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Morphometric Analysis and Prioritization of Watersheds for Flash Floods Management in Wadi Arab Catchment, North Jordan

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Abstract

Objectives: Flash floods are among the most devastating natural disasters, costing lives and causing property damage. The aim of this study was to map the sub-basins that could be exposed to flooding in the Wadi Arab Basin (WAB) and to take necessary measures to mitigate flood risk disasters.

Methods: This study utilized morphometric analyses to estimate the flash flood hazard in the WAB, employing a Geographic Information System (GIS). Morphometric analyses involved the measurement of basic, linear, shape, relief, and hypsometric integral parameters.

Results: The WAB has been divided into seven sub-basins, which were prioritized for analysis. The results indicate that two sub-basins (SW2 and SW4) exhibit a very high susceptibility to flooding, covering approximately 22% of the basin's total area. Key morphometric parameters contributing to this susceptibility include stream order, basin length, stream lengths, bifurcation ratio, drainage density, stream frequency, elongation ratio, and relief indices. The study area is primarily composed of carbonate rocks, significantly influencing the basin's morphometric characteristics.

Conclusions: The findings of this study align with those of other studies employing different approaches. These results can aid decision-makers in comprehending flood risk susceptibility in the study area and serve as guidance for competent authorities when initiating flood mitigation or artificial groundwater recharge measures.

Keywords: Flash flood, Wadi Arab basin, morphometric analysis, prioritization, GIS.

التحليل المورفومتري وترتيب الأحواض المائية ذات الحاجة لإدارة الفيضانات في حوض وادي العرب، شمال الأردن

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ملخّص

الأهداف: الفيضانات المفاجئة هي واحدة من أكثر الكوارث الطبيعية تدميرًا التي تكلف خسائر بشرية ومادية. من المهم للغاية إجراء تقدير للأحواض التي يمكن أن تتعرض للفيضانات، واتخاذ التدابير اللازمة لتجنب كوارث أخطار الفيضانات.

المنهجية: استخدمت هذه الدراسة التحليل المورفومتري بهدف تحديد خطر الفياضانات المفاجئة في حوض وادي العرب (شمال الأردن) بالاعتماد على نظم المعلومات الجغرافية. أجرِيَ التحليل المورفومتري من خلال قياس المعاملات الأساسية، الشكلية، الخطية والتكامل الهبسومتري للحوض.

النتائج: جرى تقسيم الحوض إلى 7 أحواض فرعية. خلصت الدراسة إلى ان الحوض الفرعي 2 والحوض الفرعي 4 لديهما قابلية عالية لحدوث الفيضانات، واللذين يشكلان نسبة 22% من المساحة الإجمالية للحوض. المعاملات الرئيسة الكامنة وراء ذلك هي رتبة المجاري المائية، وطول الحوض، وأطوال المجاري المائية، ونسبة التشعب، وكثافة التصريف، وتواتر المجاري المائية، ونسبة الاستطالة، ومؤشرات التضرس. وتهيمن الصخور الكربونية في منطقة الدراسة والتي لعبت دورًا رئيسيًا في الخصائص المورفومترية للحوض.

الخلاصة: لقد وجد أن نتائج الدراسة مقاربة لنتائج دراسات أخرى استخدمت منهجيات مختلفة. إن نتائج هذه الدراسة يمكن أن تساعد صانعي القرار على فهم وتحديد قابلية حدوث خطر الفيضانات في منطقة الدراسة واستخدامها كمرشد من أجل بدء تدابير التخفيف من الفيضانات أو إعادة تغذية المياه الجوفية الاصطناعية.

الكلمات الدالة: الفيضان الوميضي، حوض وادي العرب، التحليل المورفومتري، الأولويات، نظم المعلومات الجغرافية.

1. Introduction

Geomorphology is known as one of the most important branches of geography and is concerned with describing and analyzing the various forms of the earth's surface. Morphometric studies are important applications of geomorphology and the basic premise for the fields of water resources and terrain forms. Morphometry analysis refers to the measurement and mathematical analysis of the configuration of the earth's surface, shape, and dimension of its landforms (Rai *et al.*, 2014). Statistical methods are applied to find the relationship between morphometric variables in order to understand the characteristics of the terrain and their influence on environmental processes such as flash floods and erosion (Al-Sababha and Zaitoun, 2018), and consequently adopt the proper management of natural water resources. The study of the morphometric characteristics of any river basin helps well in determining the hydrogeological characteristics of the basin for the management of surface water resources and the characteristics of the drainage system, due to the strong relationship between the morphometric and hydrological characteristics, and it is not possible to reduce floods without an understanding of the morphometric characteristics (Koshak and Dawod, 2011). Floods are one of the sudden natural hazards of high danger to human life and property, and one of the most important risks that cause landslides. Therefore, watershed management is one of the important rules that control surface run-off (Obeidat, Awawdeh, and Al-Hantouli, 2021). Recently, geographic information systems have shown its ability in watershed management and flood risk management based on morphometric analysis. Geographic information systems technologies have proven their ability to extract and analyze morphometric variables for water basins, such as the area of the basin, basin relief, texture ratio, and drainage density.

Bajabaa, Masoud, and Al-Amri (2014) used morphometric analysis. to assess the risk of flash floods in Wadi Al-Leith Basin (Saudi Arabia). Nine morphometric parameters were relied upon to assess the degree of risk of flash floods, then the sub-basins were identified and classified into three groups (high, medium, and low). Bisht, Sharma, and Chaudhry (2016) produced maps of areas exposed to flash floods in the GAGAS Watershed (Himalayas), which is characterized by a wide topographical diversity. The sub-basins in the study area were classified into 4 categories (very high, moderately high, low) according to their susceptibility to flash floods. Taha *et al.* (2017) used remote sensing techniques and geographic information systems to assess the risks of flash floods in Wadi Qena (Egypt), which is characterized by semi-arid environment. A flash flood risk map was prepared where most of the sub-basins ranged from low to medium risk.

