Assessment of surface runoff in arid, data scarce regions; an approach applied in Wadi Al Hamd, Al Madinah Al Munawarah, Saudi Arabia

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Abstract: Protection of Al Madinah Al Munawarah from the environmental hazardous as flash flood is very serious task. Assessment of surface runoff is very important for the catchment management. Usually, the application of hydrologic models in arid regions are faced by scarcity in the required data that may not allow for the application of rainfall-runoff models. This is also true for the western coast of Saudi Arabia which receives good amounts of flash floods that occur as a consequence of excessive rainfall which occasionally causing major loss of property and life. Wadi Al Hamd basin which is consider the major basin in Al Madinah Al Munawarah, is located in the western region of Saudi Arabia and characterized by extremely arid conditions. The aim of this study is to provide a general framework for assessing runoff and abstraction estimations that can be applied in arid regions despite the scarcity of data through the integration between Geographic Information System (GIS), morphometric parameters and very scarce data measurements. In this study, ASTER data were used for preparing digital elevation model (DEM) 30 m resolution, and GIS was used in evaluation of linear, areal and relief aspects of morphometric parameters. The major parameters such as watershed boundary, flow accumulation, flow direction, flow length, stream ordering were prepared using ArcHydro Tool. Surface Tool in ArcGIS-10 software was used to create different thematic maps such as DEM, contour, slope aspect and hill shade maps. Depending on the morphometric parameters that consider controlling factors of surface runoff, a hazard map of the study basin was created. Depending on Storm water Management and Design Aid (SMADA6) and scarce available measurements of rainfall and runoff a synthetic hydrographs and rainfall runoff modeling of the study sub-basins were generated. The direct runoff ranged from 9% to 24% of the total rainfall.

Keywords: Watershed, Hydrology, Runoff, Geomorphology, Flash flood hazard, Morphometric parameters

1 Introduction

Surface runoff (flash floods) can develop rapidly in the catchment without warning leaving many deaths and lost many millions of dollars. Because of Al Madinah Al Munawarah is receiving daily many thousands of the Worshipers, so it is very important to assess the flash flood of this area to create like flash flood guidance. This flash flood guidance is formulated in the flash flood mapping and the relation between rainfall runoff.

Flash floods often occur in arid regions as a consequence of excessive rainfall which occasionally causing major loss of property and life (Subyani, 2009). Flood hazard mapping is 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 mapping in arid regions is an extremely important but difficult task, the main reason is the scarcity of data in arid regions.

Flood hazard mapping is very important for the catchment 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 essential hydrological elements in the flood mapping of basin systems. So, according to that 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 (Sen *et al.*, 2012), therefore, this study based on the integration between physiographic features of the study area and GIS techniques.

The integration of GIS to create flood hazard maps and disaster decision support has been continually upgraded and widespread since beginning of 21st 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; He *et al.*, 2003 Guzzetti and Tonelli, 2004; Sanyal and Lu, 2006; Fernadez and Lutz, 2010).

The application of geomorphological principles to flood potential or flood risk has led to a noteworthy amount of researches, attempting to identify the relationships between basin morphometric and flooding impact (Patton, 1988). Identification of drainage networks within basins or sub-basins can be achieved using traditional methods such as field observations and topographic maps, or alternatively with advanced methods using remote sensing and Digital Elevation Model (Macka, 2001; Maidment, 2002).

A number of studies have applied the transmission losses in similar conditions from the point of view of arid to hyper-arid environment, hydrologic characteristics and geologic setting. Savard (1997) evaluated the relationship between stream flow records and measured water levels in nearby wells in Fortymile Wash in Yucca Mountain, Nevada. Abdulrazzak and Sorman (1994) provided equations to derive transmission losses knowing inflow volume, active flow width, and antecedent soil moisture measurements

The magnitude and frequency of recharge from ephemeral streams is dependent on the amount of water lost through infiltration into the wadi bed as the flood wave progresses in the downstream direction. Alluvial channels usually infiltrate large volumes of flood flow. The amount of abstraction, which represents the cumulative infiltrated volume, depends on the soil profile, certain physical conditions, and rainfall and runoff characteristics. The infiltrated volume initially satisfies the soil moisture deficit and evaporation requirements, and may eventually contribute towards recharging the alluvial aquifer (Abdulrazzak and Sorman, 1988).

