

Geoinformatics application for assessing the morphometric characteristics' effect on hydrological response at watershed (case study of Wadi Qanunah, Saudi Arabia)

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Abstract This study deals with the evaluation and inundation of flash flood hazard in the ungauged Wadi Qanunah basin depending on detail morphometric characteristics of Qanunah basin and its sub-basins. Data for this study were depending on ASTER data for digital elevation model (DEM) with 30-m resolution, topographic map (1:50,000) and geological maps (1,250,000) which were verified during the fieldwork for evaluation of linear, areal, shape, and relief aspects of morphometric parameters. About 39 morphometric parameters were measured and calculated and interlinked to produce nine effective parameters to evaluate the flash flood hazard degree of the Wadi Qanunah basin. This study examined the physiographic features of the study basin with emphasis on their implication for hydrologic processes through the integration analysis between physiographic features and geographical information system (GIS) techniques. Wadi Qanunah basin was classified into 13 sub-basins, and according to their hazards degree, it is classified into three groups: basins of high hazard degree as for Wadi Qanunah sub-basin, basins of medium hazard degree as for Wadi Al Hafyan and Baydan 1 sub-basins, and basins of low hazard degree as for the rest of the sub-basins. Watershed Modeling System (WMS) and Hydrologic Engineering Center-Hydrologic Modeling System software (HEC-HMS) were applied to generate the hydrograph of the two main sub-basins of Wadi Qanunah and Wadi Khatm Al Jurrah. The results of the model for maximum daily rainfall events of a total of 65,

79, 97, 110, and 123 mm with return periods of 5, 10, 25, 50, and 100 years, respectively. Total volume of discharge of Wadi Qanunah sub-basins ranges from 66×10^6 to 138×10^6 m³, while for Wadi Khatm Al Jurrah sub-basin, it ranges from 11×10^6 to 24×10^6 m³ at return periods from 5 to 10 years, respectively.

Keywords Hydrology · Basin · Wadi · Flash flood · Runoff · Hazard · Morphometric · Modeling

Introduction

Mapping of flash flood hazard and inundation is very important for the watershed managements (i.e., for the sustainable development of the water resources and for the protection from the flood hazard and drought). Rainfall and runoff data are of the main hydrological elements in the flood mapping of basin systems. So, according to the study, area is suffering from the scarcity of data and the flood inundation maps are dependent on the topographic and geomorphic features of a Wadi (Şen et al. 2013), so this study is based on the integration between physiographic features of the study area and geographical information system (GIS) techniques.

According to Ward and Robinson (2000), flooding results from climatological events such as excessive and/or prolonged precipitation including cloud burst and failure of dams. Floods can be controlled by basin characteristics or with drainage network. Gardiner (1981) reported that there are a number of controlling factors that can affect the process of flooding; these factors can be physical or human or both. Chow (1964), Strahler (1964), Ward and Robinson (2000), and Hudson and Colditz (2003) summarized that similarly, morphometric parameters such as stream order, drainage density, stream frequency, channel slope, relief, length of overland

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flow, and other geomorphological aspects of basin system are very important to study and understand the hydrology of the basin system.

Barry and Chorley (1998) and Ward and Robinson (2000) concluded that the surface runoff response of the catchment is different according to slopes, shapes, lengths, widths, and areas of basins. Physiographic features such as land cover, soil, and geology that have significant effect upon the characteristics of the watershed hydrograph need to be considered for studying the flood behavior. This is largely influenced by the permeability and water storage of the watershed.

Watershed characteristics in many areas of the world have been studied using conventional geomorphologic aspects (Horton 1945; Strahler 1964; Rudriaih et al. 2008; Nageswararao et al. 2010; Al Saud 2009). Gardiner (1990) reported that in some studies, the morphometric parameters of watershed have been used for prediction and describing the flood peaks and estimation of erosion rate, underlying the importance of such studies.

Application of geomorphological aspects to flood potential or flood hazard has led to noteworthy amount of researchers, attempting to identify the relationships between watershed characteristics and flood impact (Patton 1988). Determination of drainage basin networks can be achieved using traditional methods such as field observations and topographic maps or alternatively with advanced methods using remote sensing and digital elevation models (Macka 2001; Maidment 2002; Masoud 2014; El Osta and Masoud 2015).

Flash floods often occur in arid regions as a consequence of excessive rainfall which occasionally causes major loss of property and life (Subyani 2009). Wadi Qanunah basin which belongs to arid regions is suffering from the scarcity of hydrological data, and the flood inundation maps are depending upon the topographic and geomorphic features of the study Wadis (Şen et al. 2013). Flood hazard mapping is a needful component to appropriate land use in the flooded areas. It creates easily read, rapidly accessible chart and maps which mitigate their effect (Bapalu and Sinha 2005). Flood hazard inundation and mapping in arid regions is an extremely important but difficult task; the main reason is the scarcity of data in arid regions. So, integration of GIS and physiographic features to create flood hazard maps and disaster decision support has been continually upgraded and widespread since beginning of twenty-first century, as a result of the increased availability of spatial databases and GIS software (Zerger and Smith 2003). Several studies were cited in the literature, relating to flood hazard mapping and zonation using GIS (Sui and Maggio 1999; Merzi and Aktas 2000; Guzzetti and Tonelli 2004; Sanyal and Lu 2006; He et al. 2003; Fernadez and Lutz 2010).

So, this study aims flash flood risk assessment depending on the integration between morphometric and physiographic

features, GIS, and hydrologic software such as Watershed Modeling System (WMS), Hydrologic Engineering Center for Hydrologic Modeling System and for River Analysis System (HEC-HMS and HEC-RAS respectively) for mapping of flash flood inundation to protect the urban and cultivated areas and to plan rainwater harvesting and watershed management in the flash flood alert zones.

Location, geomorphology, and geology of Wadi Qanunah basin

Location

Wadi Qanunah basin covers a large area of the southwestern region of Al Qunfudah governorate in Saudi Arabia, and it originates from the Red Sea Escarpment directed toward the Red Sea Coast. It extends from NE to SW with 2393.7 km² area, and it is located between longitudes 41° 05' and 41° 55' E and latitudes 19° 05' and 19° 50' N as shown in Fig. 1.

Geomorphology

Geomorphology of Wadi Qanunah basin shows a typical Wadi system, which starts from eastern high mountainous slopes of the escarpment and decreases down to the west of flat sediments of the Tihama coastal plain close to the Red Sea. The elevation of the Wadi Qanunah basin ranges from 0 to 2378 m with mean elevation 586 m (above mean sea level (amsl)) as shown in Figs. 1 and 2. The elevation area of 0–200 m (amsl) is about 21 % of the total area which equals nearly the area of Quaternary and Tertiary deposits at the Delta. About 60 % of the total area has elevation ranges from 0 to 650 m (amsl) with the sub-basins of low hazard degree, while 40 % of the total area has elevation ranges from 650 to 2378 m (amsl) with the sub-basins of moderate to high hazard degree. Wadi Qanunah basin and its surrounding areas exhibit different geomorphologic units (Figs. 1 and 2) as follows:

High mountainous

Area is composed essentially of Precambrian rocks with high elevation values that reach to 2300 m (amsl) as shown in Figs. 1 and 2 which is representing the main catchment of the Wadi. The high mountainous area of the study area plays an important role in the rainfall intensity. The high mountainous area with their orographic effect prompts the atmospheric convection that plays as heat raps to cause low level atmospheric convergence which finally produces different intensities of rainfall.

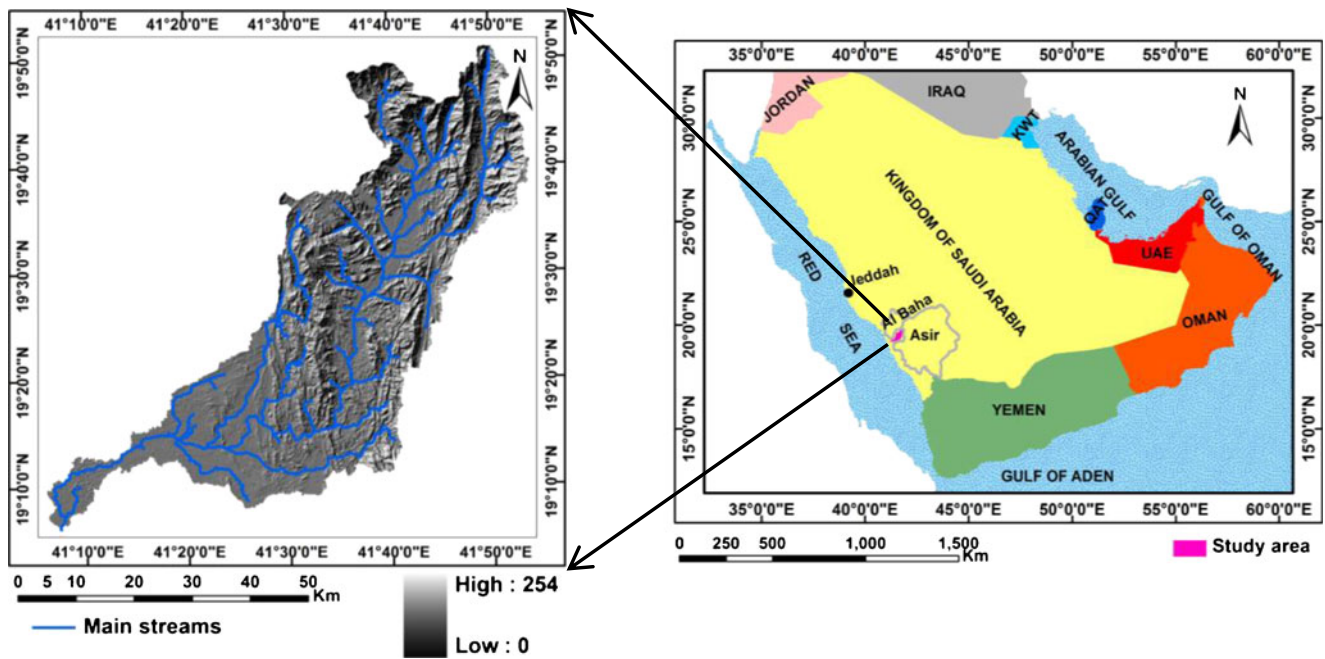


Fig. 1 Location map of Wadi Qanunah basin and its hillshade map

Hilly area

The hilly area occupies the northeastern and middle parts of the Wadi. This area is composed of hilly dissected and weathered zone as shown in Figs. 1 and 2.

Pediment plain

The Piedmont plain occupies the low land area between the mountainous area and the Red Sea. It comprises morphotectonic depressions and main channel of the Wadi.

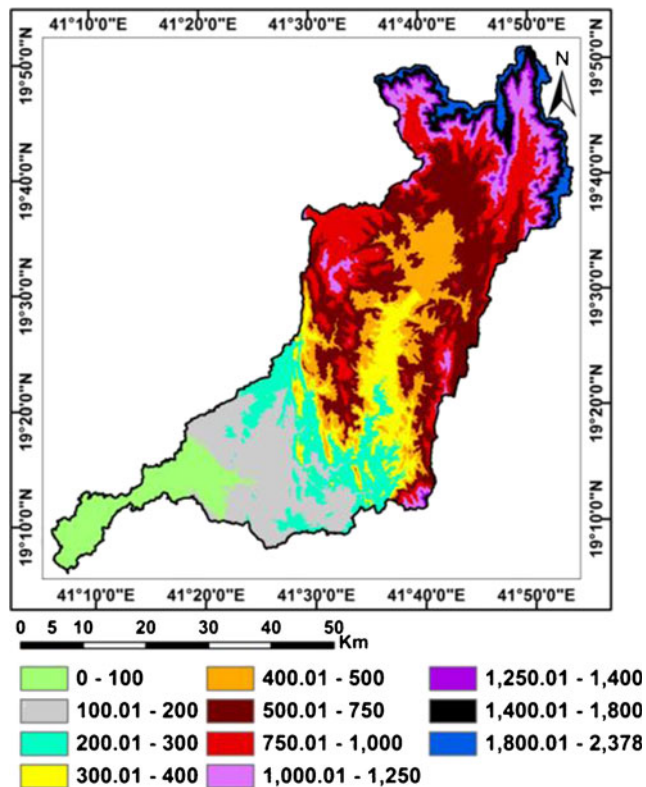


Fig. 2 Digital elevation map (DEM) of Wadi Qanunah basin

Geology

Geologically, according to Prinz (1983) and Greenwood (1975a, b), the study area is located within the geologic complex of the Arabian Shield in the southwestern region of Saudi Arabia. Throughout this geologic period, this area has been affected with long and complicated geological structures as shown in Fig. 3 and geomorphological changes. Sequence lithology of the study basin ranges from Precambrian, Tertiary to Quaternary as follows:

Precambrian rocks

According to Greenwood (1975a, b), the Precambrian rocks include three groups of Baysh group which consists of mafic and pyroclastic rocks: Baha group which is composed of volcanic, clastic, and sedimentary rocks while Jeddah group consists of volcanic andesite and basalt and Ablah group which consists of sedimentary beds that are unconformable overlying the Baysh, Baha, and Jeddah groups.

