface, as well as the shape and dimensions of its landforms (Kaur, Singh, Verma, & Pateriya, 2014; Obi Reddy, Maji, & Gajbhiye, 2002; Vaidya, Kuniyal, & Chauhan, 2013). Morphometric parameters represent relatively simple approaches that can be utilised to investigate a hydrologic basin, and its geological and geomorphic history (Strahler, 1964). Morphometric characteristics of watersheds are a crucial factor that influences flash flood intensity; hence, investigation of the watershed morphometry provides useful insights regarding their hydrological response to rainfall (Borgia, Gaume, Creutin, & Marchi, 2008). Morphometric parameters involve linear aspects, areal aspects, and relief aspects, which can be employed in several investigations such as natural resources assessment and protection, and environmental hazards assessment (Arrous, Aboulela, & Green, 2011; Charizopoulos et al., 2019). They help predicting the response of watershed during periods of heavy rainfall (Kumar, Kumar, Lohani, Nema, & Singh, 2000). Worldwide, morphometric analysis was successfully used for flash flood susceptibility mapping (e.g., Adnan, Dewan, Zannat, & Abdallah, 2019; Alam et al., 2020; Arefin, Mohir, & Alam, 2020; Bhatt & Ahmed, 2014; Das, 2020; Gabriel, Yusuf, & Bwadi, 2020; Mahmood & Rahman, 2019; Ogarekpe, Obio, Tenebe, Emenike, & Nnaji, 2020; Pan et al., 2020; Rajasekhar, Sudarasana Raju, & Siddi Raju, 2020). Watershed prioritisation refers to ranking sub-watersheds of a watershed according to the order in which they must be considered for the purposes of treatment (Biswas, Sudhakar, & Desai, 1999; Puno & Puno, 2019). Morphometric analysis involves computation of basic parameters, linear parameters, relief parameters, and shape parameters of a watershed, and those gain insights about the watersheds characteristics (Melton, 1957; Strahler, 1964).

Recently, geospatial techniques (RS and GIS) have been applied efficiently with the goal of watershed management (Chatterjee, Krishna, & Sharma, 2013; Okumura & Araujo, 2014). The availability of free access high quality resolution digital elevation (DEM) has further enhanced the strength of the effective GIS tools that enabled many researchers to study drainage basins and to investigate with high accuracy the parameters of drainage basins. This development led to the possibility of applying and using morphometric analysis based on GIS tools in several topics of research; one of which is sub-watersheds prioritisation in terms of susceptibility to erosion and flash floods (Ratnam, Rao, & Amminedu, 2005).

In the last 50 years, Jordan has been exposed to many incidents of flash flood, where 345 persons have lost their lives, and more than 24,321 people were adversely affected (Al-Qudah, 2011). In March 1966, the city of Mā'an (south of Jordan) was exposed to severe flash flood, where more than 200 were killed, hundreds were injured, and half of the city was destroyed. Between 2006 and 2012, more than 11 were killed, and losses of US$4 million were estimated due to flash flood in Aqaba city, south Jordan. Flash floods incidents have been documented to affect Amman, the capital city of Jordan. For example, in 2014, 2 people were killed, and losses of properties of US$4 million were estimated due to flash flood in Aqaba city, south Jordan. Flash floods incidents have been documented to affect Amman, the capital city of Jordan. For example, in 2014, 2 people were killed, and losses of properties of US$4 million were estimated. In November 2015, a severe flash flood has flooded 500 shops, and more than US$5 million losses of property has been estimated. In 2018, more than 25 were killed, most of them are school students due to flash floods in Wadi Zarqa Mā'in, which is a Dead Sea side Wadi. Wadi Easal, located south of the Zarqa Mā'in, demonstrates similar landscape and physical conditions. The overall objective of this study is sub-watersheds prioritisation of the Wadi Easal basin with respect to flash floods based on...
morphometric analysis and GIS as efficient and cost-effective tools. Specific objectives include delineating sub-watersheds within the drainage basin and computing the morphometric parameters at the micro-level and basin level. The study area is characterised by high diversity in topography, morphology, and climatic regime. The frequent and severe flash floods which took place over the last years in Jordan have triggered the authors to carry out this study. Moreover, the findings of the study can be a starting point for the purpose of flood management and surface runoff harvesting. Quantitative morphometric analysis is particularly important, since the study area is ungauged, and no information about its past hydrological behaviour is available. In this context, the Jordan Valley Authority has carried out a geological and geotechnical reconnaissance study of the wadi for the purpose of constructing a dam in attempt to reduce flash flood hazard and water utilisation in agricultural irrigation (MEECP, 2016). The results of this study can be considered to help official authorities to take measures in those areas that are prone to flash floods, or of good potential for runoff harvesting.

2 | STUDY AREA

The Wadi Easal Basin (WEB) is located approximately four kilometres west of Karak city and just east of the southern Dead Sea basin (Figure 1). It covers an area of approximately 63 km² with altitude varying from 235.5 m below sea level at the mouth of the basin in the northwest to more than 1,279 m above sea level in the southeast (Figure 2a). The climate is semi-arid to arid, where the high southeastern and central parts follow the
Mediterranean climate with hot and dry summers and slightly warm, rainy winters, whereas the western Ghor parts, are located in the dry climatic region and characterised by low precipitation throughout the year (Al-Nawaiseh, 2011). The rainfall increases from the northwest (<180 mm) to the southeast (300 mm), reaching an annual mean of more than 320 mm, while the mean annual temperature decreases from 25 to 16°C in the same direction.