Assessment of surface runoff in arid regions is an extremely important but difficult task; the main reason is the scarcity of data in arid regions. The aim of this study is to provide an approach for runoff assessment and estimation of groundwater recharge through the transmission loses (infiltration) that can be applied in arid regions suffering from the scarcity of data using the integration between Geographic Information System (GIS), morphometric parameters and very scarce data measurements.

2 Location and hydrogeology of Wadi Al Hamd

Wadi Al Hamd in one of the largest basins in Saudi Arabia, which is located in Al Madinah Al Munawarah province. Wadi Al Hamd is located between 37º 00' and 42º 02' E and 23º 30' and 27º 30' N, and is covering an area about 104679 Km². Geologically, Wadi Al Hamd is essential part of the middle-western Precambrian Arabian Shield, which is bounded from the east by the Paleozoic and younger sedimentary rocks and from the west by the Red Sea rift. Geological outcrops of the study area range from Pre-Cambrian to Quaternary as shown in Figure 1.

The Proterozoic Formation (Pre-Cambrian rocks) covered an area about 55% of the study basin and composed of metavolcanic and metasedimentary rocks. Paleozoic Formations (Cambrian and Cambrian-Ordovician rocks) covered an area about 8% of the study area and composed of coarse to fine grained cross-bedded sandstone with intercalated microgabbro flows. Cenozoic formations (Tertiary to Quaternary) are covering an area about 25% of the studied basin and are composed of lava flows in the Al Madinah quadrangle from the southern end of Harrat Khaybar and the northern end of Harrat Rahat. These plateaus composed of fissure flows that are porous and fractured basalt.
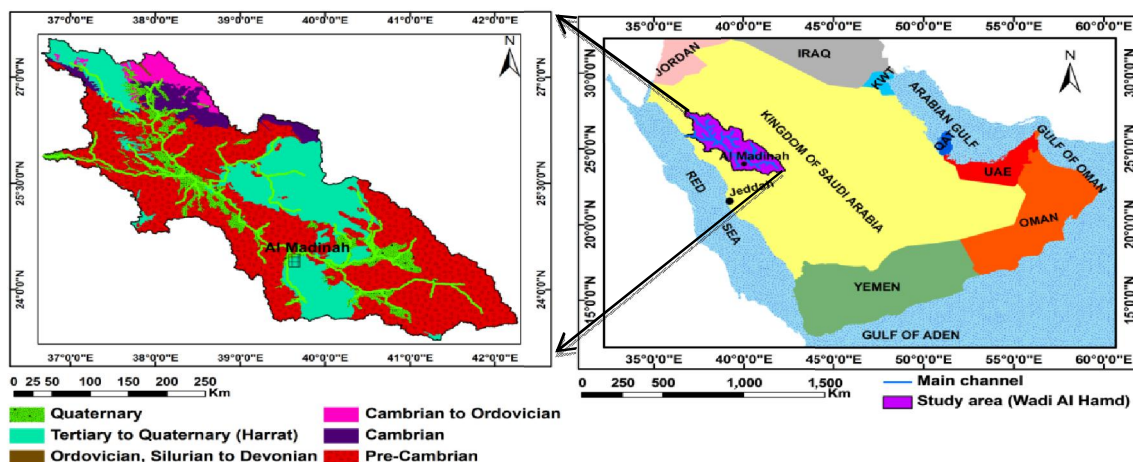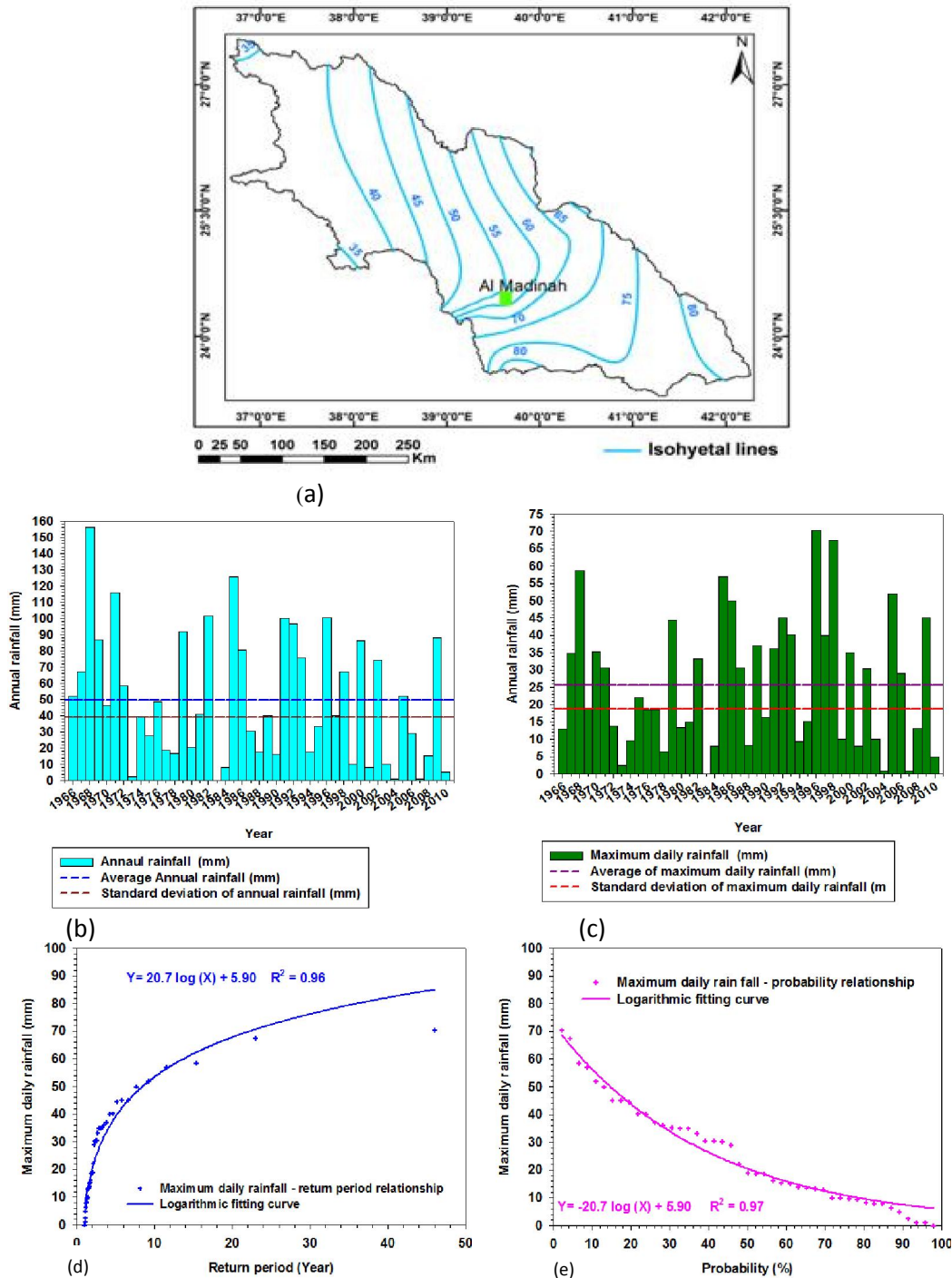