Tertiary rocks

Tertiary rocks are restricted to the western part of the study Wadi, covering small area about 2 % of the total area. Tertiary

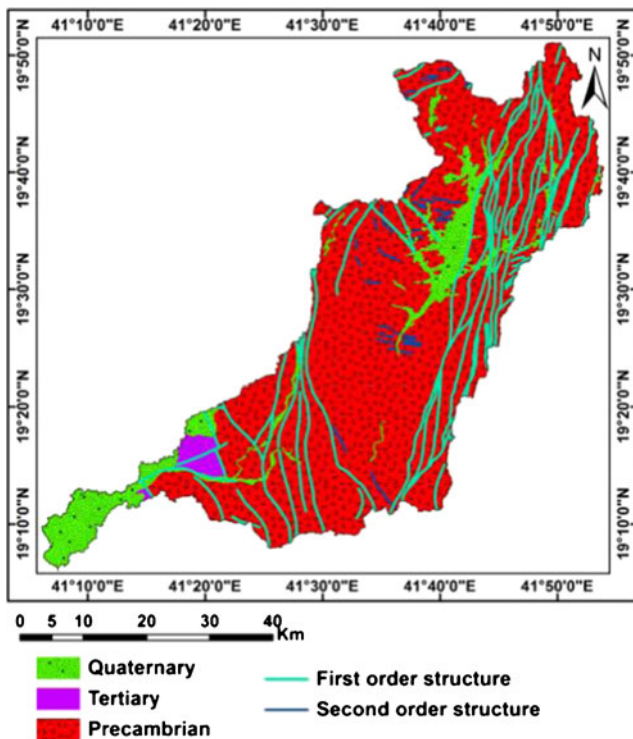


Fig. 3 Geological map of Wadi Qanunah basin

rocks are composed of Baid formation (sandstone, limestone, and chert), gabbro dikes, leucogranite, and Bathan formation (conglomerates and sandstone).

Quaternary deposits

It composed mainly of gravel, sand, silt, and Sabkha deposits and occupies the coastal plain and Wadi channels with an area of 12 % of the total area.

Rainfall distribution in the study area

Due to the scarcity of detailed scientific analysis of rainfall data in the literature for flash flood risk evaluation and inundation in arid zone, this study suggests a systematic approach to analyze rainfall data in arid basins for flood evaluation and inundation. The results will be linked with rainfall–runoff modeling for runoff potential estimation in the study basins.

Methodology of rainfall distribution

The methodical approach presented in this section is ordered according to the following steps:

1. Creating map for spatial distribution of average annual rainfall based on 14 rainfall stations.
2. Daily rainfall data is collected from available three stations in the study area.

3. Frequency analysis is applied to maximum daily rainfall depths to estimate the return period and probability.
4. The common probability distribution functions for extreme values are fitted to the data using distribution analysis module in Stormwater Management and Design Aid (SMADA 6) software.
5. The best probability distribution function is selected based on the root mean square error (RMSE) criterion.
6. Using the predicted maximum daily rainfall from the previous steps for generating the hydrographs and estimating the inundation areas at different return periods.

Data from rainfall stations surrounding the study area were used to develop the annual average rainfall contour maps. The analyses and diagnostic tests regarding these stations have been performed. One of these analyses is the frequency analysis for each individual station as well as regional spatial analysis. The available daily rainfall records contain data for about 15 to 40 years from three stations. For flood assessment, statistical analysis has been performed on the maximum daily rainfall values, and then, various probability distributions and tests were used to obtain estimated rainfall depths corresponding to different return periods. Several different frequency distributions were fitted to the rainfall data at the stations to obtain the best distribution that well represents the data for each station. In this study, evaluated distributions are normal, Gumbel, two-parameter log normal, three-parameter log normal, Pearson type III, and log Pearson type III). SMADA6 program was used to perform these tests. However, the best distribution is chosen based on the RMSE criterion (Chow et al. 1988) given by

$$\text{RMSE} = \sqrt{\frac{1}{n} \sum_{i=1}^n [\hat{R}_i - R_i]^2} \quad (1)$$

where R_i is the observed rainfall depth at the station, \hat{R}_i is the expected rainfall depth from the probability distribution, and n is the number of data points at the station.

RMSE values for the various cases describe the average discrepancy between the expected and the observed values.

Results and discussion of rainfall distribution

In the Wadi Qanunah basin and its surroundings, 14 rainfall stations of annual data and 3 stations of daily data have been collected to generate the isohyetal map of the average annual rainfall which shows the spatial distribution of the rainfall as shown in Fig. 4. It is obvious from this figure that the average rainfall ranges from 100 to 400 mm. The reason behind this variation is that the upper mountainous area of the Wadis

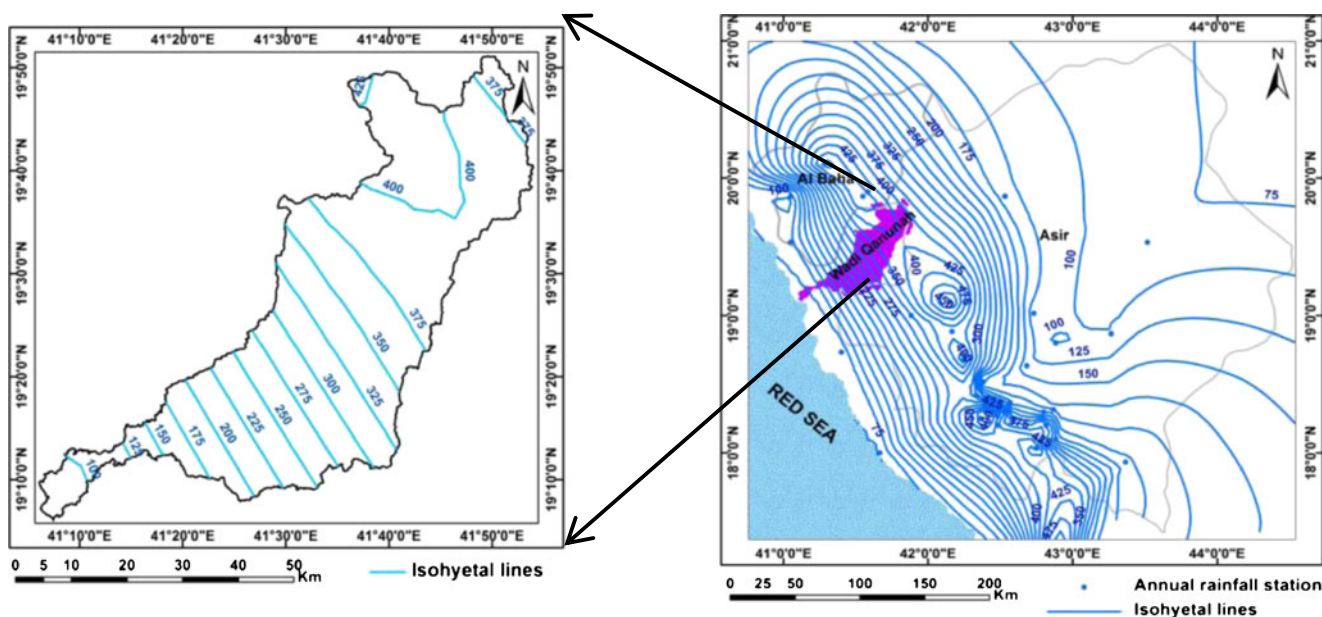


Fig. 4 Spatial distribution of mean annual rainfall of the study basin and its surroundings

always receives higher amount of rainfall, while the lower area at the Wadis outlet receives less rainfall.

Table 1 shows the best distribution based on the minimum RMSE as shown by the highlighted cells in the Table 1 where the fitting distribution for the station (243 J127) is Gumbel type 1 but for the other stations are fitting with three-parameter log normal. Results from abovementioned analysis are presented in Fig. 5. This figure shows the graphical representation of the rainfall depth at different return periods for the temporal analysis of rainfall data at the stations (based on the best probability distribution) as shown in Table 2.

Morphometric characteristics of the study basin

Study of ungauged basin is morphometrically evaluated to determine the flash flood prone areas based on the integration between morphometric parameters and GIS techniques. Data

Table 1 Root mean square error of the rainfall stations at Wadi Qanunah

Distribution type	Stations		
	243 J127	520 SA 120	953 B009
Normal	4.18	6.34	8.60
Two-parameter log normal	3.33	4.18	5.25
Three-parameter log normal	3.36	4.08	5.20
Pearson type III	18.80	4.11	5.24
Log Pearson type III	12.71	4.15	5.30
Gumbel type I	3.03	4.33	5.71

for this study were obtained from ASTER data for digital elevation model (DEM) with 30-m resolution, topographic map (1:50,000) and geological maps (1,250,000) which were checked during the fieldwork.

Methodology of morphometric analysis

Morphometric analysis of the Wadi Qanunah basin and its sub-basins is essentially based on the geomorphological features and morphometric parameters. These analyses have been carried out based on hydrology model of spatial analyst module of Arc GIS 10. ASTER data were used for preparing DEM, and GIS was used in the evaluation of drainage network, basin geometry, drainage texture, and basin relief characteristics of morphometric parameters.

The major parameters such as watershed boundary, flow accumulation, flow direction, flow length, and stream ordering are prepared using the Arc Hydro Tool. Surface Tool in ArcGIS-10 software and ASTER (DEM) was used to create different thematic maps such as DEM, contour, slope aspect, and hill shade maps. Tracing the drainage network and water divide of Wadi Qanunah basin and its sub-basins is automatically extracted from DEM of SRTM with 30-m resolution.

Results and discussions of morphometric analysis

Thirty-eight morphometric parameters of Wadi Qanunah basin and its sub-basins were measured and calculated based on several authors as shown in Table 3 (El Bastawesy et al. 2013; Masoud 2014). Morphometric characteristics of the study basin and its sub-basins were classified into four classes as shown in Tables 3 and 4 as follows: drainage network

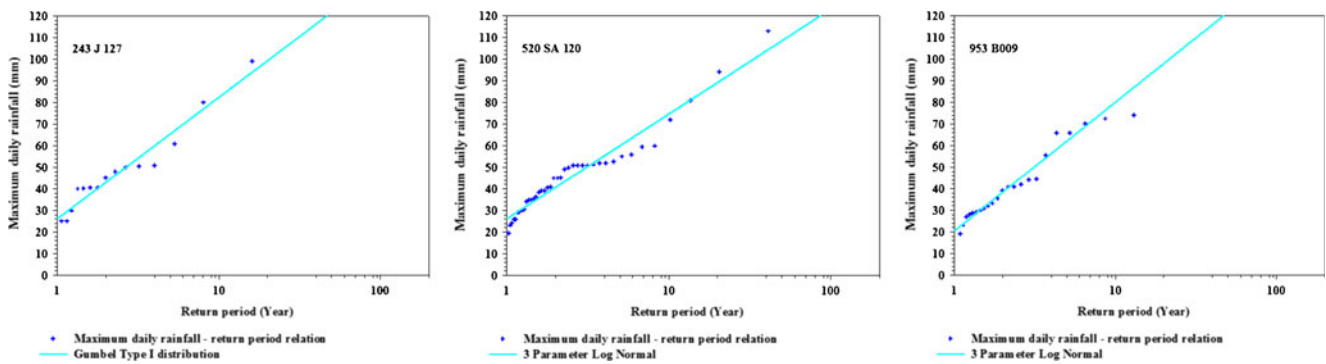


Fig. 5 Graphical representation of maximum daily rainfall at different return periods for the temporal analysis of rainfall data at the stations based on the Gumbel type I and three-parameter log normal probability distribution

characteristics, basin geometry characteristics, drainage texture characteristics, and basin relief characteristics.