The geology of the basin consists of the Upper Burj and Umm Ishrin formations of the Cambrian age that dominate the western and middle parts of the basin, whereas the upper northeastern section is mainly dominated by the presence of the Kurnub Group of the Lower Cretaceous (Figure 2b). The Burj Dolomite Formation (Rum Group) consists of sandstone, dolomite and shale. The Umm Ishrin Sandstone Formation consists mainly of medium to coarse-grained, subarkosic to quartzose sandstone. Ajlun group includes Na‘ur, Hummar, Shueib, and Wadi Es Sir Formations, and Belqa group includes Wadi Umm Ghudran and Amman Silicified Limestone Formations. The two groups are of Upper Cretaceous age. Na‘ur Limestone Formation consists of marly nodular limestone with intercalations of yellowish marl, chert, and dolomite. Fuheis, Hummar, and Shueib formations consist of sandy limestone and marl. Wadi Es Sir Formation consists of massive limestone and dolomitic limestone with intercalations of chert. The upper part of the formation consists of soft white chalk. Wadi Umm Ghudran Formation prevails in the eastern and middle parts of the basin and consists of chalk and chert. Amman Silicified Limestone Formation consists of hard chert and massive chalk (Abed, 2014; Bender, 1974; Powell, 1988).

### 3 DATA AND METHODS

Figure 3 illustrates a summary of the methods adopted in this research work. Twenty-two morphometric parameters were determined for the purpose of basin characterisation and prioritisation of the WEB sub-watersheds with respect to susceptibility to flash floods (Table 1). Basic parameters were measured directly from the DEM using GIS techniques, and include basin area, basin length, perimeter, number of streams, and lengths of streams for each stream order. The DEM resolution is 12.5 m (Radar Imagery 2001–2006), downloaded from Alaska Satellite Facility (2017). The DEM is a RADARSAT-1’s... synthetic aperture radar (SAR) that utilised a microwave energy pulse (C-band at 5.3 GHz frequency). The DEM was preprocessed to fill missing data. The WEB was subdivided into sub-watersheds based on the stream network and flow accumulation maps.

Other morphometric parameters including stream frequency, drainage density, elongation ratio, circularity ratio, relief ratio, basin relief, relative relief ratio, basin slope, hypsometric integral, bifurcation ratio, length of overland flow, and ruggedness number were calculated.
using the mathematical equations presented in Table 1. The Morphometric Ranking Method (Total Rank) was utilised for the purpose of sub-watersheds prioritisation (Patel, Dholakia, Naresh, & Srivastava, 2012).

Each morphometric parameter was classified into one of many rank groups where each category denotes a certain degree of the risk. For example, rank 1 refers to a very low degree of possibility for floods risk, and so on. Twelve parameters were selected to assess the sub-watersheds susceptibility for flooding: basin area, drainage density, length of overland flow, stream frequency, elongation ratio, circularity ratio, shape factor, relief ratio, relative relief ratio, basin slope, ruggedness number, hypsometric integral. Morphometric parameters are either directly- or inversely correlated with flash flood. Eight parameters have a direct relationship with the degree of possibility for floods risk, which means that the higher value of the parameter, the higher is the risk degree. These parameters include basin area, drainage density, stream frequency, circularity ratio, shape factor, relief ratio, relative relief ratio, basin slope, and ruggedness number.

On the other hand, 4 parameters have an inverse relationship to the degree of possibility for floods risk, which means that the higher value of the parameter, the lower is the risk degree. These parameters are length of overland flow, elongation ratio, shape factor, and hypsometric integral.

After morphometric ranking, values for each sub-watershed were summed to classify the sub-watersheds and determine their susceptibility to flash floods occurrence. Five classes were obtained by using a simple equation to determine the interval length, which is \((\text{Max} - \text{Min})/5\) (Farhan & Anaba, 2016). The values for each parameter were categorised into five intervals.

The summed morphometric parameters rank values were normalised from 0 for the lowest rank value and 1 for the highest rank value to obtain flash floods susceptibility index for each sub-watershed. Parameters having the same values were assigned similar rankings. Finally, the floods priority map was generated by classifying results into five categories of flooding susceptibility: very low, low, moderate, high, very high priority.