CADRI (2017) reported that flood risk, especially flash floods, are increasing due to unplanned urbanization and the short capability of drainage systems. Flood risks are particularly severe for urban infrastructure that are encroaching on natural drainage areas (wadis). Many studies have been carried out in Jordan to prioritize watersheds for flash floods or soil erosion using morphometric and hypsometric analysis (Farhan and Anaba, 2016; Farhan *et al*., 2017; Farhan *et al*., 2017). All these studies used the same approach, but with different morphometric parameters. Farhan and Ayed (2017) assessed flash-flood hazards in the arid watersheds of Wadi Wuheida and Wadi Rajil (Jordan). Two methods were employed to assess flash floods and to generate flooding risk susceptibility maps. The first method is El-Shamy's approach, and the second is the morphometric hazard degree assessment method. The sub-basins in the study area were classified into 4 categories (very high, moderately high, low) according to their susceptibility to flash floods. demarcated and displayed spatially using GIS. The World Food Program (WFP) (2019) prepared a flood hazard map at district level through integrating the Watershed Modelling System outputs with GIS spatial analysis tools. They utilized the Integrated Context Analysis (ICA) for producing flash flood hazard at district level. Obeidat, Awawdeh, and Al-Hantouli (2021) conducted morphometric analysis to prioritize the sub-watersheds in the Wadi Easal Basin (Jordan), which is characterized by a high topography and arid environment. The results showed that 15 out of 21 sub-basins, which represent 64% of the basin total area, have a high susceptibility for flash floods. Hyarat (2016) used GIS based hydrologic and hydraulic modeling to estimate the flood hazard of Wadi Al Arab area. She determined areas prone to flooding during high rainfall events or dam failure in the Wadi Al Arab catchment area. The unsteady-flow simulations revealed that large areas of the settlement are exposed to flood hazard. Flood runoffs with several return periods were found to exceed the flow carrying capacity of the channel significantly so that devastating flood events are to be expected in these areas.

This study aims to determine the morphometric variables of the Wadi Arab Basin and to prioritizes its sub-basins for flash floods in a GIS environment.

2. Study area

The Wadi Arab Basin (WAB) is in the northern part of the Jordan Valley, on the eastern bank of the Rift Valley (Fig. 1). The WAB occupies an area of 293 Km^2, where the elevation varies between 850 m and 216 m below Sea level. Wadi Al Arab Reservoir is about 10 km south of Lake Tiberias, immediately south of the Yarmouk River, and about 25 km northwest of Irbid City (Hyarat, 2016). This reservoir is mainly used for irrigation.

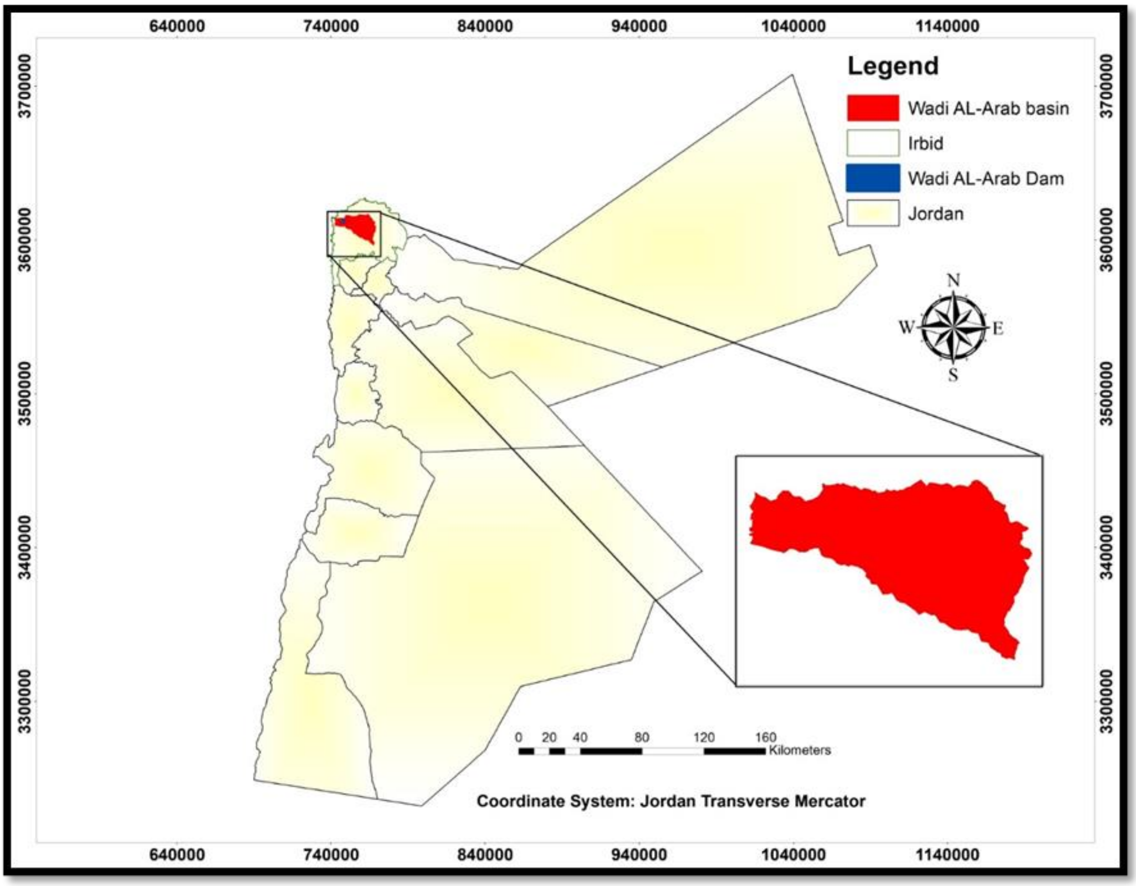

Fig. 1 Location map of the study area.