Drainage network characteristics

The stream order of the Wadi Qanunah basin is seventh order, while for the sub-basins, it ranges from fourth at sub-basin 13 to sixth for Qanunah and Al Hafyan sub-basins (Table 4 and Fig. 6). It has observed that the maximum frequency is in the case of first-order streams and there is a decrease in stream frequency as the stream order increases. The total stream length of the Wadi Qanunah is 5406.8 km, and for its sub-basins, it ranges between 91.1 km of Khatm Al Jurrah3 sub-basin to 981 km of Qanunah sub-basin. The relationship between stream order, stream number, and stream length for Wadi Qanunah basin shows a perfect negative correlation with coefficient of correlation of about 0.99 (Fig. 7). This means that the stream numbers and stream lengths increase with decrease of stream order.

In Wadi Qanunah basin and its sub-basins, both bifurcation ratio (Rb) and weighted mean bifurcation ratio (WMRb) have closed high values more than 4; this means a strong structural control on the drainage pattern. This limited variation may be attributed to lithology where the study basins have little lithological variation. The main channel length has been computed by using ArcGIS-10 software, and it is about 115.7 km for Wadi Qanunah sub-basin. It ranges from 0.8 km of Khatm Al Jurrah3 sub-basin to 36.5 km of Shisha1 sub-basin. This wide range is due to variation due of the structural control or due to

intensity of runoff events and lithology. The main channel index of Wadi Qanunah basin and its sub-basins has limited variation and ranges from 1.14 at Khatm Al Jurrah3 sub-basin to 1.54 at Al Hazim sub-basin. The sinuosity of the study basin and its sub-basin ranges from 0.09 at Khatm Al Jurrah3 sub-basin to 1.16 at Shisha1 sub-basin. This reflects that Khatm Al Jurrah3 sub-basin has the shortest travel time of water flow to the outlet, while Shisha1 sub-basin has the longest travel time with good chance for groundwater recharge.

Rho coefficient (ρ) is an important parameter relating drainage density to physiographic development of a hydrographic basin which facilitates evaluation of water storage capacity of drainage network and hence a determinant of ultimate degree of drainage development in a given watershed (Horton 1945). Low values of Rho indicate low capacity for storage of water, while high values of Rho indicate high capacity of storage of water. The climatic, geologic, geomorphologic, and anthropogenic factors determine the changes in this parameter (Pareta and Pareta 2011a). Rho values of the study basins show limited variation and ranges from 0.36 of sub-basin 13 to 1.33 of Khatm Al Jurah3 sub-basin as shown in Table 4.

Basin geometry characteristics

Wadi Qanunah basin has a large basin area of 2393.7 km², while the areas of its sub-basins were classified by size into three categories: small basins (0–50 km²), medium basin (50–100 km²), and large basins (>100 km²) as shown in Table 4. Length of the Wadi Qanunah basin is 117.2 km, while for the

Table 2 Prediction (millimeter) for distributions of selected return periods (in years) based on duration data

Rainfall station no.	Probability Return period (years)	0.80 5	0.90 10	0.96 25	0.98 50	0.99 100
243 J127		67.04	81.23	99.16	112.46	125.66
250 SA 120		59.12	70.55	85.38	96.67	108.16
953 B009		69.65	84.87	104.86	120.27	136.07
Average of rainfall (mm)		65.30	78.80	96.50	109.80	123.3

Table 3 Morphometric parameter formulas

Morphometric parameters		Formula	Reference	
Drainage network	1	Stream order (N_u)	Hierarchical rank	Horton (1945), Strahler (1952, 1964))
	2	Stream number (N_u)	$N_u = N_1 + N_2 + N_3 + \dots + N_n$	Strahler (1952)
	3	Stream length (L_u)	$L_u = L_1 + L_2 + \dots + L_n$	Horton (1932)
	4	Bifurcation ratio (Rb)	$Rb = N_u / N_{u+1}$	Horton (1945) and Strahler (1964)
	5	Weighted mean bifurcation ratio (WMRb)	$WMRb = \frac{\sum(Rb_u / Rb_u + 1)(N_u + N_{u+1})}{\sum N}$	Strahler (1953)
	6	Main channel length	GIS software analysis	
	7	Main channel index (C_i)	$C_i = (\text{main channel length}) / (\text{maximum straight of the main channel})$	Mueller (1968)
	8	Sinuosity (S_i)	$S_i = VL / LB$	Gregory and Walling (1973)
	9	Rho coefficient (ρ)	$\rho = L_{ur} / Rb$	Horton (1945)
Basin geometry	10	Watershed area (A)	GIS software analysis	Schumm (1956)
	11	The basin length (LB)	GIS software analysis	Schumm (1956)
	12	The basin perimeter (Pr)	GIS software analysis	Schumm (1956)
	13	Basin width (W)	$W = A / LB$ (km)	Horton (1932)
	14	Circularity ratio (Rc)	$Rc = 4\pi A / Pr^2$	Miller (1953)
	15	Elongation ratio (Re)	$Re = (2\sqrt{A/\pi}) / LB$	Schumm 1956
	16	Texture ratio (Rt)	$Rt = \sum N_u / Pr$	Horton (1945)
	17	Form factor ratio (FFR)	$FFR = A / LB^2$	Horton (1932)
	18	Inverse shape form (Sv) or shape factor ratio (Sf)	$Sv = LB^2 / A$	Horton (1932)
	19	Basin shape index (Ish)	$Ish = 1.27A / LB^2$	Haggett 1965
	20	Compactness ratio (S_H)	$SH = Pr / 2(\sqrt{\pi A})$	Horton (1945)
Drainage texture	21	Fitness ratio (Fr)	Fr = channel length / perimeter	Melton (1957)
	22	Lemniscate shape (Ls)	$Le = (3.14)(BL)^2 / (4A)$	Chorley et al. (1957)
	23	Stream frequency (F)	$F = \sum_{i=1}^K N_u / A$	Horton (1932 and 1945)
	24	Drainage density (D)	$D = \sum Lu / A$	Horton (1932 and 1945)
	25	Drainage intensity (Di)	$Di = F / D$	Faniran (1968)
	26	Length of overland flow (Lo)	$Lo = 1/2D$	Horton 1945
	27	Infiltration number (FN)	$FN = (F)(D)$	Faniran (1968)
Relief characterizes	28	Drainage pattern (Dp)	Stream network using GIS software analysis	Horton (1932)
	29	Maximum elevation (H_{max})	GIS software analysis using DEM	
	30	Minimum elevation (H_{min})	GIS software analysis using DEM	
	31	Relief (Rf)	Rf = highest elevation – lowest elevation	Strahler (1952)
	32	Internal relief (E)	$E = (E_{85} - E_{10})$	Strahler (1952)
	33	Mean elevation (Hm)	GIS software analysis using DEM	
	34	Relief ratio (Rr)	$Rr = (Rf / LB) 100$	Schumm (1956)
	35	Slope index (SI %)	$SI = (E / 0.75VL) 100$	Majure and Soenksen (1991)
	36	Mean basin slope (Sm)	GIS software analysis using DEM	
	37	Ruggedness number (Rn)	$Rn = Rf \cdot D$	Melton (1957)
	38	Hypsometric integral (HI)	$HI = (Elev - Elev_{min}) / (Elev_{max} - Elev_{min})$ Elev is the mean elevation, Elev _{max} is the maximum elevation, and Elev _{min} is the minimum elevation,	Strahler (1952)

Table 4 Morphometric parameters and hazard degree of the study basins

Morphometric parameters		Qanunah basin													
		Whole basin													
		Name of sub-basins													
		1	2	3	4	5	6	7	8	9	10	11	12	13	
Drainage network	1 (U_n)	7.00	6.00	6.00	5.00	5.00	5.00	6.00	5.00	5.00	5.00	5.00	5.00	4.00	
	2 ($N_{(n)}$)	9644.00	1686.00	1227.00	336.00	270.00	391.00	242.00	1042.00	246.00	128.00	736.00	316.00	185.00	
	3 (L_n)	5406.80	981.90	707.80	190.40	166.00	232.90	151.10	582.40	145.90	91.10	454.00	204.20	108.30	
	4 (Rb)	4.52	4.21	4.15	4.10	4.100	4.66	3.91	4.00	3.96	3.27	5.00	4.28	4.10	
	5 (WMRb)	3.86	4.17	4.43	4.60	5.00	4.35	4.39	4.63	4.43	4.13	4.61	4.14	4.20	
	6 (MC)	115.70	22.10	30.00	10.00	4.30	9.60	11.20	31.80	16.20	0.80	36.50	5.30	17.20	
	7 (MCI)	1.53	1.22	1.33	1.18	1.54	1.17	1.46	1.30	1.41	1.14	1.33	1.29	1.46	
	8 (Si)	0.99	0.80	0.71	0.61	0.37	0.87	0.93	0.66	0.88	0.09	1.16	0.28	0.98	
	9 (ρ)	0.40	0.44	0.42	0.46	0.56	0.43	0.56	0.46	0.47	1.33	0.70	0.53	0.45	
	Basin geometry	10 (A)	2393.70	431.40	315.30	90.70	78.20	103.40	74.80	261.20	60.30	36.90	203.40	80.10	51.30
		11 (LB)	117.20	28.00	42.00	16.50	11.60	11.00	12.00	48.40	18.50	8.90	31.50	19.20	13.30
		12 (Pr)	509.30	145.30	157.00	75.50	61.40	90.20	58.40	180.60	78.70	39.90	131.30	79.20	53.30
		13 (W)	20.40	15.40	7.50	5.50	6.70	9.40	6.20	5.40	3.26	4.15	6.50	4.20	3.90
		14 (Rc)	0.12	0.26	0.16	0.20	0.26	0.16	0.28	0.10	0.12	0.29	0.15	0.16	0.22
		15 (Re)	0.47	0.84	0.48	0.65	0.86	1.00	0.81	0.38	0.47	0.77	0.51	0.53	0.61
		16 (Rt)	18.94	11.60	7.82	4.45	4.40	4.33	4.14	5.80	3.13	3.21	5.61	3.99	0.48
		17 (FFR)	0.17	0.55	0.18	0.33	0.58	0.85	0.52	0.11	0.18	0.47	0.21	0.22	0.29
18 (Sv) or (Sf)		5.74	1.82	5.60	3.00	1.72	1.17	1.93	9.00	5.70	2.15	4.90	4.60	3.45	
19 (Ish)		0.22	0.70	0.23	0.42	0.74	1.08	0.66	0.14	0.22	0.59	0.26	0.28	0.37	
Drainage texture	20 (S_H)	2.94	1.97	2.50	2.24	1.96	2.50	1.90	3.15	2.86	1.85	2.60	2.50	2.10	
	21 (Fr)	0.23	0.15	0.19	0.13	0.07	0.11	0.19	0.18	0.21	0.02	0.28	0.07	0.24	
	22 (Ls)	4.50	1.43	4.40	2.36	1.35	0.92	1.51	7.00	4.46	1.69	3.83	3.61	2.71	
	23 (F)	4.03	3.91	3.89	3.70	3.45	3.78	3.24	3.99	4.10	3.47	3.62	3.95	3.61	
	24 (D)	2.26	2.28	2.25	2.10	2.12	2.25	2.02	2.22	2.42	2.47	2.23	2.55	2.22	
	25 (Dt)	1.78	1.72	1.73	1.77	1.63	1.68	1.60	1.79	1.69	1.41	1.62	1.55	1.72	
	26 (Lo)	0.22	0.22	0.22	0.24	0.24	0.22	0.25	0.22	0.21	0.20	0.22	0.20	0.23	
	27 (FN)	9.10	8.90	8.70	7.78	7.33	8.52	6.54	8.90	9.90	8.60	8.10	10.10	8.49	
	28 (Dp)	Dendritic	Dendritic	Dendritic	Dendritic	Dendritic	Dendritic	Dendritic	Dendritic	Dendritic	Dendritic	Dendritic	Dendritic	Dendritic	
	Relief characterizes	29 H_{max}	2378.00	2050.00	2000.00	950.00	1100.00	900.00	1050.00	900.00	250.00	200.00	1500.00	200.00	950.00
30 H_{min}		0.00	450.00	450.00	450.00	400.00	400.00	300.00	100.00	100.00	50.00	100.00	100.00	250.00	
31 (Rf)		2378.00	1600.00	1550.00	500.00	700.00	500.00	750.00	800.00	150.00	150.00	1400.00	100.00	700.00	
32 (E)		800.00	1250.00	700.00	350.00	450.00	300.00	400.00	650.00	100.00	75.00	375.00	60.00	325.00	

Table 4 (continued)