4 | RESULTS AND DISCUSSION

4.1 | Morphometric parameters

The Wadi Easal Basin (WEB) was divided into 21 sub-watersheds using the Hydrology toolbox of ArcGIS 10.3 (Figure 4). The results of the morphometric analysis of the whole basin are presented in Table 2, and those for the sub-watersheds are shown in Table S1. The dominating drainage pattern is dendritic (Figure 4), which is
**TABLE 1** Methods used to compute morphometric parameters

| Parameter no. | Morphometric parameter | Formula/definition | Reference |
|---------------|------------------------|--------------------|-----------|
| 1. Basic      | Basin area (A)         | Plan area of the watershed (km²) | Horton (1945) |
| 2. Basic      | Basin perimeter (P)    | Perimeter of the watershed (km)  | Horton (1945) |
| 3. Basic      | Basin length (Lb)      | Length of the basin (km)          | Horton (1945) |
| 4. Basic      | Stream order (U)       | Hierarchical rank               | Strahler (1952), Farhan, Anbar, Enaba, and Al-Shaikh (2015) |
| 5. Linear     | Total number of streams (Nu) | Total no. of streams of all orders | Strahler (1952) |
| 6. Linear     | Stream length (Lu)     | Length of the stream (km)        | Horton (1945) |
| 7. Linear     | Mean stream length (Lum) | \( \frac{L_u}{N_u} \) (km), where \( N_u \) = total no. of stream segments of order “u” | Horton (1945) |
| 8. Linear     | Stream length ratio (Rl) | \( R_l = \frac{L_u}{L_{u-1}} \), where \( L_{u-1} \) = the total stream length of its next lower order | Horton (1945) |
| 9. Linear     | Bifurcation ratio (Rb) | \( R_b = \frac{N_u}{N_u + 1} \), where \( N_u + 1 \) = no. of segments of the next higher order | Strahler (1957) |
| 10. Linear    | Mean bifurcation ratio (Rbm) | \( R_{bm} = \) average of the bifurcation ratio of all orders | Strahler (1957) |
| 11. Linear    | Drainage density (Dd)  | \( D_d = \frac{L_u}{A} \), where \( A = \) area of the watershed (km²) | Horton (1945) |
| 12. Linear    | Length of overland flow (Lc) | \( L_c = \frac{1}{2D_d} \), where \( D_d = \) drainage density | Horton (1945) |
| 13. Linear    | Stream frequency (Fs)  | \( F_s = \frac{N_u}{A} \), where \( N_u = \) total no. of streams of all orders | Horton (1945) |
| 14. Shape     | Elongation ratio (Re)  | \( R_e = 1.128^\frac{(A^{0.5})}{Lb} \), where \( A = \) area of the basin (km²) \( Lb = \) basin length (km) | Strahler (1957) |
| 15. Shape     | Circularity ratio (Rc) | \( R_c = 4 \times \pi \times \frac{A}{P^2} \), where \( \pi = 3.14 \) \( A = \) area of the basin (km²) \( P = \) perimeter (km) | Schumm (1956) |
| 16. Shape     | Shape factor (Bs)      | \( Bs = \frac{Lb^2}{A} \), where \( Lb = \) basin length (km) \( A = \) area of the basin (km²) | Miller (1953) |
| 17. Relief    | Basin relief (H)       | \( H = h - h_1 \), where \( h = \) maximum height (m) \( h_1 = \) minimum height (m) | Horton (1945) |
| 18. Relief    | Relief ratio (Rr)      | \( R_r = \frac{H}{Lb} \), where \( H = \) total relief (km) \( Lb = \) basin length (km) | Malik et al. (2011) |
| 19. Relief    | Relative relief ratio (Rr) | \( \frac{H}{P} \), where \( H = \) total relief (km) \( P = \) perimeter of the basin (km) | Schumm (1956) |
| 20. Relief    | Basin slope (Sw)       | \( H/(Lb \times 60) \), where \( H = \) total relief (km) \( Lb = \) basin length (km) | Melton (1957) |
typical for homogeneous impermeable, non-porous rock types, and steep slopes, with no structural control, developing on a land surface where the underlying rock is of uniform resistance to erosion (Gizachew & Berhan, 2018). The study area is characterised by high relief reaching 1,515 m. Moreover, it is dominated by rocks of uniform resistance to erosion that is, carbonate rocks of the Upper Cretaceous and sandstones of Lower
Cretaceous and Cambrian ages. The WEB is a fifth-order basin with a total area of about 63 km², a length of 14.41 km, and a perimeter of 40 km. The total number of streams is 643, where first-order streams account for 51%. The mean bifurcation ratio is 2.05 indicating a structurally less-disturbed watershed, or no clear distortion of drainage patterns (Soni, 2017).

4.1.1 | Basic parameters

Basin area (A) and basin perimeter (P)
The spatial distribution of the morphometric parameters is depicted in Figure S1. Clear variations in the basic parameters of the sub-watersheds (area, perimeter, basin length) can be observed. Basin area is a very significant hydrological feature as it determines water quantity that could result from rainfall. It ranges from 0.87 km² for SW 19 to 7.16 km² for SW 21 (Table S1), which is located in the part with highest precipitation that is, greatest runoff. Perimeter can be used as an indicator of the sub-watershed shape and size. A strong correlation ($r = .85$) was found between the sub-watershed area and the perimeter (Figure 5a). The maximum value of perimeter was found for SW 16 and the minimum value was reported for SW 14.