The WAB is characterized by a Mediterranean type of climate with 400 mm annual precipitation and relative humidity in the range 9% (June) to 67% (February) (Ibrahim and Al-Mashakbeh, 2016). The maximum daily temperature reaches 40 °C during summer while it drops to below 10 °C during the winter season. The monthly mean temperatures range between 31 °C and 14 °C (Hadadin, Al-Majali, and Eljufout, 2022). The study area is characterized by its richness of natural vegetation (pastoral and arboreal) and cultivation, where oak and cypress forests are among the most important types of plants that are subject to significant deterioration (Farhan and Nawaieh, 2019). A land use/land cover (LULC) map of Wadi al-Arab basin, produced by ESRI was derived from ESA Sentinel-2 imagery (Fig. 2). Five land use classes were identified in: water (Wadi Al Arab Reservoir), trees, crops, urban, bare ground, and rangeland distributed as 0.20%, 0.20%, 21%, 36.20%, 0.40%, and 42%, respectively. Rangelands are open areas of land covered by inhomogeneous grasses, when grazing by livestock reduces leachate water within the soil and runoff increases, thus increasing the likelihood of flooding.

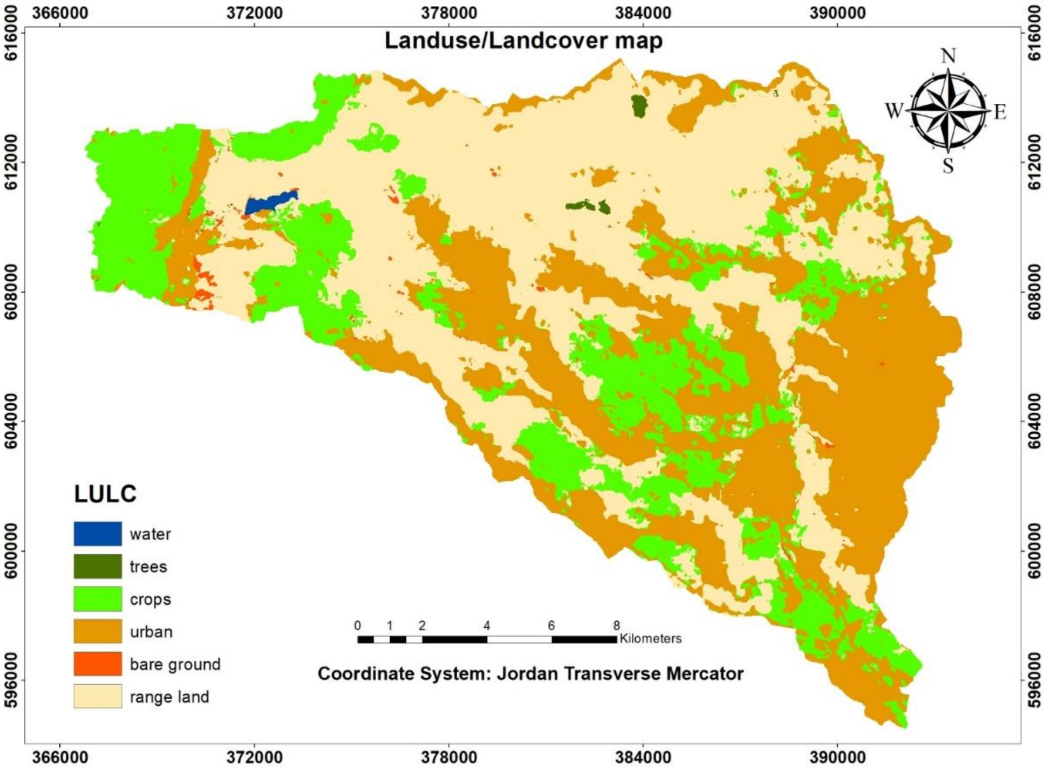

Fig. 2 Land cover map of study area (source: ESRI, 2023).

Approximately 35% of the basin is covered with soil. Generally, the lithostratigraphic units covering the catchment area consist of Muwaqqar Chalk Marl, MCM (24%), Amman Silicified Limestone, ASL (20%), Umm Rijam Chert Limestone, URC (14%), Wadi Umm Ghudran, WG (2.25%), and igneous rocks (1.13%) (Fig. 3). The WG formation consists of marl, marly limestone, chalk, and chert. The overlying limestone, chert, chalk and phosphorite beds are members of the ASL. This part of the formation is overlain by a unit that is composed of phosphorite. coquina and marl. This is followed by bituminous marl and clayey marl of the MCM (Parker 1970; Makhlouf, Hiayri, and Azzam, 1996; Mohd 2000) formation. Alternating beds of limestone, chalk, and chert of the URC formation of Paleocene age overlies the MCM formation (Awawdeh and Jaradat, 2010). In the eastern part of the basin area, several types of igneous rocks cover rocks of the Balqa Group in the western part of the basin.