Morphometric parameters		Qanunah basin												
		Whole basin												
		Name of sub-basins												
		1	2	3	4	5	6	7	8	9	10	11	12	13
33 (Hm)		586.00	916.00	1132.00	669.00	629.00	609.00	515.00	162.30	123.40	311.00	133.00	366.00	412.00
34 (Rr)		0.02	0.057	0.037	0.030	0.045	0.063	0.017	0.008	0.017	0.044	0.005	0.046	0.053
35 (SI %)		0.009	0.075	0.031	0.047	0.042	0.048	0.027	0.008	0.125	0.014	0.015	0.025	0.032
36 (Sm)		11.80°	16.00°	18.40°	13.70°	13.50°	15.60°	10.60°	2.90°	2.80°	9.00°	2.60°	10.20°	11.70°
37 (Rn)		5.20	3.64	3.48	1.05	1.13	1.52	1.78	0.36	0.37	3.13	0.26	1.78	1.48
38 (HI)		0.26	0.29	0.44	0.44	0.46	0.41	0.52	0.42	0.49	0.15	0.33	0.27	0.23
Summation of hazard degree			37.91	28.95	20.60	27.12	22.43	23.09	20.50	24.89	24.46	22.77	23.54	19.13
Hazard degree		5	5	3	2	3	1	2	1	2	2	2	2	1

1 Wadi Qanunah sub-basin, 2 Wadi Al Hafyan, 3 Wadi Ad Daymirah, 4 Wadi Al Hazim, 5 Wadi Baydan 1, 6 Wadi Baydan 2, 7 Wadi Khatm Al Jurrah1, 8 Wadi Khatm Al Jurrah2, 9 Wadi Khatm Al Jurrah1, 10 Wadi Shisha1, 11 Wadi Shisha 2, 12 Wadi Usbutah, 13 sub-basin 13

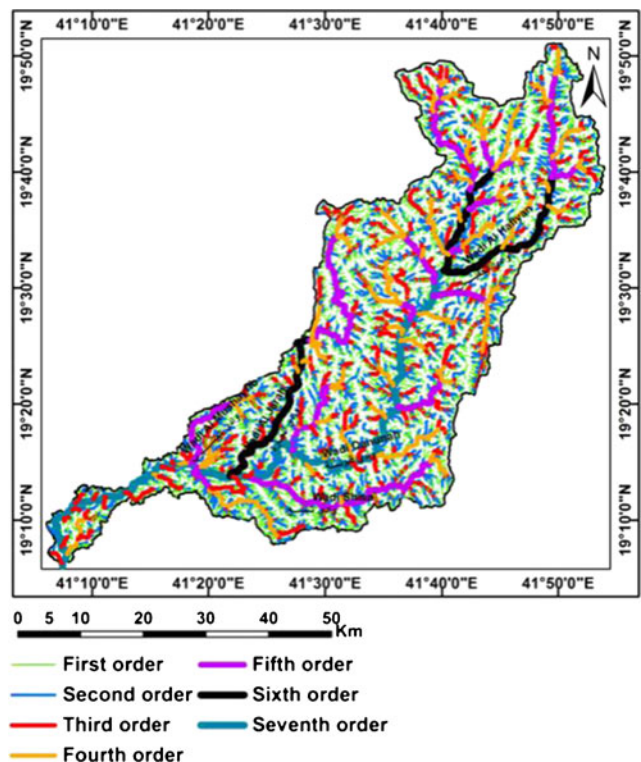
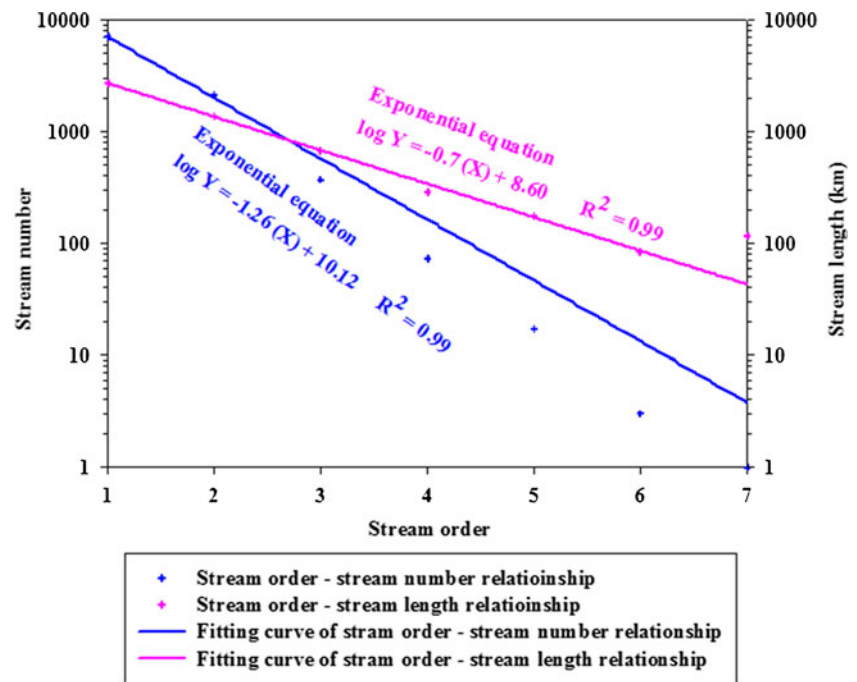


Fig. 6 Stream order of Wadi Qanunah basin

sub-basins, it ranges from 8.9 km of Khatm Al Jurrah3 sub-basin to 48 km of Khatm Al Jurrah1 sub-basin. The travel time of Khatm Al Jurrah1 sub-basin is the greatest one which gives good chance for groundwater recharge than the shortest travel time of Khatm Al Jurrah3 sub-basin. The perimeter of Wadi Qanunah sub-basin is 509.3 km, while for its sub-basins, it ranges from 39.9 km of Khatm Al Jurrah3 sub-basin to 180.6 km of Khatm Al Jurrah1 sub-basin as shown in Table 4. The basin width of the Wadi Qanunah basin is 20.4 km, while for its sub-basin, it ranges from 3.26 km for Khatm Al Jurrah2 sub-basin to 15.4 km for Qanunah sub-basin. The small values of the basin width indicate elongated shape which leads to groundwater recharge more than larger values.

The calculated values of the circularity ratio for Wadi Qanunah basin and its sub-basin show limited variations and range from 0.10 for Khatm Al Jurrah1 sub-basin to 0.29 for Khatm Al Jurrah3 sub-basin (Table 4), which indicates elongated shape with good potentiality of groundwater recharge. Elongation ratio shows a wide variation due to lithology and geologic structures. It ranges from 0.38 for Khatm Al Jurrah1 sub-basin to 1 for Baydan 1 sub-basin. These values are low to high which reflect their low to medium hazard degree and indicate elongated shape. According to Horton (1945), the texture ratio (Rt) of Wadi Qanunah basin is 18.94 km⁻¹, while for its sub-basins, it ranges from 3.13 km⁻¹ for Khatm Al Jurrah2 sub-basin to 11.6 km⁻¹ for Qanunah sub-basin. Smith (1958) classified the texture ratio of the basins into

Fig. 7 Relationship between stream order, stream number, and stream length of the study basin



coarse ($<6.4 \text{ km}^{-1}$), intermediate ($6.4\text{--}16 \text{ km}^{-1}$), and fine ($>16 \text{ km}^{-1}$). Table 4 shows that the Wadi Qanunah basin is fine texture, but Qanunah and Al Hafyan sub-basins are intermediate, while the rest of sub-basins are coarse texture. According to Schumm (1965), texture ratio is an important factor in the drainage morphometric analysis which depends on the underlying lithology, infiltration capacity, and relief aspect of the terrain. The similarity of the texture ratios of the study sub-basins is due to the similarity of their lithology and geologic structure. The lower values of texture ratio indicate that the basin has a good chance for groundwater recharge, while the basins of higher values, where they are composed of hard rocks that have no ability for water infiltration, have a good chance to produce flash flood (Pareta and Pareta 2011a).

According to Horton (1932), the form factor ratio (FFR) is defined as a numerical index that shows shape of the basin, and its value ranges from 0.1 to 0.8. Table 4 shows that the values of FFR of the study basin and its sub-basins have a wide variation and range from 0.11 of Khatm Al Jurrah1 sub-basin to 0.85 of Baydan 1 sub-basin, while the FFR of the whole Wadi Qanunah sub-basin is about 0.17. Basins of low value of form factor are more elongated, less intense rainfall simultaneously, and also have lower peak runoff of longer duration over its entire area than an area of equal size with a large form factor (Gupta 1999). The basins with high values of form factor have a high peak runoff of longer duration. According to Gregory and Walling (1985), the form factor is the governing factor of the water courses which enter the main streams.

The calculated value of the inverse shape form S_v for Wadi Qanunah basin, and its sub-basin ranges from 1.17 for Baydan 1 sub-basin to 9.0 for Khatm Al Jurrah1 sub-basin. The higher value indicates that the basin length is high which results in a good chance for groundwater recharge, while lower values result in more flash flood hazard. The calculated value of basin shape index (Ish) for Wadi Qanunah basin and its sub-basin ranges from 0.14 for Khatm Al Jurrah1 sub-basin to 1.08 for Baydan 1 sub-basin. The higher value indicates long basin length which results in a good chance for groundwater recharge, while the lower values result in more flash flood hazard. The value of compactness ratio (S_H) for Qanunah basin and its sub-basin ranges from 1.85 for Khatm Al Jurrah3 sub-basin to 3.15 for Khatm Al Jurrah1 sub-basin. Lower value of S_H indicates more elongation of the Wadi and less erosion, while higher value indicates more circular and high erosion. A circular basin with high value of S_H is the most hazardous from a drainage standpoint, because it will yield the shortest time of concentration before peak flow occurs in the basin.

According to Melton (1957), the fitness ratio (Fr) is the ratio of main channel length to the length of the basin perimeter which is a measure of topographic fitness (Pareta and Pareta 2011a). The fitness ratio of the study basin and its sub-basins ranges from 0.02 of Khatm Al Jurrah3 sub-basin to 0.28 of Shisha1 sub-basin and sub-basin 13 sub-basin. This indicates that the sub-basins of higher values of Fr is more elongated and has a good chance for groundwater recharge than the other study basins. According to Chorley et al. (1957), the lemniscate value (Ls) is one of the parameters which describe the shape and slope of the basin. The calculated lemniscate value of the Wadi Qanunah basin and its sub-basins ranges from 0.92 of

Baydan 1 sub-basin to 4.50 of Wadi Qanunah basin. The ideal values of lemniscate of elongated basins vary from 0.50 to 1.80. For values less than 0.50, the shape of the basin tends to be circular, while for values higher than 2, the basin is fully elongated (Lykoudi and Zanis 2004). So, the whole Wadi Qanunah basin tends to be elongated, but for its sub-basins separately tends to be circular and is more prone to erosion hazard. This is due to the shorter time of concentration from the remotest point in the basin to reach the outlet for runoff in compact basin compared to that in elongated ones (Chorley et al. 1957; Morgan 2005).

Drainage texture

Stream frequencies (F) of the study basin and its sub-basins range from 3.24 km^{-2} for Baydan 2 sub-basin to 4.10 km^{-2} for Khatm Al Jurrah2 sub-basin (Table 4). This limited variation is due to the similarity of rainfall intensity, relief, and infiltration rate, initial resistivity of terrain to erosion, and total drainage area of the basin. The calculated values of drainage density (D) are ranging from 2.02 km^{-1} of Baydan 2 to 2.55 km^{-1} of Shisha2 sub-basin. A high value of basin drainage density indicates that large amounts of rainfall results in runoff. On the other hand, a low drainage density reflects erosion-resistant fractured hard rock of the study area and indicates that most of the rainfall infiltrates to recharge the groundwater. Drainage intensity value (Di) of the study basin and its sub-basins ranges from 1.41 of Khatm Al Jurrah3 sub-basin to 1.78 of Wadi Qanunah basin. Low value of drainage intensity implies that drainage density and stream frequency have a little effect on the extent to which the surface has been lowered by agents of denudation. Low drainage densities are often associated with widely spaced streams due to the presence of less resistant materials (rock types), and consequently, the surface runoff is not rapidly removed from the basin or those of high drainage intensity with high infiltration capacities which give a good chance from groundwater recharge.

In the study basin and its sub-basins, length of overland flow (Lo) values have very limited variation and are ranging from 0.20 km for Khatm Al Jurrah and Shisha2 sub-basins to 0.25 km for Baydan 2 sub-basin. Low value of Lo indicates that the surface water is concentrated faster than that of basins with higher values of Lo.