### Table 2: Morphometric parameters of the WEB

| Par. No. | Morphometric parameter                              |
|----------|-----------------------------------------------------|
|          | **Basic**                                           |
| 1.       | Basin area (A) (km²)                                | 62.718 |
| 2.       | Basin perimeter (P) (km)                            | 40.041 |
| 3.       | Basin length ($L_b$) (km)                           | 14.405 |
| 4.       | Stream order ($U$)                                  | 5      |
| 5.       | Total number of streams ($N_u$)                     | 643    |
| 6.       | Stream length ($L_u$) (km)                          | 200    |
| 7.       | Mean stream length ($L_{um}$) (km)                  | 0.31   |
| 8.       | Stream length ratio ($R_{L}$)                       |        |
|          |          | II/I     | II/II    | III/II   | IV/III  | V/IV    |
|          |          | 0.61     | 0.48     | 0.21     | 1.61    |
|          |          | I/II     | II/III   | III/IV   | IV/V    |
| 9.       | Bifurcation ratio ($R_b$)                           | 2.05   |
|          |          | I/II     | II/III   | III/IV   | IV/V    |
|          |          | 2.0      | 2.01     | 3.73     | 0.48    |
|          |          | II/III   | III/IV   | IV/V     |
| 10.      | Mean bifurcation ratio ($R_{bm}$)                   | 2.051  |
| 11.      | Drainage density ($D_d$) (km/km²)                   | 3.19   |
| 12.      | Length of overland flow ($L_o$) (km)                | 0.157  |
| 13.      | Drainage texture ($D_t$)                            | 16.059 |
| 14.      | Stream frequency ($F_s$)                            | 10.252 |
|          | **Linear**                                          |
|          |          |          |          |          |          |          |
|          |          |          |          |          |          |          |
|          | **Shape**                                          |
| 15.      | Elongation ratio ($R_e$)                            | 0.620  |
| 16.      | Circularity ratio ($R_c$)                           | 0.491  |
| 17.      | Shape factor ($B_s$)                                | 3.308  |
| 18.      | Compactness coefficient ($C_c$)                     | 1.422  |
|          | **Relief**                                          |
| 19.      | Basin relief ($H$) (m)                              | 1,514.5|
| 20.      | Relief ratio ($R_r$)                                | 105.137|
| 21.      | Relative relief ratio ($R_n$)                       | 0.038  |
| 22.      | Basin slope ($S_w$)                                 | 6.308  |
| 23.      | Ruggedness number ($R_m$)                           | 4.831  |
|          | **Hypsometric**                                     |
| 24.      | Hypsometric integral ($HI$)                         | 0.6416 |

Basin length ($L_u$)
Basin length is an indicator of surface runoff characteristic, where longer streams indicate flatter gradients (Christopher, Idowu, & Olugbenga, 2010; Taha et al., 2017). This relation is depicted in Figure 5b, where a strong negative correlation ($r = -.69$) between stream length and basin slope was found. $L_u$ for the 21 sub-watersheds is in the range of 1.76 km for SW 14 and 5.47 km for SW 16. SW 14 represents the shortest stream.
(i.e., highest runoff), whereas SW 16 represents the longest one with relatively flat gradient. The relationship between basin length and stream length is depicted in Figure 5c, where a strong correlation \((r = .73)\) was found.

**Stream order \((U)\), total number of streams \((N_u)\), and stream length \((L_u)\)**

The 21 sub-watersheds of the WEB vary from second-order to fourth-order. Stream number is the count of streams of different orders in a given drainage basin (Strahler, 1964). Watersheds with high stream number have high runoff and rapid peak flow compared with watersheds having low stream number (Bhat, Alam, Ahmad, Farooq, & Ahmad, 2019). The total number of streams for the 21 sub-watersheds is 643, and the first order accounts for 51% of the total number of streams in all sub-watersheds having 328 streams. The details of the stream characteristics are confirmed by the first law of Horton (1945), which states that the number of streams of different orders in a given drainage basin tends to closely approximate an inverse geometric ratio. This inverse geometric relationship for 21 sub-watersheds is shown graphically in the form of a straight line when log values of \(N_u\) are plotted on an ordinary graph (Figure 5d). Among the 21 sub-watersheds, SW 21 has the largest \(L_u\), whereas SW 14 has the lowest \(L_u\). The first order streams have the maximum value of total length of stream segments of 97 km, accounting for 49% of the total stream length. A strong negative correlation \((r = −.99)\) was found between stream order and length of stream (Figure 6a). Additionally, a strong correlation \((r = .95)\) was found between stream length and basin area (Figure 6b). Stream length ratio \((R_L)\) is the ratio of the mean length of the one order to the next lower order of the stream segments (Horton, 1945). There is a noticeable variation in \(R_L\) values between the streams of different orders. The variation in \(R_L\) can be attributed to changes in slope and relief (Magesh et al., 2011).