Figure 1. Location and geology of the study area

Quaternary deposits, which cover an area of about 12%, include the coastal plain and the main tributaries of the Wadi, and composed of sand, gravel, silt and sabkha, (George and Shorbaji, 1987). According to Daessle (1973), the Harrat Rahat is the best recognized Tertiary and Quaternary lava flows complex. The whole complex is acting as a groundwater aquifer with good permeability which is fractured permeability resulted from thermal shrinkage cracks and the fissured lineaments between adjacent and superimposed flows which permit the infiltration of rainfall.

(a)

(b)　　　　　　(c)

(d)　　　　　　(e)

Figure 2. Rainfall distribution of the study area where (a) isohyetal map, (b) annual rainfall, (c) maximum daily rainfall, (d) return period of the maximum daily rainfall and (e) the probability of the maximum daily rainfall (Duration period 1966-2010)

Rainfall patterns and runoff in the study area are characterized by extremely high temporal and spatial variability. Unfortunately, accurate and continuous hydro- meteorological data are limited or incomplete (Subyani and Al-Ahmdi, 2011). From the available rainfall data (1966-2010) of Al Madinah Al Munawarah province, it is clear that, the study area is characterized by average to extremely arid climate. Rainfall distribution of the study area shows the average annual rainfall ranges from 35 mm to 80 mm (Figure 2a). The annual rainfall distribution of the Al Madinah airport meteorological station ranges between 0 to 156 mm with an average value about 49.3 mm with standard deviation about 39.2 mm (Figure 2b). While the distribution of maximum daily ranges between 0 to 70 mm with an average value about 28.8 and standard deviation is about 18.8 mm (Figure 2c). Return period and probability of the maximum daily rainfall were calculated by Weibull's plotting position formula (Chow, 1964) for the time period from 1966 to 2010 (Figures 2d and 2e).

3 Geomorphology of study basin

According to George and Shorbaji (1987), the study area exhibits three main geomorphologic zones as following (Figures 3a and 3b):

- The western part has an elevation ranged from sea level (main channel of the Wadi) to more than 2000 m above mean sea level (amsl) where is traversed by the Hijaz mountain range especially at Jabal Warqan on the south west of the study area.
- The eastern part of the study area where the Najd Plateau with average elevation ranges from 750 m to 1600 m (amsl).
- Northern and southern parts of the study area where the lava flows belonging to Harrat Hirmah at the north and extends to the south where Harrat Rahat and the southern part of Harrat Khaybar.
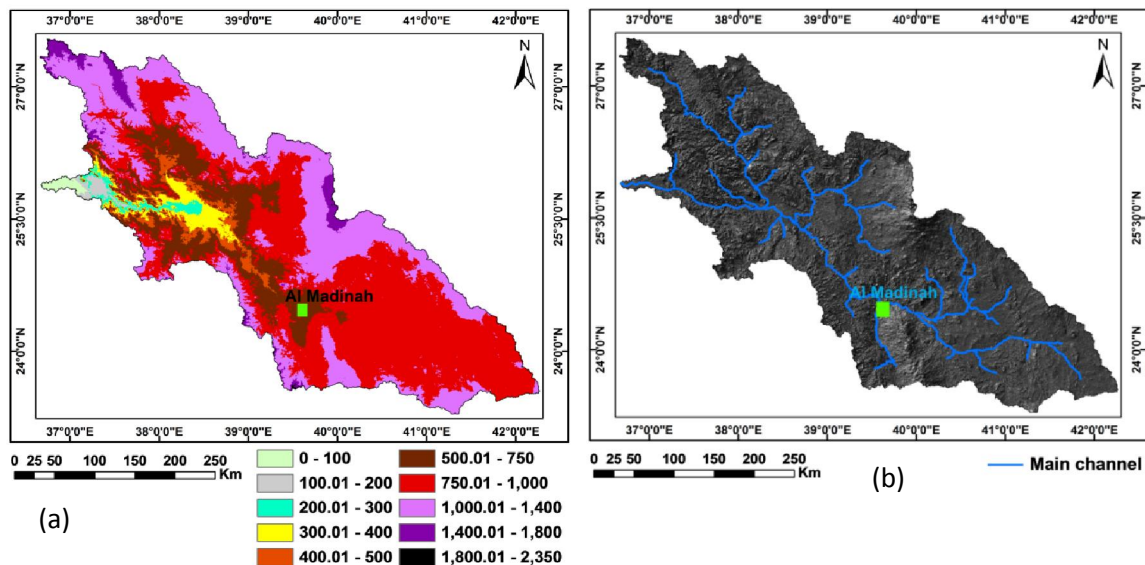

Figure 3. (a) Digital elevation model and **(b)** hillshade map of Wadi Al Hamd

4 Morphometric characteristics of study basin

Morphometric analysis of the study basin and its sub-basins is essentially based on the geomorphological features and morphometric parameters. These analyses had been done by tracing of the drainage network using digital elevation model (DEM) with 30 m resolution and topographic maps (scale 1:50,000) (Figures 3a and 3b). Depending on Strahler method (Strahler, 1957), the streams are ordered and the different parameters are measured and calculated according to Horton (1932, 1945) as shown in Tables 1 and 2. The study ungauged basin is morphometrically evaluated to estimate the relationship between rainfall and runoff based on hydrological characteristics through the integration between morphometric parameters, SMADA 6 and GIS techniques.