Infiltration number (FN) gives an idea about the infiltration characteristics of the basin that reveals the impermeable lithology and higher relief. The higher the infiltration number, the lower will be the infiltration and consequently the higher will be the surface runoff. This leads to the development of higher drainage density. All the calculated values of FN for Wadi Qanunah and its sub-basins range from 6.54 of Baydan 2 sub-basin to 10.10 of Shisha2 sub-basin. According to Howard (1967), drainage pattern (Dp) of the drainage basin helps in identifying the stage of the cycle of erosion and

reflects the influence of slope, lithology, and structure (Pareta and Pareta 2011b). Dendritic pattern is the main pattern in Wadi Qanunah basin and its sub-basins.

Relief characteristics

Wadi Qanunah basin is a high elevated basin, where the elevation ranges from 0 at the Red Sea Coast to 2378 m above mean sea level at the water divide of the basin with mean elevation about 586 m above mean sea level as shown in Fig. 2. The study sub-basins can be grouped into three groups: low relief group (<500 m), moderate relief group (500–1000 m), and high relief group (>1000 m) as shown in Fig. 2 and Table 4. Relief ratio (Rr) of the study basin has a wide variation and ranges from 0.005 for Shisha2 sub-basin to 0.063 for Baydan 2 sub-basin (Table 4). High values of (Rr) indicate steep slope and high relief, while the lower values may indicate presence of hard rocks of basement and tertiary that are exposed in the form of small ridges and mounds with lower degree of slope.

The main channel slope (SI %) is an indication for the channel slope from which an assessment of the runoff volume can be evaluated. Generally, the Wadi Qanunah basin and its sub-basins are characterized by moderate to high relief and topography except for Khatm Al Jurrah3 and Shisha2 sub-basins as shown in Table 4. The slope index (SI %) ranges from 0.008 for Khatm Al Jurrah2 sub-basin to 0.139 of Al Hazim sub-basin. The calculated main flow direction (BFD) of the study basins is matched with the direction of its main channel (Fig. 8) in which it drains into the Red Sea.

Mean basin slope (Sm) is the most important and specific feature of the drainage basin form. Maximum slope line is well marked in the direction of a channel reaching downwards on the basin. Slope maps of the study basin and its sub-basins (Fig. 9) have been created by using surface analysis tool in ArcGIS-10. The mean slope of the Wadi Qanunah is about 11.8° , and for its sub-basins, it ranges from 2.6° of Shisha2 sub-basin to 18.4° of Al Hafyan sub-basin as shown in Fig. 9 and in Table 4. The wide variations between the values of mean slope are due to the variation of the topography and lithology of the basins. Generally, the slope of the terrain affects the total runoff volume and time of concentration to the peak of hydrograph. Basins of gentle slope produce less runoff volume and smaller peaks of the runoff hydrograph. In gentle slope basins, the velocity of overland flow will be low and there will be more time for water to infiltrate thereby reducing the amount of surface runoff reaching the stream. A steep slope produces greater velocities and allows faster removal of the runoff from the watershed, therefore shorter concentration times to peak of hydrograph. According to Melton (1965), it is a slope index that provides specialized representation of relief ruggedness within the watershed. Extremely high values of ruggedness number occur when

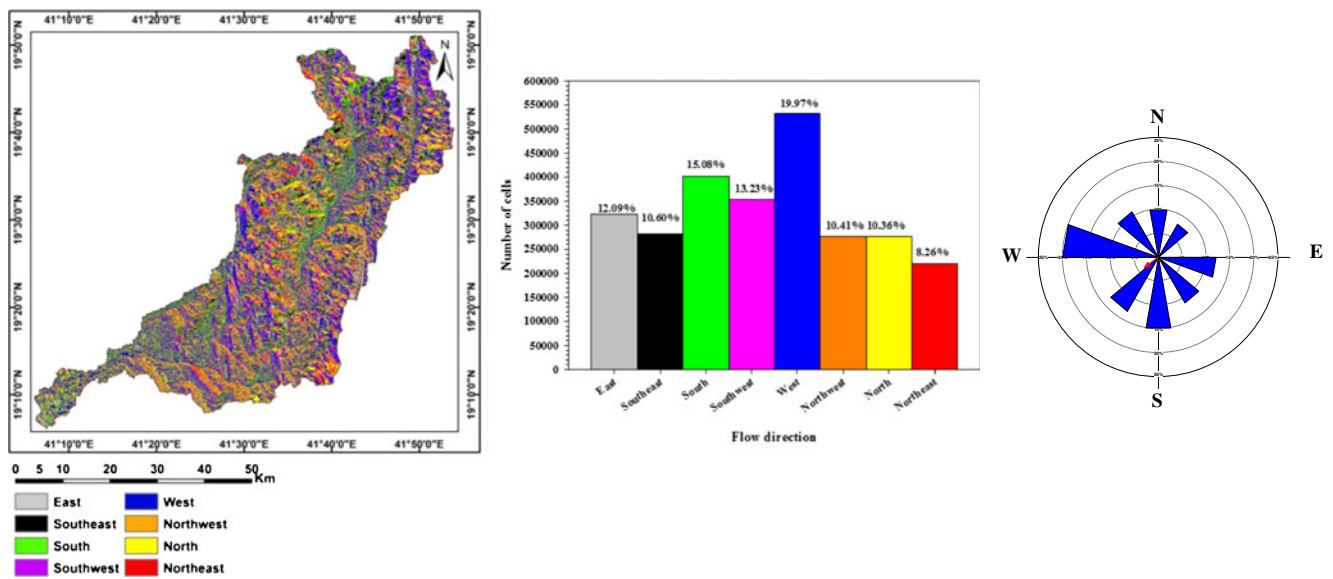


Fig. 8 Flow direction map, histogram distributions, and rose diagram of Wadi Qanunah basin

the basin has steep and long slope. Rn of Wadi Qanunah is about 2.86, and for its sub-basins, it ranges from 0.26 of Shisha2 to 3.64 of Qanunah sub-basin, as shown in Table 4.

Hypsometric curve is a non-dimensional measure of the proportion of the drainage area above a given elevation. According to Schumm (1956), Strahler (1964), Leopold et al. (1964), and Hurtrez et al. (1999), hypsometric curves are related to geomorphic and tectonic evolution of drainage basins in terms of their forms and processes. Strahler (1952, 1957, and 1964) identified three types of landforms, namely

young, mature, and old (monadnock), on the basis of hypsometric curve shape. Factors of tectonic uplift and down wasting are due to erosion control landscape form and its evolution. Landscape evolution can be formulated as a continuity equation relating uplift, elevation, and erosion for sediment transport (Willgoose and Hancock 1988). The hypsometric curves can be interpreted as youth (convex upward curves), mature (S-shaped curves), and peneplain or distorted (concave upward curves) stages of landscape evolution. Convex hypsometric curves are most likely for plateaus with

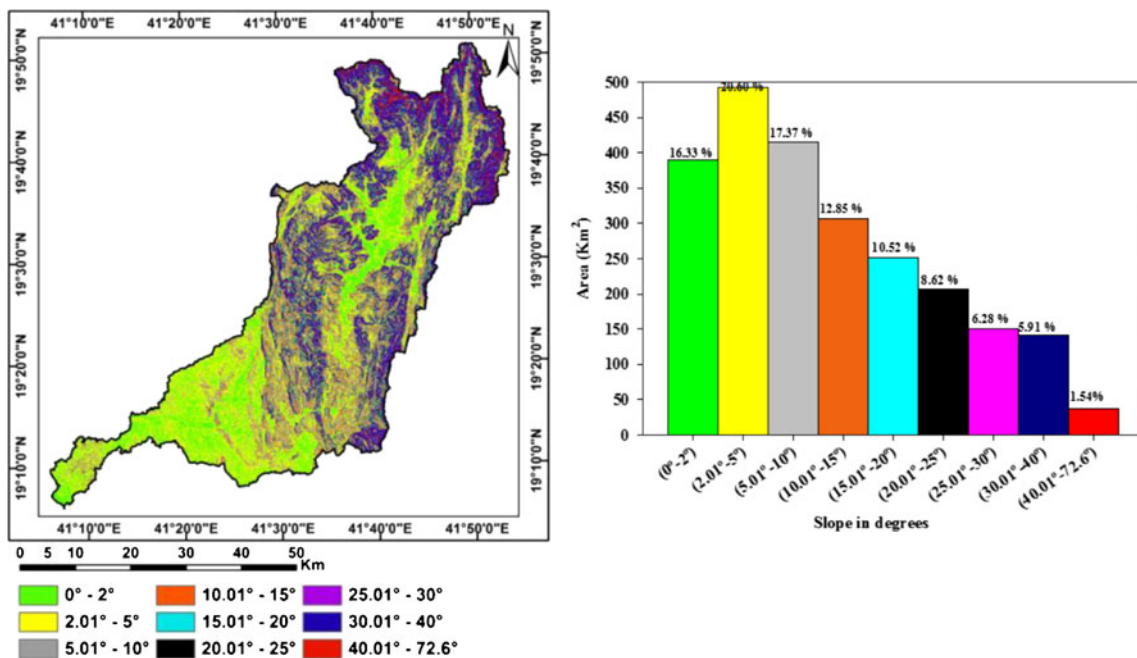


Fig. 9 Slope map and histogram distribution percentage of slope of Wadi Qanunah basin

little erosion, which can evolve into S shape, while concave hypsometric curves indicate a greater importance of erosion (Hurtrez et al. 1999). Wadi Qanunah shows peneplain or distorted (concave upward curves) stages of landscape evolution hypsometric curve shapes as shown in Fig. 10a, b. The hypsometric integral assists in explaining the erosion that has taken place during the geological timescale (Bishop et al. 2002). The comparison of the shapes of the hypsometric curves for different basins under similar climatic conditions and an approximately equal area also provides relative insight into the past soil movements in the basins. For the selected basins, the range of basin altitude was divided into equal intervals. For each interval, the proportion of the basin area was calculated. Elevations and areas were then divided by the relief and total basin area, so that they range from 0 to 1. The hypsometric integral (HI) represents the area under the hypsometric curve and is computed as follows (Hurtrez et al. 1999). Generally, a HI value of Wadi Qanunah is about 0.26; this lower value indicates that Wadi Qanunah basin is an old basin (Chorley and Morley 1959; Haan and Johnson 1966; Pike and Wilson 1971). Singh et al. (2008) presented an HI-based classification for the main landscape development stages. According to their classification, basins with HI values above 0.6 were classified as young, whereas catchments with HI values below 0.3 were classified as old or monadnock. Mature stage catchments have HI values greater than 0.3 and lower than 0.6. Resulted HI values of hypsometric integral are of less than 0.6 which indicated that the Wadi Qanunah basins and its sub-basins are mature to old, which are eroded and dissected drainage basins as shown in Table 4.

Flash flood hazard evaluation

To evaluate the flood hazard of the study basins, nine morphometric parameters having a direct effect on flooding were chosen, and their relationship with the flash flood was analyzed.

These parameters are watershed area (A), drainage density (D), stream frequency (F), shape index (Ish), slope index (SI), relief ratio (Rr), ruggedness ratio (Rn), texture ratio (Rt), and weighted mean bifurcation ratio (WMRb). All these parameters have a directly proportional relationship with the hazard morphometric parameters except for the WMRb which shows an inverse proportion.

Methodology of flash flood hazard evaluation

A hazard scale number starting with 1 (lowest) to 5 (highest) has been assigned to all parameters. The distributions of the hazard degrees for the study basins have been carried as Davis 1975 and Masoud 2014 as follows:

- Determination of the minimum and maximum values of each morphometric parameter for the study basins.
- Assessments of the actual hazard degree for all parameters which are located between the minimum and maximum values were depending on the empirical relation between the relative hazard degree of a basin with respect to flash floods and the morphometric parameters. The equal spacing or simple linear interpolation between data points procedure was chosen.
- Assuming a straight linear relation exists between sample points, and intermediate values of hazard degree can be calculated from the geometric Eqs. 2 and 3 of Davis 1975. Equation 2 is used to evaluate the hazard degree of the morphometric parameters that have a directly proportional relationship with surface runoff accumulation, while Eq. 3 is used for the hazard degree of the morphometric parameters that have inverse proportion with surface runoff accumulation (WMRb).