### 4.1.2 Linear parameters

**Drainage density \((D_d)\)**

Slope gradient and relative relief are the main controlling factors on drainage density (Magesh et al., 2011). Low \(D_d\)
values prevail in watersheds having low relief, and vice versa (Strahler, 1964). Low drainage density is an indicator of highly permeable subsoil material under dense vegetation, low relief, and low runoff, whereas high drainage density implies high runoff, and low infiltration rate (Harlin & Wijeyawickrema, 1985; Kelson & Wells, 1989). A well-drained basin has a drainage density of 0.73, whereas a poorly drained one has a drainage density of 2.74 (Horton, 1945). The WEB has a $D_d$ value of 3.19, where the lowest value of $D_d$ was found for SW 6, and the highest value was found for SW 9. Generally, the $D_d$ values are relatively high, implying the presence of highly dissected topography, steep slopes, and impermeable subsurface materials, and thus high potentiality for flooding.

A moderate positive correlation ($r = .53$) was found between the drainage density and basin relief (Figure 6c). $D_d$ is directly correlated with flash flood; therefore, SW 9 was given the highest rank (5), and SW 6 was given the lowest rank (1).

**Length of overland flow ($L_{o}$)**

$L_{o}$ is the length of water flow over the land surface before it becomes concentrated into defined stream channels (Horton, 1945). The main influential factors that affect $L_{o}$ include rock and soil properties, climatological conditions, vegetative cover, and relief (Youssef, Pradhan, Gaber, & Buchroithner, 2009). $L_{o}$ for the WEB is 0.16. It varies from 0.14 for SW 9 (high susceptibility to flood) to 0.24 for SW 6 (low susceptibility to flood). The highest $L_{o}$ values were found for sub-watersheds 4, 6, 11, 12, 14, 16, and 21. $L_{o}$ has an inverse relation with floods; therefore, sub-watersheds 1, 2, 5, 7, 8, 9, 10, 17 and 18 were given the highest rank (5). A moderate negative correlation ($r = -.5$) was found between the length of overland flow and the basin relief, indicating that the higher the relief the less is the length of the overland flow, and thus the more susceptibility to flooding.

**Stream frequency ($F_s$)**

$F_s$ is the ratio between the total number of streams and area (Horton, 1932). The lower are the stream frequency and the drainage density, the slower is the surface runoff (Taha et al., 2017), and consequently the less susceptible is the basin to flooding (Carlston, 1963). Low values of stream frequency (1.0–3.5) indicate that the stream is controlled by fractures, and high stream frequency (4–10) signifies low impermeability and more surface runoff (Melton, 1957).

The WEB has a stream frequency of 10.3, whereas it varies from 5.3 for SW 10 to 13.3 for SW 14. These values denote high surface runoff and low infiltration of the surface water. It confirms that the study area is generally not influenced by the tectonics in the Dead Sea region. SW 14 is the most susceptible sub-watershed for flooding.
with low infiltration capacity. Variation in $F_s$ may be attributed to differences in lithology, and initial resistance of rocks to erosion. Most of the sub-watersheds have stream frequency values in the range of 5.3–10.09. Stream frequency has a direct relationship with the susceptibility to flooding; therefore, sub-watershed 14 was given the highest rank (5), whereas sub-watersheds 10 and 15 were given the lowest rank (1).

**Bifurcation ratio ($R_b$) and mean bifurcation ratio ($R_{bm}$)**

Bifurcation ratio ($R_b$) is defined as the ratio of the number of stream segments of given order to the number of segments of the next higher order (Schumm, 1956). Low values of $R_b$ dominate structurally less disturbed watersheds, or watersheds without any distortion of drainage pattern (Strahler, 1964). High $R_b$ indicates high runoff producing potential of a watershed and short lag time (Howard, 1990). The mean bifurcation ratio ($R_{bm}$) is a measure of the degree of distribution of the stream network (Mesa, 2006). Maturely dissected basins have ($R_{bm}$) values in the range of 3–5, which indicates a geological control (Vittala, Govindaiah, & Honne, 2004).

The WEB has $R_{bm}$ value of 2.05, and it varies from 1.33 for SW 6 to 4.14 for SW 18. The susceptibility of the WEB sub-watersheds to flooding was assessed using El-Shamy (1992). The method is based on the relationship between bifurcation ratio ($R_b$) and drainage density ($D_d$), and the relationship between bifurcation ratio ($R_b$) and stream frequency ($F_s$). The two relationships are presented graphically, where each plot contains two curves, dividing the area into three fields or classes:

- **Class A**, where $R_b$ is high, and $D_d$ and $F_s$ are low. Sub-watersheds falling in this file have high groundwater recharge potential but low flash flood possibility.
- **Class B**, where $R_b$ is low, and $D_d$ and $F_s$ are high. Sub-watersheds falling in this field have low groundwater recharge potential, but high possibility of flash flood.
- **Class C**, where $R_b$, $D_d$, and $F_s$ are moderate. Sub-watersheds falling in this field have moderate potentiality of both groundwater recharge and flooding.

The relationship between the $R_b$ and $F_s$ for all sub-watersheds within the WEB reveals that all the sub-watersheds have high flood potential (Figure 7a). In the case of the relationship between $R_b$ and $D_d$, it can be seen that 20 sub-watersheds out of 21 are falling in the high flood potential field (Figure 7b).