4.1 Drainage network characteristics
4.1.1   Stream order

Stream ordering is the essential parameter of qualitative and quantitative analysis of the drainage. The stream ordering systems has first advocated by Horton (1945), but Strahler (1952) has proposed this ordering system with some modifications. Stream order of the study basins has been done based on the method proposed by Strahler, Table 2 and Figure 4. The stream order of the study basin and its sub-basins ranges from 6 to 8 as shown in Table 2 and Figure 4.

It has observed that the maximum frequency is in the case of first order streams. It has also noticed that there is a decrease in stream frequency as the stream order increases.

Table 1. Morphometric parameters formulas

Morphometric Parameters			Formula	Reference
Drainage Network	1	Stream order ($_u$)	Hierarchical Rank	Horton (1945), Strahler (1952, 1964)
	2	Stream number (N_u)	Nu = N1+ N2 + N3+.....Nn	Strahler (1952)
	3	Stream length (L_u) in Km.	Lu= L1+L2+...... Ln	Horton (1932)
	4	Bifurcation ratio (Rb)	$Rb = Nu/\mathrm{Nu}+1$	Horton (1945) and Strahler (1964)
	5	weighted mean bifurcation ratio (WMRb)	$WMRb = \dfrac{\sum(Rbu/Rbu+1)(Nu+Nu+1)}{\sum N}$	Strahler (1953)
	6	Main channel Length(MC) in Km.	GIS software Analysis	
	7	Main channel index (Ci)	Ci = (Main channel length) / (Maximum straight of the main channel)	Mueller (1968)
	8	Sinuosity (Si)	$Si = VL/LB$	Gregory and Walling (1973)
Basin Geometry	9	Watershed Area (A) in Km^2	GIS software Analysis	Schumm (1956)
	10	The basin length (LB) in Km.	GIS software Analysis	Schumm (1956)
	11	The basin perimeter (Pr) in Km.	GIS software Analysis	Schumm (1956)
	12	Basin Width (W) in Km.	$W = A/LB$ (km)	Horton (1932)
	13	Circularity ratio (Rc)	$Rc = 4\pi A/\mathrm{P}r^2$	Miller (1953)
	14	Elongation ratio (Re)	$Re = (2\sqrt{A/\pi}/LB$	Schumm 1956
	15	Texture ratio (Rt):	$Rt = \sum Nu/\mathrm{Pr}$	Horton (1945)
	17	Inverse shape form (Sv) or Shape factor ratio (Sf)	$Sv = LB^2/A$	Horton (1932)
	18	Basin shape index (Ish)	$Ish = 1.27\, A/LB^2$	Haggett (1965)
	19	Compactness ratio (S_H)	$S_H = \mathrm{Pr}/2(\sqrt{\pi A})$	Horton (1945)
Drainage texture	21	Stream Frequency (F)	$F = \sum_{i=1}^{K} Nu/A$	Horton (1932, 1945)
	22	Drainage density (D)	$D = \sum Lu/A$	Horton (1932, 1945)
	23	Drainage Intensity (Di)	Di = F/D	Faniran (1968)
	24	Length of overland flow (Lo) in Km	$Lo = 1/2D$	Horton (1945)
	25	Infiltration Number (FN)	FN = (F)(D)	Faniran (1968)
	26	Drainage pattern (Dp)	Stream network using GIS software Analysis	Horton (1932)
Relief Characterizes	27	Maximum elevation (H_{max}) in meter	GIS software Analysis using DEM	
	28	Minimum elevation (H_{min}) in meter	GIS software Analysis using DEM	
	29	Relief (Rf) in meter	Rf = Highest elevation-Lowest elevation	Strahler (1952)
	30	Internal relief (E), in meter	E= (E85-E10)	Strahler (1952)
	31	Mean Elevation (Hm), in meter	GIS software Analysis using DEM	
	32	Relief ratio (Rr)	$Rr = (Rf/LB)100$	Schumm (1956)
	33	Slope index (SI%)	$SI = (E/0.75VL)100$	Majure and Soenksen (1991)
	34	Mean basin slope (Sm)	GIS software Analysis using DEM	
	35	Ruggedness number (Rn)	$Rn = Rf\,.D$	Melton (1957)
	36	Basin flow direction (BFD)	GIS software Analysis using DEM	
	37	Hypsometric Integral (HI)	$HI = (Elev - Elev_{min})/Elev_{max} - Ele$ Elev is the mean elevation, $Elev_{max}$. is the maximum elevation and $Elev_{min}$ is the minimum elevation,	Strahler(1952)

4.1.2   Stream number (Nu)

The total of order is the outcome of stream segments which is known as stream number. Horton (1945) states that the numbers of stream segments of each order form an inverse geometric sequence with order number, Table 2.