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

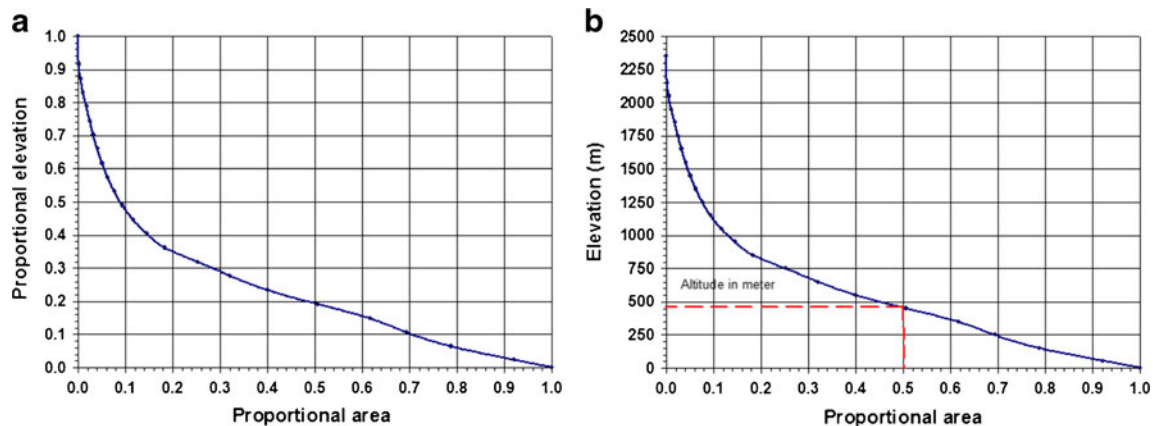


Fig. 10 Hypsometric curve (a) and altitude (b) of Wadi Qanunah basin

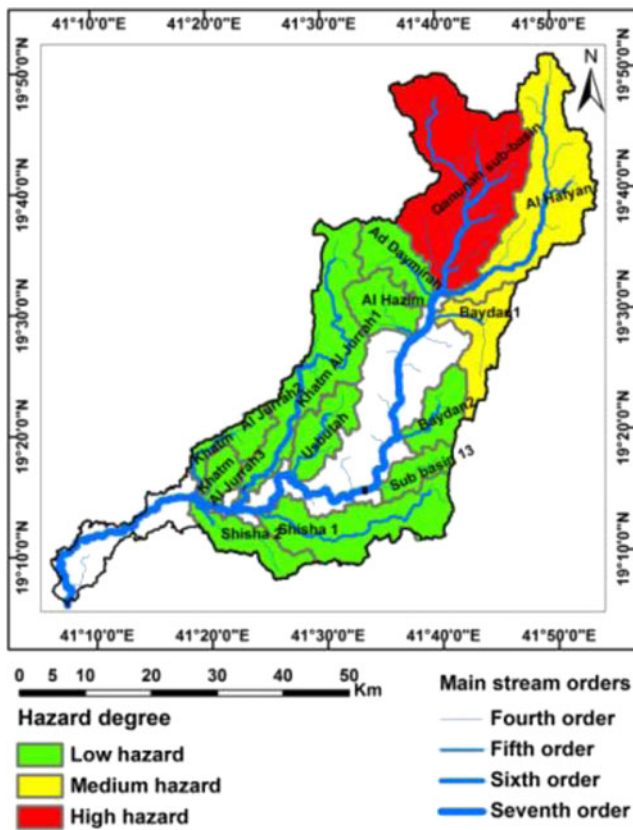


Fig. 11 Hazard degree map of Wadi Qanunah sub-basins

$$Hazard\ degree = \frac{4(X - X_{max})}{(X_{min} - X_{max})} + 1 \quad (3)$$

where X is the morphometric parameter of the study sub-basin, X_{max} is the maximum value of the morphometric parameter of all study sub-basins, and X_{min} is the minimum value.

Results and discussion of flash flood hazard evaluation

Summation of the hazard degrees for each sub-basin represents the final flood hazard of that sub-basin (Table 4). These values range between 19.13 (sub-basin 13) and 37.91 (Qanunah sub-basin). From the calculated values, according to their hazards, one can classify the study sub-basins into three groups as shown in Fig. 11 and Table 4 as follows:

Basins of high hazard degree (Wadi Qanunah sub-basin); this means that this sub-basin has the maximum potentiality for surface runoff with short time of concentration and travel time which needs to create hindering dams at the stream tributaries of fourth and fifth orders.

Basins of medium hazard degree such as Wadi Al Hafyan and Baydan 1 sub-basins, that are characterized by mild potentiality of groundwater recharge.

Basins of low hazard degree (rest of the sub-basins), that are characterized by high potentiality of groundwater recharge.

Hydrological model construction

Hydrologic model construction of rainfall–runoff relationships is very significant for the sustainable development of the water resources and for the protection from the flood hazard and drought. Rainfall is one of the essential hydrological elements in the modeling of basin systems. Predicting extreme events such as droughts and floods and estimating both quantity and quality of surface water and groundwater require basic information regarding rainfall.

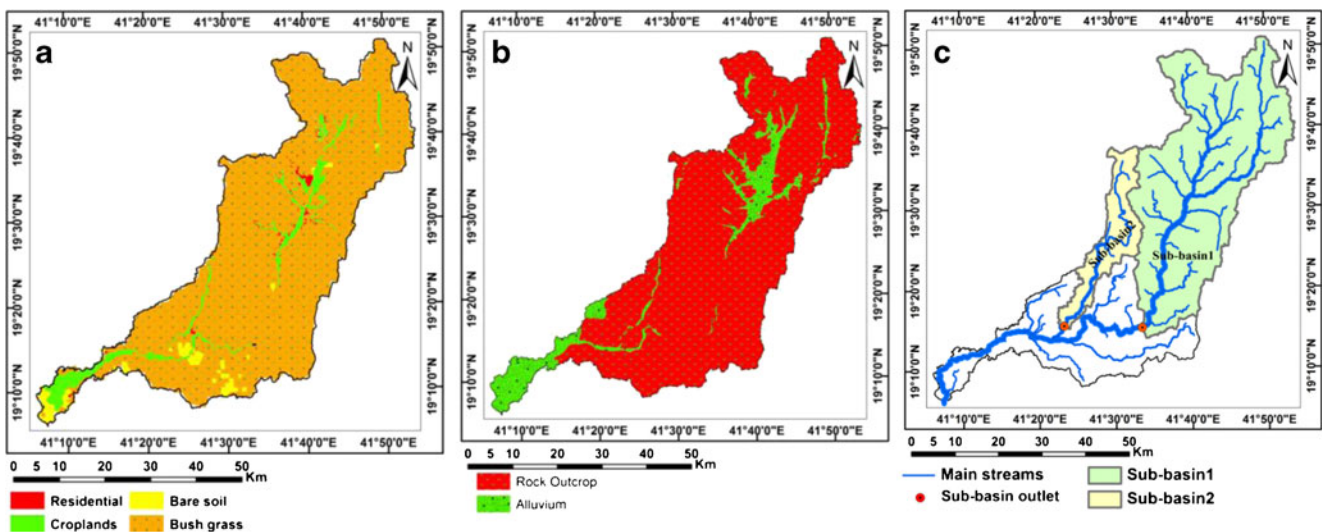


Fig. 12 Land use (a), soil types (b), and modeled sub-basin (c) maps of Wadi Qanunah basin

Table 5 Estimation of the weighted average CN over the catchment

Matrix calculating CN land use—soil	CN _i	Area (km ²) (A _i)	% Area	Weighted CN _i for each area
Bare soil—alluvium	63	22.43	0.9	0.6
Bare soil—rock outcrops	88	34.40	1.4	1.3
Bush grass—rock outcrops	80	2044.67	85.4	68.3
Cropland—alluvium	74	109.89	4.6	3.4
Cropland—rock outcrop	86	24.40	1.0	0.9
Residential—rock outcrops	87	6.12	0.3	0.2
Bush grass—alluvium	80	144.98	6.1	4.8
Lake—rock outcrop	100	0.08	0.0	0.0
Lake—alluvium	100	0.01	0.0	0.0
Residential—alluvium	80	7.21	0.3	0.2
Total		2394.20	100	80

Methodology of hydrologic model construction

Rainfall–runoff modeling in this study depends on the integration between morphometric parameters, GIS techniques, WMS, HEC-HMS, and the available scarce data of return period of maximum daily rainfall. Infiltration characteristics in this program depend on the type of curve number (CN) used in the Soil Conservation Service (SCS 1972, 1985) formula which now is changed to Natural Resources Conservation Services (NRCS).

Land use and land cover analyses and curve number estimation

Runoff is the excess rain, which is the total precipitation volume after subtracting infiltration and the potential maximum retention. The infiltration and the potential maximum retention depend on soil characteristics and surface complexity. Soil characteristics include soil physical properties such as texture, compaction, structure, and soil moisture while surface complexity includes land use, land treatment and practice as well as topography. Therefore, runoff amount depends on

precipitation, soil type, land use, land cover, soil moisture conditions, and topography.

NRCS of the USA developed an equation to calculate runoff from a drainage basin called SCS runoff curve number method which is as follows:

$$Q = (P - 0.2S)^2 / (P + 0.8S) \tag{4}$$

where *Q* is the runoff depth, *P* is the precipitation depth, and *S* is the potential maximum retention depth. The potential maximum retention is calculated using a hydrological parameter called CN as in the following equation:

$$S = (25400 / CN) - 254 \tag{5}$$

The *CN* is a hydrologic parameter used to describe storm water runoff potential from a catchment. It is a numerical value to be used in runoff calculating equation. The CN relates soil characteristics, land surface conditions, and soil moisture content in the land to the retention part of precipitation. Accordingly, the CN is an index that represents the combination of hydrologic soil group and land use.

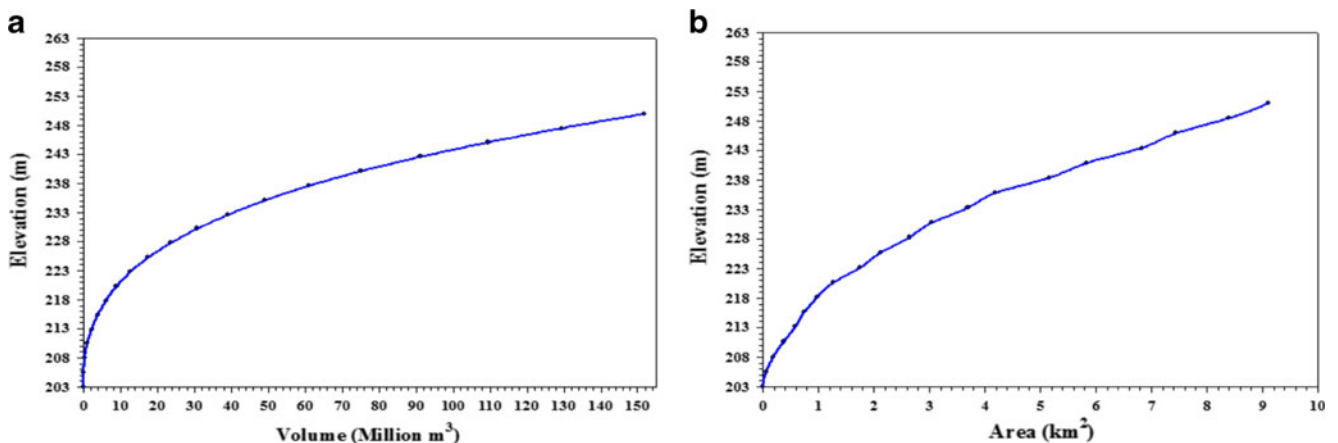


Fig. 13 Surface area-elevation and the capacity-elevation curves of the dam reservoir