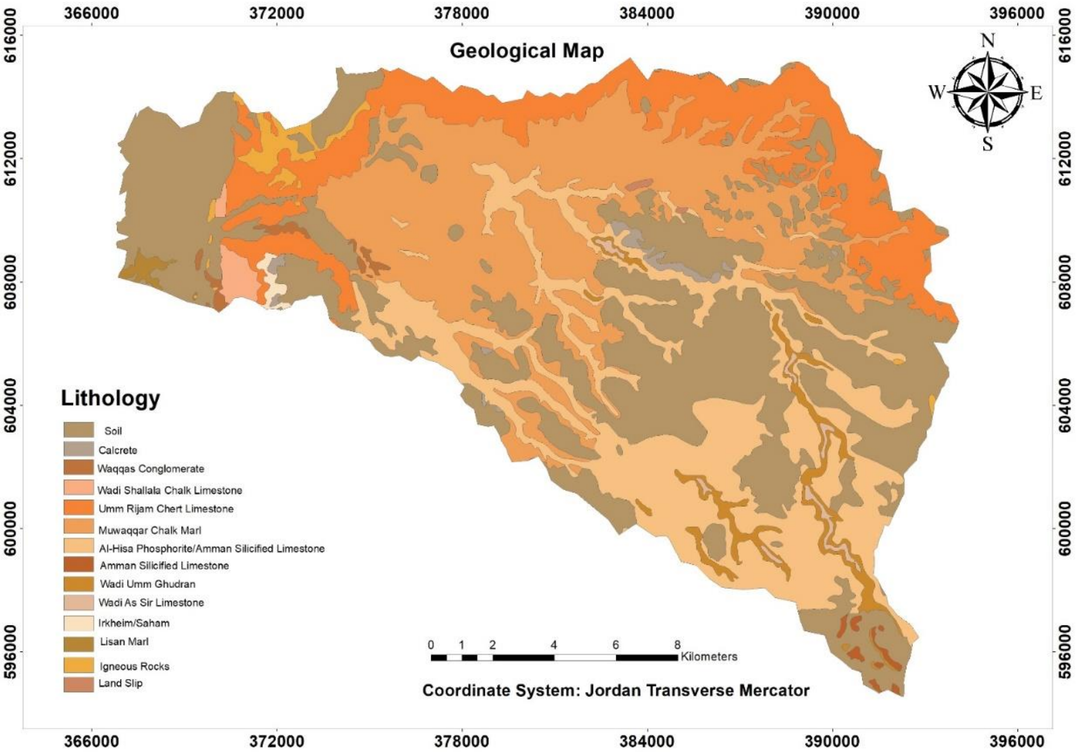

Fig. 3 Lithology map of study area.

3. Data and methods

Figure 4 shows the processes that were relied upon to complete this study. Twenty-two morphometric parameters were determined for the purpose of basin characterization and prioritization of the Wadi Arab sub-basins with respect to susceptibility to flash floods.

Morphometric parameters were measured directly from the DEM using GIS techniques and mathematical equations presented in table 1. There are measurements related to topographic properties (e.g., area, perimeter, stream order), measurements related to areal properties (e.g., elongation ratio, and circularity ratio), measurements related to relief properties (e.g., relief ratio, and total basin relief), and measurements related to the network (e.g., stream frequency, and drainage density). The DEM resolution is 12.5 m (Alaska Satellite Facility, 2022). The DEM was preprocessed to fill the sinks and remove missing data. The WAB was subdivided into sub-basins based on the flow accumulation maps and stream network. The method used for sub-basins prioritization is the ranking method (Total Rank**)** (Obeidat, Awawdeh, and Al-Hantouli, 2021)**.** Each morphometric parameter was classified into one of many rank groups where each category denotes a certain degree of the risk. Twelve parameters were selected to assess the sub-basins susceptibility for flooding based on the appropriate criteria for the study area: 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, and hypsometric integral.

There are parameters that 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. Such parameters are basin area, drainage density, stream frequency, circularity ratio, relief ratio, relative relief ratio, basin slope, and ruggedness number. Other parameters (e.g., length of overland flow, elongation ratio, shape factor, and hypsometric integral) have an inverse relationship to the degree of possibility for flood risk, which means that the higher value of the parameter, the lower is the risk degree. After morphometric ranking, values for each sub-basin were summed to classify the sub-basins and determine their susceptibility to flash floods occurrence. Five classes were obtained by using a simple equation to determine the interval length, which is (Max – Min)/5. The values for each parameter were categorized into five intervals. The summed morphometric parameters rank values were normalized from 0 for the lowest rank value and 1 for the highest rank value to obtain flash floods susceptibility index for each sub-basin. 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, and very high priority.

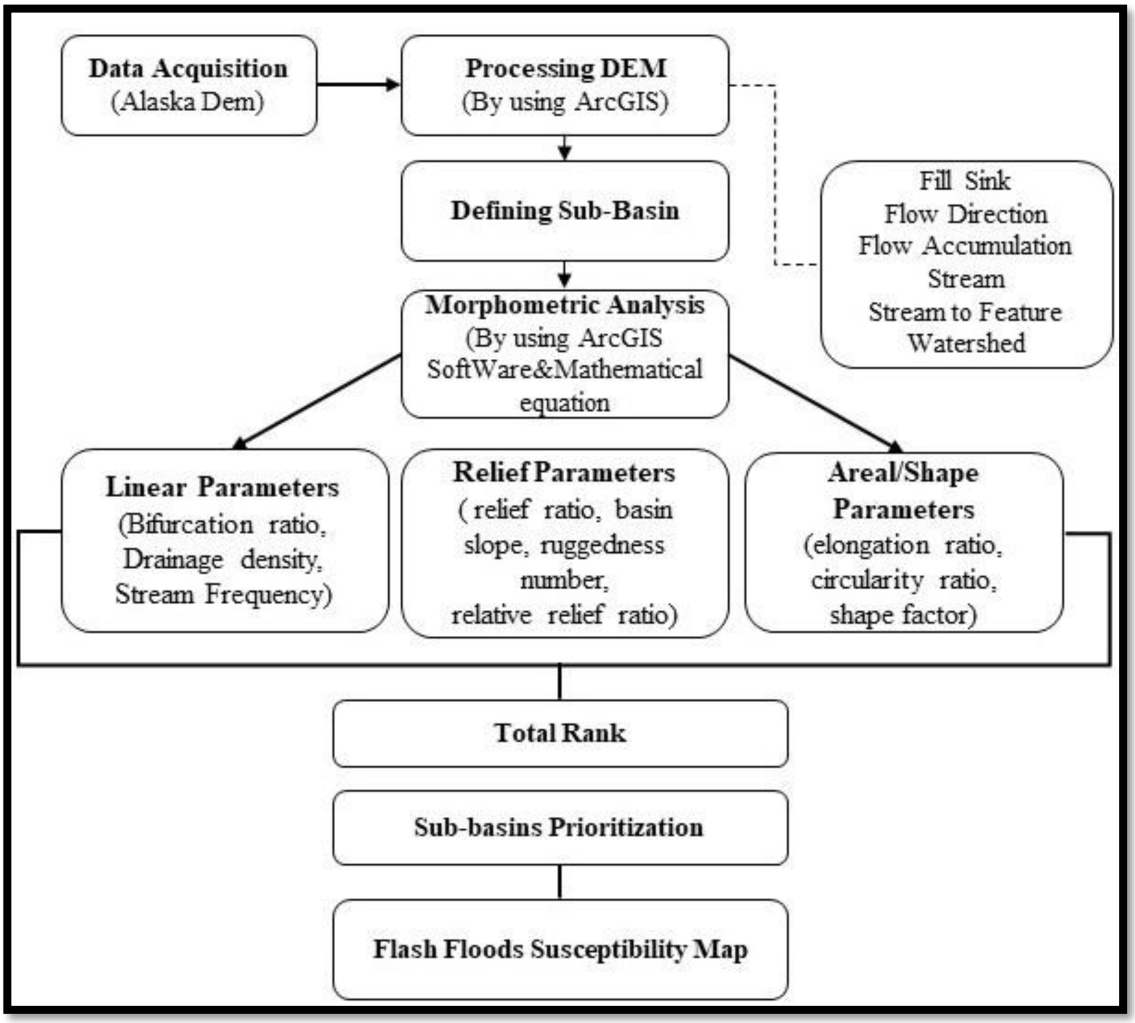

Fig. 4 Schematic representation of the methodology used in the study.