### 4.1.3 | Shape parameters

**Elongation ratio ($R_e$)**

$R_e$ is a measurement of the basin shape (Horton, 1932). The values of $R_e$ can be divided into three groups (Magesh et al., 2011): circular with $R_e$ values greater than 0.9, oval with $R_e$ in the range of 0.9–0.8, and less elongated with $R_e$ less than 0.7. If $R_e$ value approaches 1, the shape of the basin approaches a circle (Abdel-Lattif & Sherief, 2012), and circular basins are more efficient in runoff than elongated ones (Singh & Singh, 1997). $R_e$ reflects basin relief where values close to 1 are characteristic of basins having very low relief, and values in the range of 0.6 to 0.8 are characteristic of basins having high relief and steep slopes (Dar, Chandra, & Romshoo, 2013).

The WEB has $R_e$ value of 0.62, and can be described as an elongated basin with high relief and steep slopes. SW 20 has the lowest sensitivity to flooding ($R_e = 0.66$), whereas SW 6 has the lowest $R_e$ (0.41) indicating more susceptibility to flooding. Generally speaking, the SWs can be described as elongated, with high relief, and steep slopes. $R_e$ has an inverse correlation with flooding; therefore, sub-watersheds 6, 15, and 19 with $R_e$ in the range of 0.41–0.46 were given the highest rank (5), whereas sub-watersheds 1, 5, 11, 13, 14, and 20 with $R_e$ in the range of 0.61–0.66 were given the lowest rank (1).

**FIGURE 7** Bifurcation ratio versus stream frequency (a) and bifurcation ration versus drainage density (b)
Circularity ratio ($R_c$)
The circulatory ratio is defined as the proportion of the basin area to the area of circle having the same perimeter of the basin (Miller, 1953). $R_c$ is influenced by the length and frequency of streams, geological structures, climate, roughness, and slope (Bisht, Chaudhry, Sharma, & Soni, 2018). Elongated basins have $R_c$ close to 0, whereas circular basins have $R_c$ close to 1 (Bisht et al., 2018). The basin shape is strongly elongated and has high infiltration rate if the circularity ratio is in the range of 0.4–0.5 (Ali et al., 2018; Aparna, Nigee, Shimna, & Drissia, 2015). $R_c$ is directly correlated with flash floods that is, higher values of $R_c$ indicating less availability of time for surface runoff to infiltrate and thus flooding. The WEB has $R_c$ value of 0.49, indicating that the basin is at an early stage of topographical maturity. Based on $R_c$ values, all sub-watersheds in the WEB can be described as strongly elongated. The lowest $R_c$ was found for SW 15, and the highest $R_c$ was found for SW 20, and thus high potential for flooding. The highest $R_c$ values were found for sub-watersheds 1, 5, 11, 13, 14, 20 and 21; therefore, sub-watersheds were given the highest rank (5), whereas the lowest values were found for sub-watersheds 2, 3, 6, 15, 16, and 19, which were given the lowest rank (1).

Shape factor ($B_s$)
The shape of the basin as well as basin length and relief determine the rate of sediment and water yield (Farhan, Anbar, Al-Shaikh, & Mousa, 2017). Low $B_s$ values indicate high relief and steep slopes, which enhances flooding. The WEB has $B_s$ value of 3.31, where it varies from 2.92 for SW 20 to 7.61 for SW 6. These values indicate that the elongated shape is the characteristic feature of the sub-watersheds as found in the circulatory ratio above. Shape factor has an inverse relationship with flooding; therefore, sub-watersheds 1, 5, 11, 12, 13, 14, 20, and 21 with low $B_s$ values were given the highest rank (5), and sub-watersheds 6, 15, and 19 with high $B_s$ values were given the lowest rank (1).

4.1.4 Relief parameters
Basin relief (H), relief ratio ($R_r$), relative relief ratio ($R_v$)
Basin relief is the difference in elevation between the highest and lowest points in the basin. It has an important role in landforms development, drainage development, surface and subsurface water flow, permeability, and erosional properties of the terrain (Magesh et al., 2011). The total basin relief (H) of the WEB is 1,514.5 m. This high value indicates low infiltration and high surface runoff conditions. The lowest H value was found for SW 7 (444 m), whereas the highest value was found for SW 7 (1,030 m), indicating that the latter has a high potentiality to produce surface runoff.

Relief ratio ($R_r$) is the horizontal distance along the longest dimension of the basin parallel to the principal drainage line (Magesh et al., 2011). High $R_r$ values signify short lag time, sudden peak discharge, and thus high potentiality of flash flood occurrence (Abuzied et al., 2016; Ameri et al., 2018). The WEB has relief ratio of 105.1, which means high potential of flash flood occurrence. SW 12 ($R_r = 0.32$) is the most sensitive sub-watershed to flooding, whereas SW 21 ($R_r = 0.09$) is least sensitive one. The highest values of $R_r$ were found within those sub-watersheds located in the northwest part of the WEB where the land surface slope is low.

Relative relief ratio ($R_v$) can be utilised to present a basin relief dimensions without taking into consideration the sea level (Bisht et al., 2018). The WEB has $R_v$ value of 0.04. $R_v$ value varies between 0.03 (SW 21) and 0.1 (SW 7). These values indicate low to high sensitivity to flooding, respectively. $R_v$ has a direct relationship with flooding (Macka, 2001); therefore; sub-watersheds 7 and 10 with the highest $R_v$ values were given the highest rank (5), and sub-watersheds 4 and 21 with low $R_v$ values were given the lowest rank (1).