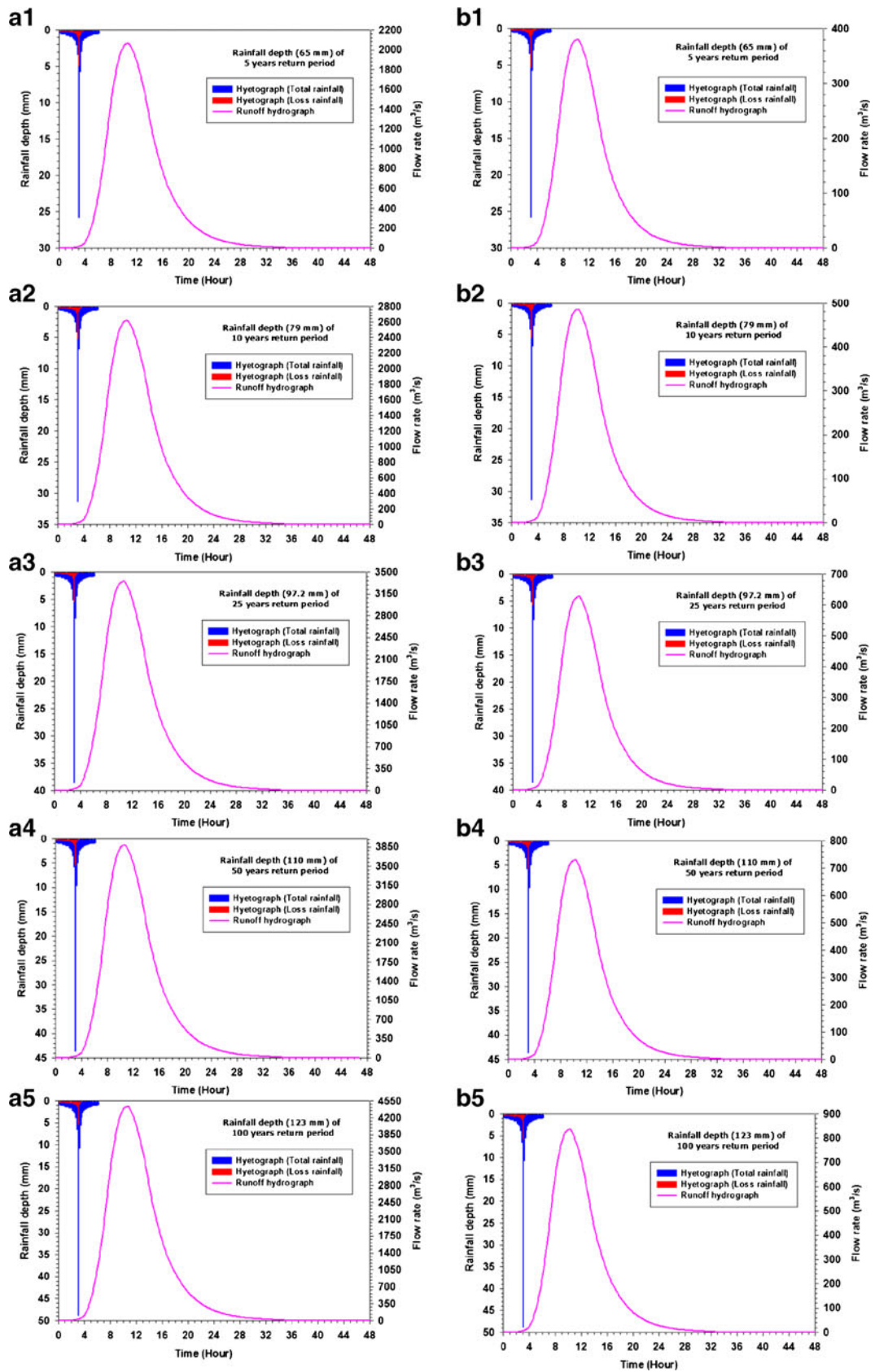


Fig. 14 Hydrographs of sub-basin 1 (a1–a5) and sub-basin 2 (b1–b5) at different return periods

According to the NRCS, soils are classified into four groups and assigned a letter for each group as A, B, C, and D. Each group can be identified with specific characteristics, so one can classify any soil in one of those four groups. The A soil group represents deep sand, deep loess, and aggregated silts. The B soil group represents shallow loess and sandy loam. The C soil group represents clay loam, shallow sandy loam, soils low in organic content, and soils usually high in clay. The D soil group represents soils that swell significantly when wet, heavy plastic clays, and certain saline soils. The NRCS soil group can be identified at a site using either soil characteristics or county soil survey maps. In Saudi Arabia, soil group can be classified either by soil characteristics or soil maps that can be obtained from soil survey maps of the Ministry of Agriculture.

Creation of capacity curve

Storage capacity curve defines a relationship between elevation/area/volume and is computed using an option in WMS based upon DEM. Storage capacity curves are stored in the storage list used by the time series editor so that they can be used later to define routing in one of the supported hydrologic models or in the detention basin calculator. WMS computes these relationships by beginning at the outlet elevation and incrementing the elevation by the number of specified divisions until the specified water surface elevation is obtained. At each increment, the area between that elevation and the outlet elevation is computed, and then, volumes between adjacent surface elevations are computed using the conic method. The storage capacity (elevation, area, volume) data can be stored in either English or metric units.

Rainfall–runoff modeling in the presence of dam

The catchment of Qanunah has been divided into two main sub-basins and modeled to estimate the runoff resulted from the rainfall storms of 5, 10, 25, 50, and 100 return periods respectively for each sub-basin.

Since modeling watershed integrates GIS and hydrological models, two professional models are used: WMS 10.0.9 and HEC-HMS 3.3. Details of the model are found at Environmental Modeling Research Laboratory (2004). The HEC-HMS, version 3.5 developed by the US Army Corps of Engineers, is designed to simulate the rainfall–runoff processes of dendritic watershed systems. HEC-HMS allows the modeler to choose between numerous infiltration loss and unit hydrograph parameterizations (HEC, 2000). The SCS-CN method is used to estimate the excess rainfall.

Results and discussions of hydrologic model construction

From land use analysis of areal images for Wadi Qanunah (Fig. 12), it is found that almost 80 % of the Wadi’s area is bare soil. In the northern part of the Wadi, in the upstream, almost 15 % of the Wadi’s area contains bush and grass cover. Very small spots of residential areas, less than 10 % of the Wadi’s area, were scattered especially in the lower third of the Wadi toward the west. Farmland is very limited in the Wadi, less than 5 % of the Wadi’s area, scattered mainly around the main channel in the lower two thirds of the Wadi. Figure 6 shows maps for the Wadi with different land use (A) and soil types (B). Table 5 displays estimated weighted average of the CN value for the whole catchment which is equal 80 that is used for the hydrological analysis.

Figure 13 shows both the elevation-volume and the elevation-surface area curves (a and b respectively) at the proposed dam site (25-m height) at elevation that is about 205 m (amsl). In the elevation-volume capacity, the maximum volume is about $88 \times 10^6 \text{ m}^3$ with an area is about 9 km^2 . In the surface area-elevation curves, one may observe irregular curve with some jumps. These jumps mean that the reservoir area does not change with elevation. In other words, the mountains’ sides are almost vertical at those elevations.

For rainfall distribution over the storm duration, the SCS type II hyetograph is used which is commonly used in arid regions. Figure 14 shows the rainfall hyetographs and the corresponding flood hydrographs at different return periods.

Table 6 Summary of the first scenario considered (with dam) in Wadi Qanunah basin

Return period (years)	Total rainfall (mm)	Sub-basin 1 (Qanunah sub-basin)			Sub-basin 2 (Khatm Al Jurrah)		
		Maximum Q (m^3/s)	Volume (10^6 m^3)	Average depth (m)	Maximum Q (m^3/s)	Volume (10^6 m^3)	Average depth (m)
5	65	2062.3	65.5	4.0	380.0	11.0	2.8
10	79	2617.0	81.8	4.4	486.0	14.1	3.0
25	97	3351.5	104.7	4.8	627.0	18.2	3.3
50	110	3883.0	121.2	5.1	729.0	21.3	3.4
100	123	4433.0	138.3	5.4	835.0	24.4	3.6

The simulated peak discharge at the proposed dam sites is 2062.3, 2617, 3351.5, 3883, and 4433 m³/s for sub-basin 1 (Qanunah sub-basin) and is 380, 486.4, 627, 729, and 835 m³/s for the sub-basin 2 (Khatm Al Jurrah) at 5, 10, 25, 50, and 100-year return periods, respectively. The corresponding runoff volumes and the other outputs are tabulated in Table 6.

From the hydrograph estimated by HEC-HMS (Fig. 14), the runoff volume is calculated for every

return period and the corresponding water surface elevation of the lake (upstream of the dam) is estimated from the capacity (Fig. 13). For 5-year return period, the reservoir lake elevation is 238 m; for 10-year return period, the reservoir lake elevation is 242.5 m; for 25-year return period, the reservoir lake elevation is 245.5 m; for 50-year return period, the reservoir lake elevation is 247 m, and for 100-year return period, the reservoir lake elevation is 249.5 m as shown in Fig. 15.

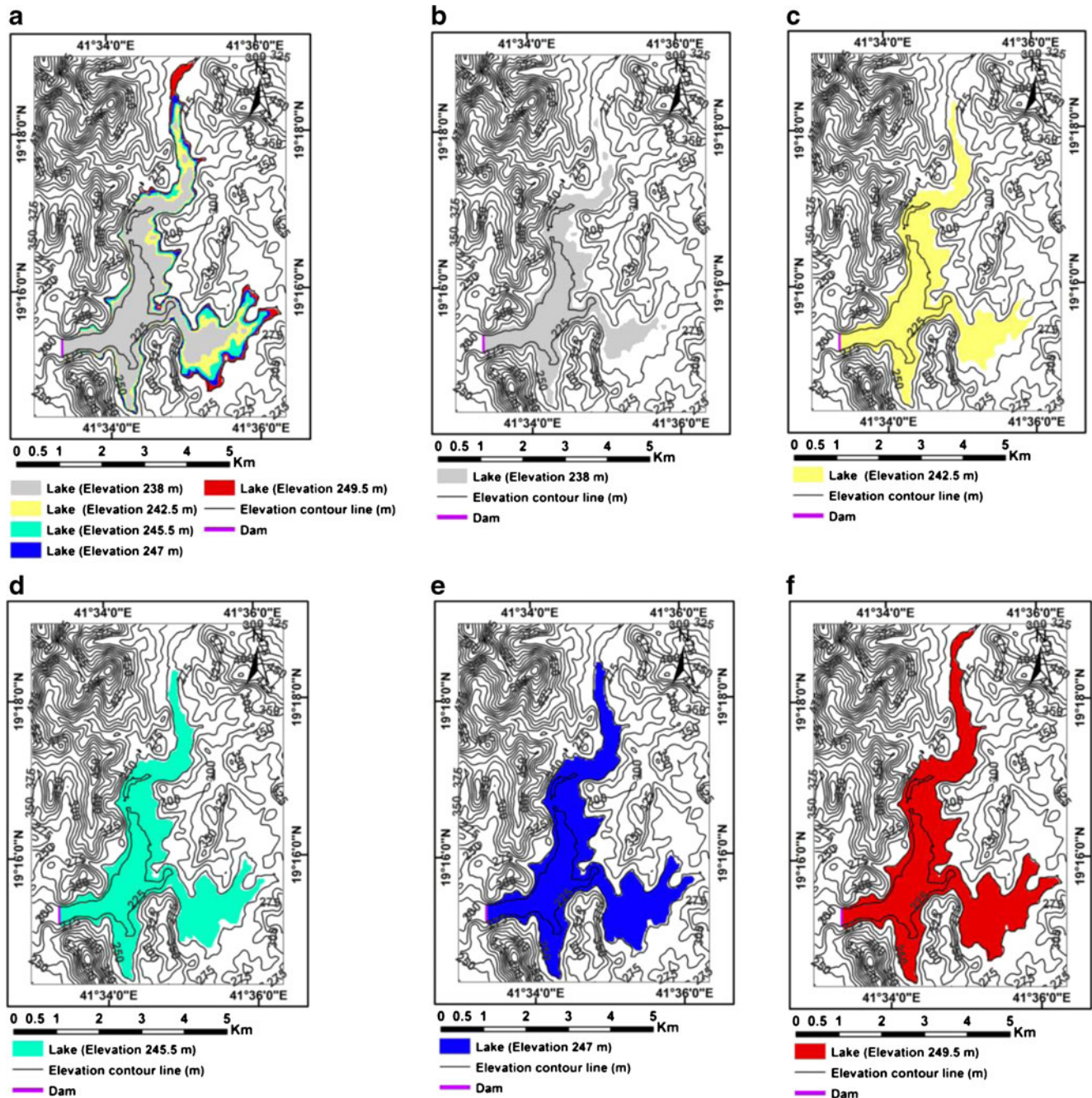


Fig. 15 Dam lake shape in the upstream side of the proposed dam and inundation areas **a** at different return periods, **b** 5 years (lake area = 5.1 km²), **c** 10 years (lake area = 6.5 km²), **d** 25 years (lake area = 7.5 km²), **e** 50 years (lake area = 8.1 km²), and **f** 100 years (lake area = 8.7 km²)