Table 1 Methods used to compute the morphometric parameters.

Parameter no.	Morphometric parameter	Definition	Reference
Basic			
1	Basin area (A)	Plan area of the watershed (km2)	Horton (1945)
2	Basin perimeter (P)	Perimeter of the watershed (km)	Horton (1945)
3	Basin length (L_b)	Length of the basin (km)	Horton (1945)
4	Stream order (U)	Hierarchical rank	Strahler (1952)
5	Total number of streams (N_u)	Total no. of streams of all orders	Strahler (1952)

Parameter no.	Morphometric parameter	Definition	Reference
6	Stream length (L_u)	Length of the stream (km)	Horton (1945)
7	Mean stream length. (L_{sm})	$L_{sm} = L_u/N_u$ (km)	Horton (1945)
8	Stream length ratio (R_L)	$R_L = L_u/L_{u-1}$, where L_{u-1} = the total stream length of its next lower order	Horton (1945)
Linear			
9	Bifurcation ratio (R_b)	$R_b = N_u/N_{u+1}$, where N_{u+1} = no. of segments of the next higher order	Strahler (1957)
10	Mean bifurcation ratio. (R_{bm})	R_{bm} = average of the bifurcation ratio of all orders	Strahler (1957)
11	Drainage density (D_d)	$D_d = L_u/A$	Horton (1945)
12	Length of overland flow (L_o)	L_o = 1/(2*Dd)	Horton (1945)
13	Stream frequency (Fs)	$F_s = N_u/A$	Horton (1945)
		Shape	
14	Elongation ratio (R_e)	$R_e = 1.128*(A^{0.5})/L_b$	Strahler (1957)
15	Circularity ratio (R_c)	$R_c = 4 \times \pi \times A/P^2$	Schumm (1956)
16	Shape factor (B_s)	$B_s = L_b^2/A$	Miller (1953)
Relief			
17	Basin relief (H)	$H = h - h_1$, where h = maximum height (m) h_1 = minimum height (m)	Horton (1945)
18	Relief ratio (R_r)	$R_r = H/L_b$ where H = total relief (km) L_b = basin length (km)	Malik et al. (2011)
19	Relative relief ratio (R_v)	R_v = H/P where H = total relief (km) P = perimeter of the basin (km)	Schumm (1956)
20	Basin slope (S_w)	$S_w = H/L_b*60$	Melton (1957)
21	Ruggedness number (R_n)	$R_n = D_d*H$	Farhan and Anaba (2016)
22	Hypsometric integral (HI)	$HI = (E_{mean} - E_{min})/ (E_{max} - E_{min})$, Emean = the weighted mean elevation Emax = maximum elevation Emin = minimum elevation	Schumm (1956)

4. Results and Discussion

4.1 Morphometric Analysis

The WAB has been divided into seven sub-basins coded as SW1 to SW7. It was classified as fifth-order basin with a total area of 293 km². The morphometric analysis was organized under five different categories: basic aspects, linear aspects, shape aspects, relief aspects, and hypsometric parameters (Table 1).

Basic aspects

Area (A) is one of the most important parameters in morphometric analysis. Increasing the area means increasing the number and length of the streams of drainage network. A larger area means a higher amount of rainfall in the basin where the more rainfall water, more runoff and therefore the greater the likelihood of flooding. Sometimes flooding occurs in small area basins where other morphometric parameters affect the occurrence of flooding (Abdeta et al., 2020). The area of the WAB sub-basins ranged from 28.29 km² (SW3) to 68.69 km² (SW7) (Table 2).

The perimeter (P) is used as an indicator of basin size and shape. It refers to the length of the drainage basin boundary. The perimeter of the WAB is 99.62 km, and the perimeter of the sub-basins ranges from 29.30 km for SW2 to 62.45 km for SW7. The basin length (L_b) is defined as the maximum straight distance between upstream and downstream in the basin. It indicates the travel time of surface runoff especially the flood waves passing through the basin (Bajabaa, Masoud, and Al-Amri, 2014). The basin length of the WAB is 31 km, and the length of the sub-basins ranges from 22.56 km (SW6) to 8.94 km (SW2). The ranking of streams has been carried out based on the method proposed by Strahler (1957), where the confluence of two 1st order streams gives stream of 2nd order, two 2nd order streams join to form a stream of 3rd order and so on. Stream order (U) analysis (Figure 4 and Table 2) showed that the WAB is a fifth order basin, whereas three sub-basins (SW1, SW3, and SW6) were identified under 3rd order, two sub-basins (SW5 and SW7) under 4th order and two sub-basins (SW2 and SW4) under 5th order. The first order streams have the maximum frequency; where its total number is 208, compared to the total number (26) of the fifth order streams (Table 2). There is an inverse relation between the stream frequency and stream order; as a stream order increases the stream frequency decreases. The total number of streams in the WAB is 413. The stream length (Lu) is one of the most significant hydrological parameters of the basin as it is an indicator of surface runoff characteristics and it's defined as the total lengths of streams of each of the different orders in basin. The total stream lengths of the WAB were accounted to 373.31 km, whereas it ranged between 37.30 km for sub-basin SW3 and 81.41 km for sub-basin SW6.