4.1.3   Stream length (Lu)

The total stream lengths of the study basins have various orders, which have computed with the help of topographical sheets (1: 50,000) and ArcGIS software. Horton's law of stream lengths supports the theory that geometrical similarity is preserved generally in watershed of increasing order (Strahler, 1964). Stream length has been computed based on the low proposed by Horton (1945). The total stream length of the Wadi Al Hamd is 57767.5 km, while for the sub-basins it ranges from 1498.8 km for Wadi Malal sub-basin to 11191.3 km for Wadi Al Jizal sub-basin.

When the logarithm of the stream number is plotted against the stream order, most drainage networks show a linear relationship (Figure 5), with only a small deviation from a straight line (Chow, 1964). According to Horton's principle the number of streams is negatively correlated with the order (Horton, 1932). The study basin and its sub-basins show a nearly perfect negative correlation with coefficient of correlation about 0.99 as shown in Figure 5. It is noticed that there is a difference in the geometric relationship between the stream length and its order for the basins of arid and semi-arid regions than for those of the humid regions. This latter geometric relationship between the stream length and the stream order is positive linear relationship as reported, (Schmidt, 1984; UNESCO/WHO/UNEP, 1992; White *et al.*, 2004). While a negative correlation as in this case of study basins (inverse relationship) are observed for other arid and semi-arid regions as also reported in India (Sreedevi *et al.*, 2005).

Hence, the stream length is an indicator of the relation between the climate, vegetation and the resistance rock and soil to erosion. Under similar conditions, impervious rocks support a longer stream length, consequently, higher drainage densities are observed than for permeable rocks. Arid and semi-arid regions show higher drainage densities than humid regions having the same geology, because of the flash flood and scarce vegetation in the former case. From Figure 7, it is noticed that, there is a proportional linear relationship between the sub-basin areas and both stream number and the corresponding stream length for all the study sub-basins.

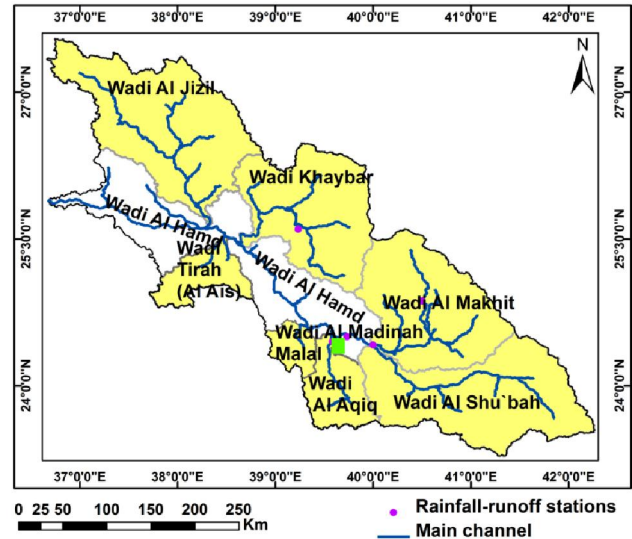#### 4.1.4   Bifurcation ratio (Rb) and weighted mean bifurcation ratio (WMRb)
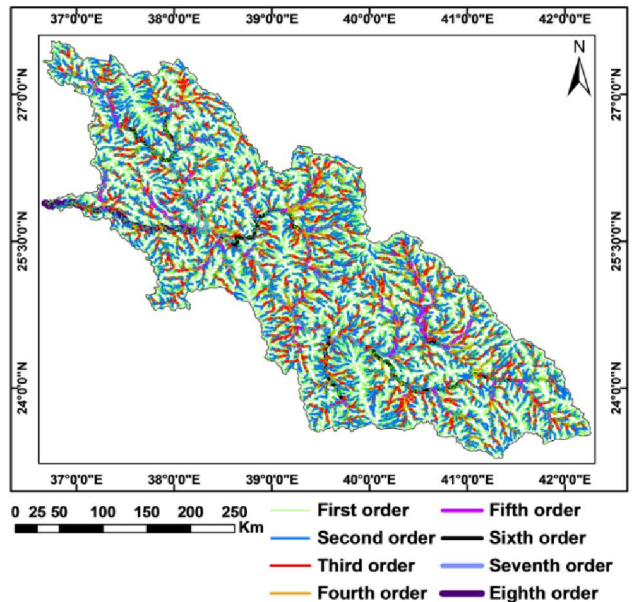