Basin slope ($S_w$)
Basin slope is a significant morphometric parameter that affects the hydrological processes, especially surface runoff amount and speed, and the time needed for runoff to enter a stream channel (Meraj, Yousuf, & Romshoo, 2013). Higher slopes lead to rapid runoff and less groundwater recharge potentiality (Bisht et al., 2018). Watersheds with high reliefs and steep slopes are susceptible to flash floods. The WEB has $S_w$ value of 6.31, which is considered high that implies high potential of flash floods. Based on $S_w$ values, SW 12 with a slope of 19.1 is the most prone sub-watershed to flooding, whereas SW 21 is the least sensitive one. The slope values are expressed here in degrees. Slope has a direct relation with flooding; therefore, sub-watersheds 2, 7, and 12 with the highest $S_w$ values were given the highest rank (5), whereas sub-watershed 21 with the lowest $S_w$ values was given the lowest rank (1).

Ruggedness number ($R_n$)
Ruggedness refers to the level of smoothness and roughness of the basin terrain or surface unevenness (Selvan, Ahmad, & Rashid, 2011). High ruggedness number indicates steep slopes, and thus resulting in flash floods and erosion (Patton & Baker, 1976). Ruggedness number becomes higher if the drainage density and relief are extremely higher, causing not only steep slopes but also long slopes (Strahler, 1957).
The WEB has $R_n$ of 4.83, and can be described as a basin of badland topography that has high potential for floods and erosion. $R_n$ varies between 0.99 for SW 14 with low sensitivity for flooding, and 3.6 for SW with high sensitivity. A strong positive correlation ($r = .80$) was found between drainage density and the ruggedness number, and strong positive correlation ($r = .92$) was found between the basin relief and ruggedness number (Figure 6d). $R_n$ is directly correlated with flooding; therefore, sub-watersheds 1, 2, 7 and 10 with the highest $R_n$ values were given the highest rank, and sub-watersheds 4, 14, and 21 with the lowest $R_n$ values were given the lowest rank (1).

Surface characteristics of the basin like relief, relief ratio, slope, relative relief ratio, and ruggedness are important parameters that determine a basin hydrological behaviour and runoff accumulation (Schumm, 1956). High values of relief ratio and slope lead to fast runoff, short lag time, and high peaks, and consequently lead to high susceptibility to flooding (Abuzied et al., 2016). In the study area, the highest values of these parameters are found in general in the middle and northwest parts of the study area, making sub-watersheds in these parts more susceptible to flooding.

### 4.1.5 Hypsometric parameters

**Hypsometric integral (HI)**

Hypsometric Integral (HI) is a function of dissection of the topography, and it provides an efficient tool to assess interactions existing between tectonic uplift, climate, lithology, and erosion (Pavano, Catalano, Romagnoli, & Tortorici, 2018). The WEB has HI value of 0.64, where it varies from 0.46 for SW 14 to 0.77 for SW 6. The lowest values of HI (0.46–0.59) are found for sub-watersheds located in the middle and northwest parts of the study area, making these sub-watersheds more susceptible to flooding. Sub-watersheds 4, 9, 11, 12, and 14 with the lowest HI values (0.46–0.53) were given the highest rank (5). The variation in the HI reflects the steps of erosional development in different sub-watersheds. Watersheds at equilibrium or on maturity have HI values in the range of 0.35–0.6 (Kumar & Joshi, 2015).

### 4.2 Flash floods prioritisation of the WEB

Watersheds characteristics determine the way these watersheds behave. Therefore, critical sub-watersheds should be demarcated for the purpose of proper and concentrated management and planning. The above discussed morphometric parameters were used for the purpose of prioritisation of the sub-watersheds in the WEB regarding its susceptibility for flooding. Basin area, drainage density, stream frequency, circularity ratio, relief ratio, relative relief ration, basin slope, and ruggedness number have a direct relationship with runoff. In other words, the higher the values of these parameters, the higher is the opportunity for flooding to occur, and sub-watersheds having the highest value was given the highest rank (5). On the contrary, length of overland flow, elongation ratio, shape factor, and the hypsometric integral have an inverse relationship with runoff. It means that the lower values of these parameters, the higher is the opportunity for flooding to take place. Accordingly, the lowest value of these parameters was given the highest rank (5).

The total rank was determined for each sub-watershed based on the computed morphometric parameters, which is then normalised and classified into 5 categories of flash flood susceptibility (Table 3). These categories are very high (0.8–1), high (0.6–0.8), moderate (0.4–0.6), low (0.2–0.4), and very low (0–0.2) priorities. The final susceptibility to flash flood map is illustrated in Figure 8.

It was found that 7 sub-watersheds (SW 1, 2, 5, 7, 9, 10, 13), which constitute about 33.8% of the total area are in the very high priority class, indicating that these sub-watersheds are very highly-susceptible to flash flood. Eight sub-watersheds (SW 3, 8, 11, 12, 14, 17, 18, 20) forming 30.2% of the total area are in the high priority class, and thus having a high susceptibility to flash flood. The moderate class involves only 3 sub-watersheds (SW 15, 19, 21) forming about 15.5% of the total area of the basin. The low category priority covers two sub-watersheds (SW 4, 16), and the very low priority consists of only one sub-watershed (SW 6).