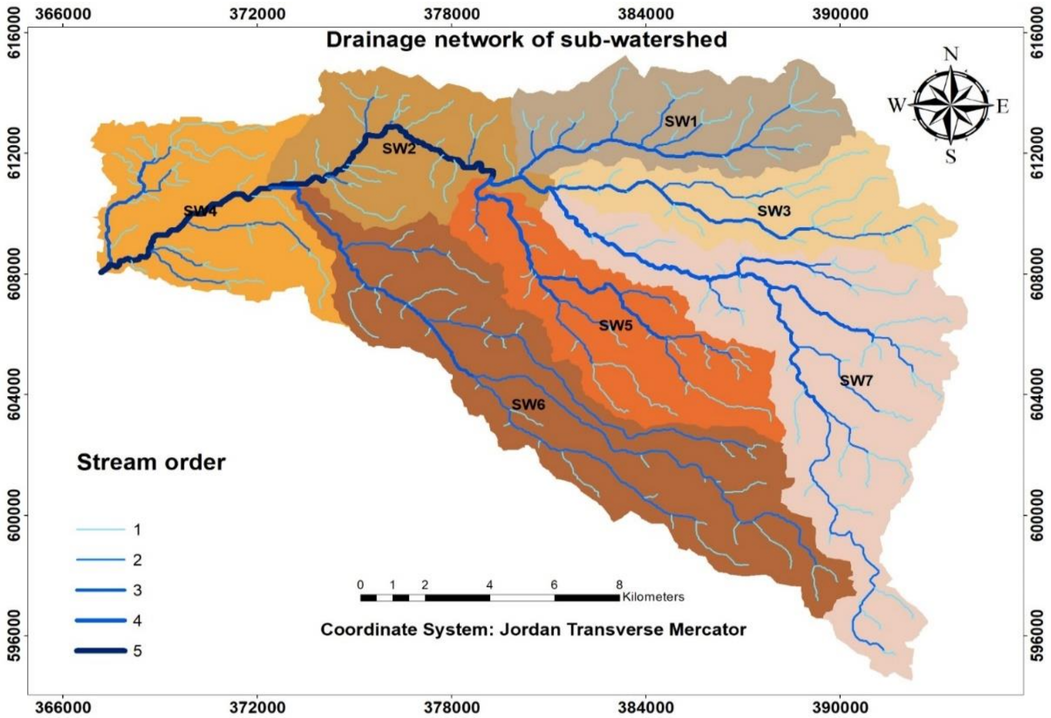

Fig. 4 Drainage network of the WAB sub-basins.

Table 2 Streams order and streams length for each sub-basin.

	Number of Streams						Streams Length (m)						Area (A) (km^2)	Perimeter (P) (km)	Basin length (km)
	1st	2nd	3rd	4th	5th	total	1st	2nd	3rd	4th	5th	total			
SW1	26	12	13	0	0	51	20.81	10.03	8.04	-	-	38.89	31.07	30.76	10.72
SW2	24	6	0	2	17	49	24.07	3.38	-	2.33	9.20	38.98	29.44	29.30	8.94
SW3	20	9	10	0	0	39	20.15	7.91	9.23	-	-	37.30	28.29	36.16	12.75
SW4	31	14	9	0	9	63	30.26	12.22	4.49	-	7.06	54.03	34.70	36.64	10.13
SW5	27	13	7	6	0	53	21.00	12.2	6.35	4.86	-	44.41	35.46	35.80	12.93
SW6	39	27	11	0	0	77	31.25	40.08	10.06	-	-	81.41	65.52	59.41	22.56
SW7	41	23	9	8	0	81	34.07	23.32	11.97	8.92	-	78.28	68.69	62.46	19.71
WAB	208	104	60	16	26	413	181.63	109.16	50.19	16.11	16.26	373.31	293.16	99.62	31

Linear aspects

Bifurcation ratio (Rb) is the ratio of number of streams of a given order to the number of streams of next higher order (Adhikari, 2020). It indicates the shape of the basin and understanding the runoff behavior of the watershed, and it is a useful measure to flooding prone area. High bifurcation ratio indicates highly dissected drainage basins, short time of concentration, and the probability of flooding will be high. In this study, the value of mean bifurcation ratio varied between 1.54 for SW1 0.58 for SW3 and 2.06 for SW2 (Table 3). Drainage density (Dd) indicates the spread and branching of the drainage network within the basin area. It is defined as the ratio of the total length of the streams in all ordered to the area of basin (Horton, 1945). High drainage density implies an increase in food peaks, whereas there is decrease in food level in low drainage density. The high value of drainage density means impermeable soil, steep slope, high surface runoff and low infiltration, therefore high potentiality for flooding and vice versa ((Obeidat, Awawdeh, and Al-Hantouli, 2021). The drainage density of the WAB is 1.27, and the drainage density of the sub-basins varied between 1.14 for SW7 and 1.56 for SW4. The length of overland flow (L) is approximately equals to half of reciprocal drainage density. It indicates the length of water over the ground before it gets concentrated into definite stream channels (Horton, 1945). The length of overland flow has an inverse relation with floods, the lower values of L indicate shorter flow paths, higher surface runoff and high relief with steep slopes therefore high potentiality for flooding and vice versa (Mohammed, Adugna, and Takala, 2018). The length of overland flow of the WAB is 0.39, and it varied between 0.32 for SW4 and 0.44 for SW7. Stream frequency (Fs) is the ratio of the total number of the streams in all orders to the area of basin (Horton, 1945). It indicates the close correlation with drainage density value of the sub-basin (Chandniha et al., 2017). Stream frequency has a direct relation with floods, therefore high potential for flooding. The stream frequency of the WAB is 1.41, and the Fs of the sub-basins varied between 1.16 for SW6 and 1.82 for SW4.