Figure 4. Stream order of Wadi Al Hamd

Figure 5. Sub-basins map of Wadi Al Hamd

Horton (1945) considered the bifurcation ratio as index of relief and dissertation. Strahler (1957) reported that the bifurcation ratios show a small range of variation for different regions or for different environment except where the powerful geological control dominates. It is observed that, the Rb of one order is differs from its next order; these irregularities are dependent upon the geological and lithological development of the drainage basin (Strahler, 1964). The bifurcation ratio is dimensionless property and generally ranged from 3.0 to 5.0. Strahler (1964) reported that, the lower values of Rb are characteristics of the watersheds, which have suffered less structural disturbances and the drainage pattern
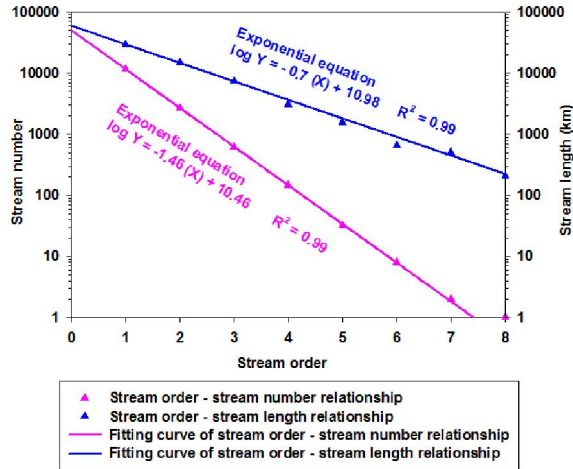
has not been distorted because of the structural disturbances (Nag 1998). Study basin and its sub-basins exhibit limited variations in Rb weighted mean bifurcation ratios (WMRb); this may be attributed to the rock type where the study basins have less variety in the geological outcrops as shown in Figure 1. Both Rb and WMRb have values greater than 3; this reflects high mountainous dissected areas and

elongated basins as shown in Table 2. Higher values of Rb indicate high effect of structural control on the drainage pattern as shown in Wadi Khaybar, Wadi Ash Shu`bah and Wadi Malal sub-basins (Table 2). While the lower values indicate that the basins are less affect by structural disturbances as shown in Wadi Al Mukhit and Wadi Tirah sub-basins (Table 2).
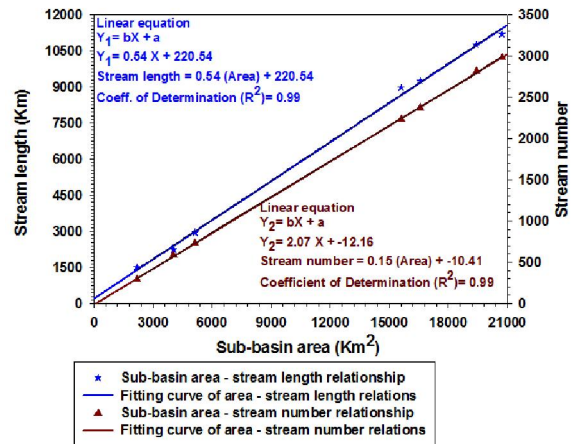
Table 2 Morphometric parameters and hazard degree of Wadi Al Hamd and its sub-basins