The average values of the morphometric parameters of the priority classes are depicted in Figure S2. The average drainage density of the high-very high, moderate, and low-very low priorities is 3.18, 2.88, and 2.28, respectively. Stream frequency ($F_s$) is directly correlated with flash flood susceptibility; the high-very high priority class has the highest average $F_s$ of 9.65, followed by the low-very low priority which has an average $F_s$ of 8.81. The moderate class has the lowest average $F_s$ of 7.89. Shape factor ($B_s$) is inversely correlated with the sub-watershed susceptibility to flash flood. The average $B_s$ value of three classes (high-very-high, moderate, low-very low) is 4.3, 5.8, and 5.7. Basin relief (H) which affects many other morphometric parameters is highest for the high-very high priority class (795m). The moderate class has the lowest average basin relief value of 597 m, and the low-very low class has an intermediate average basin relief.
value of 718 m. Basin slope ($S_w$) has a prominent effect on the potentiality of surface runoff and flooding, where sub-watersheds with steep slopes have high potentiality of flash floods. The highest average $S_w$ was found for the very high-high class (14.7%), whereas the lowest average value was found for low-very low class (9%). The moderate class has an intermediate average value of 10.9%. Ruggedness number ($R_n$) is another important morphometric parameter that affects watershed vulnerability to flash floods. The average $R_n$ for the high-very high class was the highest reaching 2.6, followed by the moderate class which shows an average $R_n$ value of 1.7. The $R_n$ of the low-very low priority class is slightly lower than that of the moderate class and approaches 1.6. Circularity ratio ($R_c$) is another shape parameter that strongly affects a watershed vulnerability to flooding. The high-very high class has the highest average $R_c$ reaching 0.29, followed by the intermediate class (0.27). The low-very low class has the lowest $R_c$ value of 0.23.

The results and analyses obtained in the present study have multiple fields for practical application and future development. Two main types of applied studies can be derived from the morphometric analysis of small river basins such as Wadi Easal in arid climate: First, locating sub-basins with high flash flood hazard, so responsible authorities take appropriate measures of reducing such hazards by devising prevention, protection and mitigation plans. In view of the variables controlling flash flood hazard and their spatial distribution, the potential hazard can be predicted in other basins with a similar hydrographic configuration as the proposed methodology provides quick, useful information for flood susceptibility.
and, eventually, vulnerability assessment. Although this methodology is perhaps one of the main potential strengths of this research and can be extended to other areas of study, validation was not possible due to lack historical records for the study area.

Second, determination of priority areas for future risk management plans. The local authorities must be aware of potential flash floods in the area. In view of agriculture as the major production sector, special emphasis will be placed on this sector in future to reverse the situation of flash flood risk. Additionally, special attention should be paid to people living down the basin outlet with specific plans and programs to adjust their flash flood risk perception. These actions must include meetings for showing the flood hazard map of the basin and evidence (e.g., photographs and reports) of the results of past flood events in the neighbouring basins. A potential dam site may be proposed to mitigate flash floods. The best location could be in the lower reaches of sub-basin no.1 as it is characterised by very high priority for flash flood management and receives huge amount of water from the sub-basins in the upper part of the basin that are also classified as very high and high priority zones for flash flood. However, this should be supported and integrated by carrying out detailed hydrological and geotechnical studies.

5 | CONCLUSIONS

Since there are not enough historical climatic and hydrological records that are required for hydrological
modelling, morphometric analysis has been efficiently used to assess sub-watershed susceptibility to flooding. Morphometric analysis of the Wadi Easal Basin has shown that the basin is a fifth-order drainage system having high-very high sensitivity to flash floods (64% of the total area). Relative relief ratio, stream frequency, relief ratio, circulatory ratio, basin slope, drainage density, and ruggedness number are the main influential parameters on the hydrological response to flooding in the WEB. Moreover, the study showed that protection of the area from flash floods should be a top priority for competent authorities to protect human lives and agricultural farms and eventually avoid tragic such as the Wadi Zarqa Ma’in incident occurred in 2018. Development of water resources by construction of a dam downstream of the basin is highly recommended which has threefold services including lowering the potential of flash floods, wise utilisation of surface water for irrigation and recharging the groundwater aquifers. The findings reached by the study indicated that flood susceptibility maps could assist disaster planners and decision makers to deal with high and very high susceptible areas to flash floods by adapting mitigating/preventive measures of flash flood, such as planting vegetation, terracing hillsides, and floodways, dams, and retention ponds construction. Furthermore, the study proved that integration of morphometric analysis with GIS can provide a significant tool to understand sub-watersheds properties related to flooding management.

DATA AVAILABILITY STATEMENT
The data that support the findings of this study are available from the corresponding author upon reasonable request.

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**SUPPORTING INFORMATION**

Additional supporting information may be found online in the Supporting Information section at the end of this article.

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