Shape aspects

Elongation ratio (Re) is the ratio between the diameter of a circle of the same area as the basin to the maximum basin length (Adhikari, 2020). It's in the range (0-1); as the ratio approaches 1 the basin has a circular shape and as the ratio approaches 0, the basin has elongated shape. It's an indicator to basin relief; when the ratio close to 1, it means that the region is characterized by low relief, whereas that of 0.6 to 0.8 are associated with high relief and steep ground slope (Ahmed, 2017). The elongation ratio of the WAB varied from 0.41 (SW6) to 0.69 (SW2). Circularity ratio (Rc) is the ratio between the basin area to the circle area has the same perimeter as this basin (Kumar et al., 2016). It is a ratio that indicates how the basin is close to the circular shape, ranging 0-1; as the ratio approaches 1 the basin has circular shape and as the ratio approaches 0 the basin has elongated shape. Circular basins are characterized by the rapid arrival of surface runoff to low-rise areas leading to an increased the likelihood of flooding (Obeidat, Awawdeh, and Al-Hantouli, 2021). The Rc of the WAB sub-basins varied from 0.22 for SW7 to 0.43 for SW2. Basins with low values of shape factor indicate high relief and steep slopes which enhances flooding and experience larger peak flows of shorter duration, whereas basins with high values of shape factor experience lower peak flows of longer duration. The shape factor (Bs) refers to the ratio of the square of the basin length to the basin area. The shape factor varies from 2.72 for SW2 to 7.77 for SW6.

Relief aspects

Basin relief (H) is the difference in elevation between the lowest and the highest point on the basin. This high value of relief indicates low infiltration and high surface runoff. The relief of the WAB is 1124 m, and the relief of the WAB sub-basins ranged from 460 m for SW1 to 892 m for SW6. Relief ratio (Rr) is the ratio between basin relief and basin length. It's an indicator of the overall slope of watershed (Adhikari, 2020). The Rr of the WAB is 0.036, and it ranged from 0.037 for SW3 to 0.06 for SW2 the sub-basins.

Relative relief ratio (Rv) is a ratio between basin relief and basin perimeter. It has a direct relation with flooding. The Rv of the WAB is 0.01, and for the sub-basins it ranges from 0.01 to 0.02. Basin slope (Sw) has a direct relation with vulnerable to flooding. Basins with higher slopes are more vulnerable to flash floods. The Sw of the WAB is 2.18, while it ranged from 2.19 for SW3 to 3.57 for SW2 sub-basins.

Ruggedness number (Rn) is a direct relation between drainage density and maximum basin relief indicates the structural complexity of the terrain (Adhikari, 2020). Basins with high Rn values are highly susceptible to an increased peak discharge, so these basins are getting flooded even higher. The Rn of the WAB is 1.43, and ranges from 0.56 for SW1 to 1.11 for SW6 to the sub-basins.

Hypsometric parameters

Hypsometric (HI) is an indication of the cycle of erosion (Strahler, 1952). . It is used in identifying areas with high surface runoff, soil erosion, floods, and landslides. It can be divided into the three stages: old (HI<0.3), in which the watershed is stabilized, mature (HI=0.3 to 0.6), and young (HI>0.6), in which the watershed is highly susceptible to erosion. The HI of the WAB is 0.50, and almost the same value for all sub-basins i.e., all sub-basins have the same degree of susceptibility to flooding in according to this parameter.

Table 3 Morphometric parameters of the WAB.

	SW1	SW2	SW3	SW4	SW5	SW6	SW7	WAB
Mean stream length (Lsm)	0.76	0.65	0.96	0.86	0.84	1.06	0.97	0.90
Mean Stream length ratio (RL)	0.64	2.05	0.78	0.39	0.62	0.77	0.61	0.60
Mean bifurcation ratio (Rbm)	1.54	2.06	1.56	1.88	1.70	1.95	1.82	2.02
Drainage density (Dd)	1.25	1.33	1.32	1.56	1.25	1.24	1.14	1.27
Length of overland flow (L)	0.40	0.38	0.38	0.32	0.40	0.40	0.44	0.39
Stream frequency (Fs)	1.64	1.66	1.39	1.82	1.49	1.17	1.18	1.41
Elongation ratio (Re)	0.59	0.69	0.47	0.66	0.52	0.41	0.47	0.62
Circularity ratio (Rc)	0.41	0.43	0.27	0.33	0.35	0.23	0.22	0.37
Shape factor (Bs)	3.70	2.72	5.75	3.00	4.72	7.77	5.65	3.28
Basin relief (H)	0.46	0.53	0.47	0.57	0.50	0.89	0.73	1.12
Relief ratio (Rr)	0.04	0.06	0.04	0.06	0.04	0.04	0.04	0.04
Relative relief ratio (Rv)	0.01	0.02	0.01	0.02	0.01	0.02	0.01	0.01
Basin slope (Sw)	2.58	3.57	2.19	3.40	2.31	2.37	2.21	2.18
Ruggedness number (Rn)	0.58	0.71	0.61	0.89	0.62	1.11	0.83	1.43
Hypsometric integral (HI)	0.50	0.50	0.51	0.50	0.50	0.50	0.50	0.50

4.2 Flash floods prioritization

Prioritization of sub-basin is a significant method to water management and vulnerability assessment of a basin to flood. The flood risk parameters adopted for the prioritization were divided into two groups, the first group, consisting of (basin area, drainage density, stream frequency, circularity ratio, relief ratio, relative relief ration, basin slope, and ruggedness number) has a direct correlation with the increased risk of flash floods as their values increase as runoff increases and therefore the likelihood of flash floods becomes greater. Accordingly, the highest value was given the highest rank (5) and the lowest value was given the lowest rank (1). The second group, consisting of (length of overland flow, elongation ratio, shape factor, and the hypsometric integrals) has an inverse relationship with the increased risk of flash floods, whereby decreasing their values the surface runoff is increased and therefore the likelihood of flash floods becomes greater. Accordingly, the lowest value of these parameters was given the highest rank (5) and highest value was given the lowest rank (1). The total rank was determined for each sub-basin based on the computed morphometric parameters, which is normalized and classified into 5 categories of flash flooding potential (Table 4).

Table 4 Prioritization of sub-basins to flash flood.