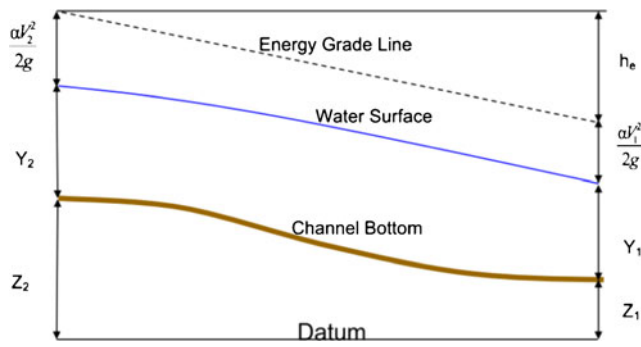


Fig. 16 Representation of the terms in the energy equation (after Brunner 2010)

(Brunner 2010). The energy equation for a steady-state flow is given by

$$Z_2 + Y_2 + \frac{\alpha_2 V_2^2}{2g} = Z_1 + Y_1 + \frac{\alpha_1 V_1^2}{2g} + h_e \tag{6}$$

where $Z1$ and $Z2$ are the elevations of the channel inverts, $Y1$ and $Y2$ are water depths at cross sections, $V1$ and $V2$ are the average velocities at the channel cross sections, α_2 are the velocity weighting coefficients at the channel cross sections, g is the acceleration due to gravity, and h_e is the energy head losses which is estimated by Manning formula as

$$h_e = L \left(\frac{Qn}{AR^{2/3}} \right)^2 \tag{7}$$

Flood inundation modeling in the absence of dam

In the flood inundation modeling, two approaches have been considered: the upstream and the downstream sides of the proposed dam. In order to study the effect of the presence of the dam on the inundation areas and for risk evaluation, two scenarios have been considered. The first scenario assumes that there is no dam (without dam).

where Q is the flood discharge along the channel, A is the channel cross-section area, R is the hydraulic radius of the channel cross section, n is the Manning roughness coefficient, and L is the distance between the two cross sections. The parameters in the energy equation are illustrated in Fig. 16. The above equations have to be solved between each two cross sections to calculate water depth and velocity in the channel at each cross section.

Methodology of flood inundation modeling

Flood inundation modeling in the downstream side at the outlet of the main sub-basins (Fig. 12c) has been performed through the application of HEC-RAS software. This software of hydraulic modeling package has been developed by US corps of engineers, and it is able to perform steady and unsteady fluid flow simulations in 1D river channel and flood plains. In this study, steady flow is used for delineation of inundation areas downstream of the proposed dam (outlets of the sub-basins). The gradually varied flow equation is considered in HEC-RAS, and therefore, water surface profiles are computed from one cross section to another cross section along the Wadi channel by using the energy equation with an iterative procedure called the standard step method

Results and discussions of flood inundation modeling

The total length of the downstream channels for both sub-basins (1 and 2) is about 70 km and is divided into 87 cross sections for the gradually varied flow computations as shown in Fig. 16. The distance between two consecutive cross sections is about 0.85 km in average and may vary between cross sections according to the changes in the flow directions; however, the cross section should always be perpendicular to direction of flow in the channel. Using interlink between GIS techniques and HEC-HMS, the average depth of the surface runoff for each channel and the inundation areas is delineated and estimated for the designated return periods as shown in Table 7 and Figs. 17 and 18).

Table 7 Summary of the second scenario considered (without dam) in Wadi Qanunah basin

Return period (years)	Total rainfall (mm)	Reach 1		Reach 2		Main stream (reach 1 + reach 3)	
		Maximum Q (m ³ /s)	Average depth (m)	Maximum Q (m ³ /s)	Average depth (m)	Maximum Q (m ³ /s)	Average depth (m)
5	65	2062.3	4.1	380.0	2.0	2442.3	3.0
10	79	2617.0	4.6	486.0	2.2	3103.0	3.2
25	97	3351.5	5.3	627.0	2.4	3978.5	3.5
50	110	3883.0	5.4	729.0	2.6	4612.0	3.7
100	123	4433.0	5.7	835.0	2.7	5268.0	3.9

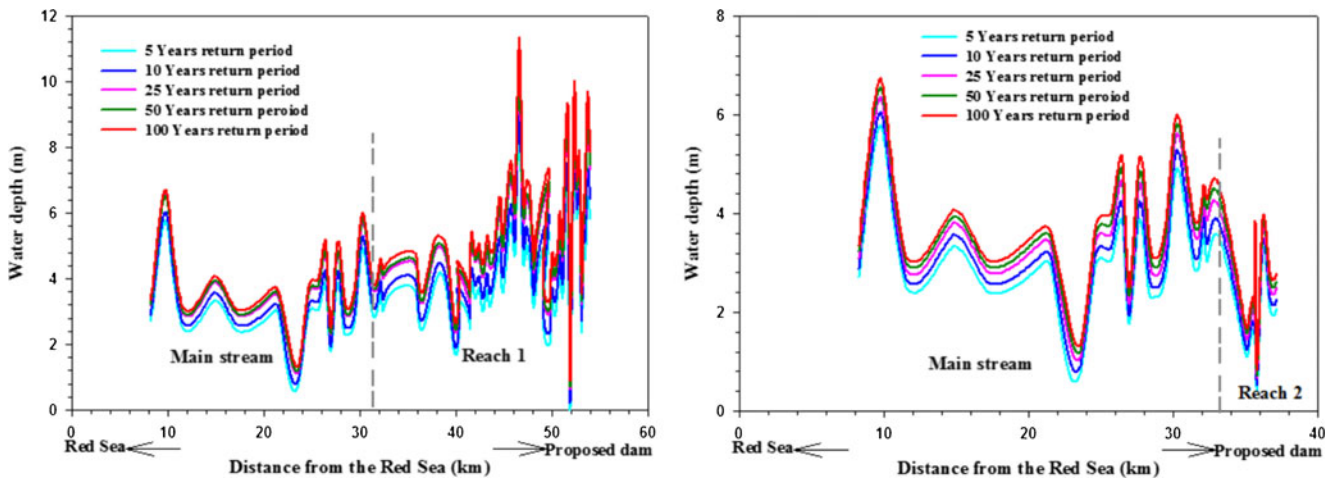


Fig. 17 Water depth distribution over the downstream channel

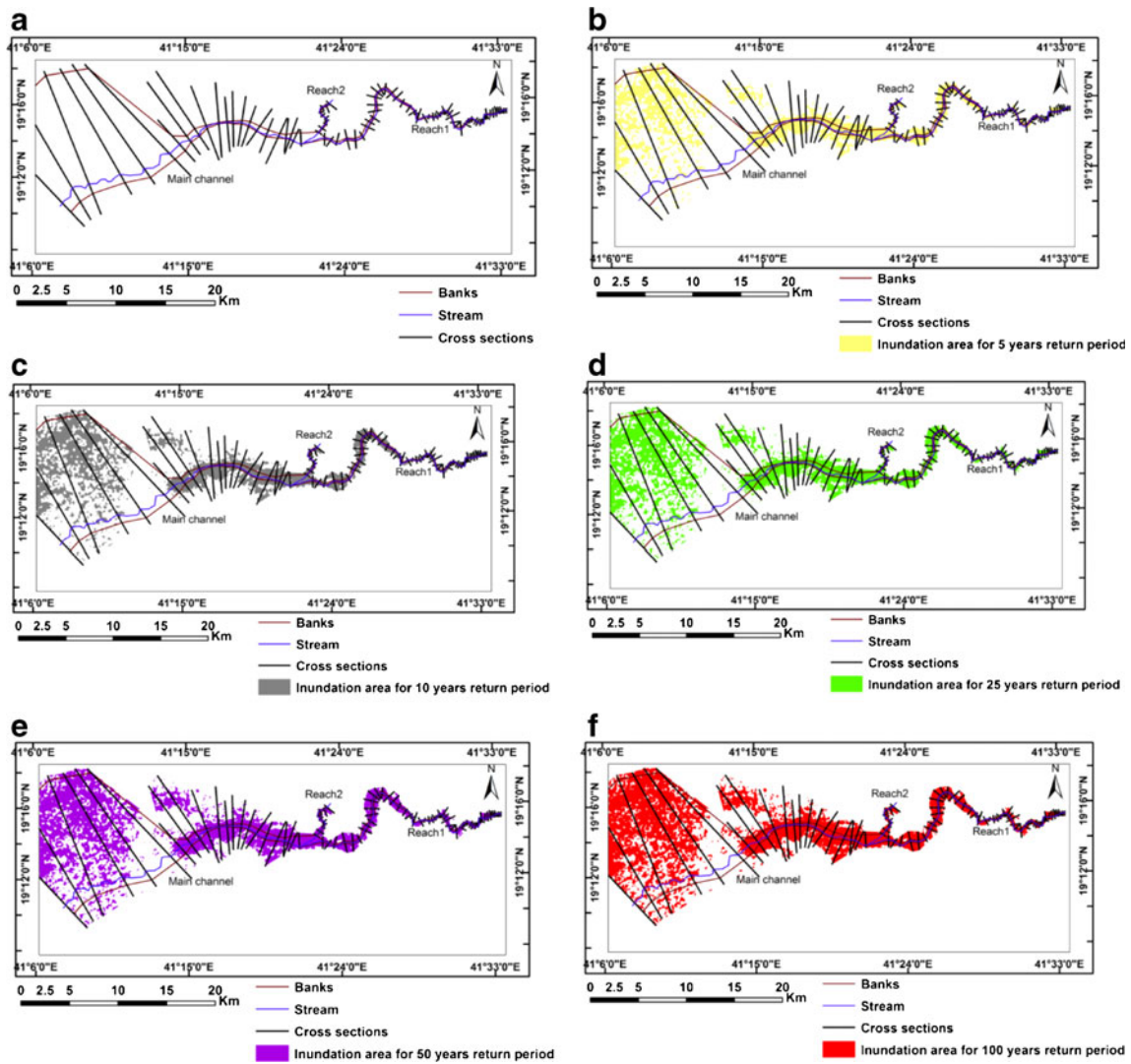


Fig. 18 Flood inundation of downstream areas at different return periods without the dam: a model boundaries, b 5 years, c 10 years, d 25 years, e 50 years, and f 100 years

Summary and conclusions

Morphometric parameters of the study basin are the significant controlling factors for surface water runoff and flood hazard evaluation particularly in the ungauged basins of arid and semi-arid regions. Flash flood hazard evaluation and inundation are very significant for the catchment managements especially for the sustainable development of the water resources and for the protection from the flood hazard and drought. Flash floods can be controlled by several elements based on the morphometric parameters of the basin such as relief, geometry, geology, and climatic conditions. In this study, 38 morphometric parameters were measured and calculated; nine of them that have a direct influence upon the surface runoff accumulation were selected and analyzed to evaluate the potentiality of the flash flood hazard and groundwater recharge.

Wadi Qanunah sub-basins could be classified into three groups: basins of high hazard degree, with high potentiality of surface runoff accumulation (Qanunah sub-basin); basins of medium hazard degree (Al Hafyan and Baydan 1 sub-basins); and basins of low hazard degree with high potentiality of groundwater recharge (rest of the sub-basins). It is recommended that some obstruction dykes are very significant to construct to permit the runoff water to infiltrate and recharge the shallow aquifer at the crossing point between the fourth stream order and fifth stream order at Qanunah, Al Hafyan, and Baydan 1 sub-basins.

This paper presents integration between rainfall–runoff modeling together with flood inundation modeling and GIS techniques for flood risk assessment in arid zones under data scarcity. Wadi Qanunah, which is located in the southwestern part of Saudi Arabian, has been chosen as an example for implementation of such an integrated approach. It is found that the presence of the dam with height about 30 m will protect all the urban areas around the main channel and at the delta of Wadi Qanunah considering the different return periods. Also, it is found that the average inundation area are about of 105, 119, 134, 152, and 175 km² at 5, 10, 25, 50, and 100-year return period, respectively. From the proposed dam evaluation procedure, it is found that the storage of Wadi Qanunah Dam is about 65 × 10⁶ m³ for 5-year return period.

To avoid the scarcity of hydrological data, some of telemetric meteorological stations should be installed on the top along of Red Sea Mountains series.

The following conclusions are drawn from the study: (1) The statistical analysis of rainfall and flood data proofs that not all stations follow Gumbel distribution, which is the common practice considered in Saudi Arabia. (2) The proposed methodology is a useful tool for dam and flood risk evaluations in arid zones under data scarcity. (3) This study provides in-depth analysis of the flash flood prone areas of Wadi

Qanunah basin and its sub-basins and the mitigation measures. (4) This study will help to plan rainwater harvesting and watershed management in the flash flood alert zones for the future.

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