Priority	Values
Very low	0–0.2
Low	0.2–0.4
Moderate	0.4-0.6
High	0.6-0.8
Very high	0.8-1

Table 5 Calculation of ranks for morphometric parameters and the total rank value for the sub-basins in the WAB for flash floods assessment

	A	Dd	Rn	Fs	Sw	Rc	Rv	Rr	L	Bs	Re	HI	Total Rank	Normalization value	Prioritized rank	Priority class
SW1	1	2	1	4	2	5	3	2	2	5	2	2	31	0.35	3	low
SW2	1	3	2	5	4	5	5	5	3	5	1	5	44	0.91	4	very high
SW3	1	3	1	2	1	2	1	1	3	3	4	1	23	0	1	very low
SW4	1	5	3	5	5	3	4	5	5	5	1	4	46	1	5	very high
SW5	1	2	1	3	1	4	2	1	2	4	3	3	27	0.17	2	very low
SW6	5	2	5	1	1	1	3	1	2	1	5	4	31	0.35	3	low
SW7	5	1	3	1	1	1	1	1	1	3	4	5	27	0.17	2	very low

It was found that there are only 3 categories of sub-basins susceptibility to flash flood (Table 5 and Figure 6). The sub-basins SW2 and SW4 were classified as having very high priority i.e., having a very high susceptibility to flash flood. Two sub-basins (SW1, SW6) were classified as low priority i.e., having a low susceptibility to flash flood, and 3 sub-basins (SW3, SW5, SW7) were classified as very low priority i.e., having a very low susceptibility to flash flood. The sub-basins SW2 and SW4 are characterized by short basin length with 5th-order streams. They are also characterized by low values of shape factor, and high values of stream lengths, bifurcation ratio, drainage density, stream frequency, elongation ratio and relief indices. Most factors indicate high relief, steep slopes, impermeable soil, and low infiltration, which enhances flooding. The dominant land covers in these sub-basins are crops and range land.

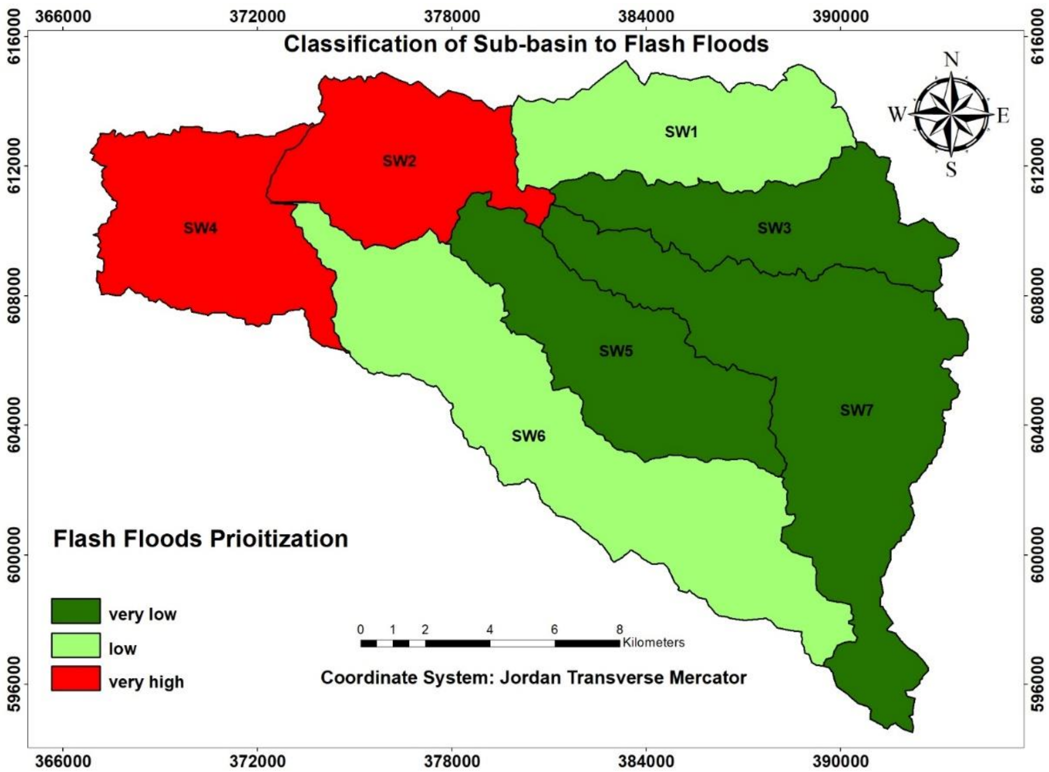

Fig. 6 Classification of Wadi Arab sub-basins vulnerability to flash flood.

Although, the results of this study are comparable to the findings of other studies with similar climatic conditions (Farhan and Anaba 2016; Farhan and Ayed, 2017); a record of historical flood events was not available for validation purposes. However, a study by WFP (2019) showed that the northern areas of ten districts among which Al Shuna Al Shmalyah are more susceptible to floods and therefore were classified as high level of flood hazard. According to CADRI (Capacity for Disaster Reduction Initiative) report, Irbid is one of the districts that is most vulnerable to flash floods. The study of Hyarat (2016) concluded that there are large areas prone to flood hazards which exceed the absorptive capacity of the main drainage channel flow in the basin that coincide with SW4.

5. Conclusions

Twenty-two morphometric parameters were calculated for 7 sub-basins in the Wadi Arab basin to assess its susceptibility to flooding. Out of the 7 sub-basins, two sub-basins (SW2 and SW4) were classified as a very high priority having high susceptibility of flash floods. The cumulative characteristics of several morphometric parameters for the sub-basins SW2 and SW4 are believed to be the driving factors for the high susceptibility to flash floods. These parameters include basin length, the high bifurcation ratio, drainage density, stream frequency, elongation ratio, shape factor, and relief indices. It is believed that the dominant carbonate lithology of the study area has played a major role in the basin morphometric characteristics of the WAB. These sub-basins need to be managed and seek solutions by the relevant government agencies to protect human lives and property as well as reduce the loss of agricultural land may be caused by flash floods. There are several possible solutions to mitigate the impact of floods in the Wadi Arab Basin. These include proper land use planning and restricting construction in areas prone to flooding, as well as regular cleaning of the Wadi al-Arab dam to reduce sediment accumulation, which increases the likelihood of flooding due to an increase in the dam's level of absorptive capacity. Additionally, promoting sustainable agriculture is important, as trees absorb water and reduce its flow.

Statements and Declarations

Competing Interests: The authors declare that they have no conflicts of interest (financial or non-financial).

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