Morphometric Parameters			Wadi Al Hamd	Sub-basins of Wadi Al Hamd						
				Al Jizal	Khaybar	Mukhit	Ash Shu`bah	Al Aqiq	Malal	Tirah
Drainage Network	1	$(_u)$	8	7	6	7	6	6	5	6
	2	(N_u)	15047	2985	2231	2373	2813	735	297	584
	3	(L_u)	57767.5	11191.3	8970.2	9249.8	10747.5	2947.6	1498.8	2239.7
	4	(Rb)	3.98	3.8	4.46	3.60	4.63	3.69	3.95	3.52
	5	(WMRb)	4.30	4.30	4.30	4.30	4.35	4.02	4.30	4.10
	6	(MC)	206.9	119	151.2	83.50	218.1	93	45.7	2.50
	7	(MCi)	1.30	1.07	1.20	1.35	1.39	1.27	1.70	1.14
	8	(Si)	0.33	0.61	1.03	0.61	0.92	0.90	0.76	0.043
Basin Geometry	9	(A)	104678.7	20735	15600.6	16583	19422.7	5133.3	2182.2	4042.50
	10	(LB)	625	195	147	137	238	103	60	62
	11	(Pr)	3436.8	1448.7	1170.8	1032.1	1386.2	593.4	372.10	613.5
	12	(W)	167.5	106.3	106.1	121.0	81.6	49.84	36.40	65.20
	13	(Rc)	0.11	0.124	0.143	0.196	0.127	0.183	0.198	0.135
	14	(Re)	0.58	0.830	0.960	1.00	0.660	0.784	0.877	1.00
	15	(Rt)	4.38	2.06	1.91	2.30	2.03	1.24	0.80	0.95
	17	(Sv) or (Sf)	3.73	1.83	1.39	1.13	2.92	2.10	1.65	0.98
	18	(Ish)	0.34	0.69	0.92	1.12	0.44	0.62	0.77	1.34
	19	(S_H)	3.00	2.84	2.64	2.26	2.81	2.34	2.25	2.72
Drainage texture	21	(F)	0.144	0.144	0.143	0.143	0.145	0.143	0.136	0.144
	22	(D)	0.550	0.540	0.575	0.558	0.553	0.574	0.687	0.554
	23	(Di)	0.26	0.266	0.250	0.260	0.260	0.250	0.200	0.260
	24	(Lo)	0.906	0.926	0.869	0.896	0.903	0.871	0.728	0.902
	25	(FN)	0.080	0.078	0.082	0.080	0.080	0.082	0.093	0.080
	26	(Dp)	Dendritic	Dendritic	Dendritic	Dendritic	Dendritic	Dendritic	Dendritic	Dendritic
Relief Characterizes	27	H_{max}	2350	2073	2074	1821	1472	2350	1865	1663
	28	H_{min}	0	270	301	730	656	557	464	263
	29	(Rf)	2350	1803	1773	1091	816	1793	1401	1400
	30	(E)	950	800	700	300	300	600	500	500
	31	(Hm)	894	1012	987	950	936	962	894	763
	32	(Rr)	0.0038	0.009	0.009	0.006	0.003	0.017	0.025	0.024
	33	(SI%)	0.006	0.089	0.006	0.005	0.002	0.009	0.015	0.27
	34	(Sm)	5.9	7.5	5.5	2.6	2.5	6.6	12.1	9.30
	35	(Rn)	1.23	0.09	0.75	0.45	0.44	0.98	1.03	0.83
Summation of Hazard degree			25.96	24.97	24.22	20.40	25.95	23.40	31.60
Hazard degree			3.00	3.00	2.00	1.00	3.00	2.00	5.00

N.B the meaning of the symbols are mentioned in Table 1

Figure 6. Stream order, stream number and stream length relationship

Figure 7. Relation between the area, stream number and stream length of studied sub-basins

4.1.5   Main channel length (MC)

It is the length along the longest watercourse from the outflow point of designated basin to the upper limit to the watershed boundary. The main channel length has computed using ArcGIS-10 software. The main channel length of Wadi Al Hamd is about 206.9 Km, while, for the sub-basins it ranges from 2.5 Km for Wadi Tirah to 218 Km for Wadi Ash Shu`bah. The wide variations between the main channel lengths of the study basins are due to the variation of the geological features of the study area.

4.1.6   Main channel index (Ci)

It is suggested by Mueller (1968), it is an index of sinuosity characteristic which measures the deviation of the main channel from its geometric path. The main channel index of Wadi Al Hamd basin is about 1.3, while for the sub-basins it ranges from 1.07 for Wadi Al Jizal to 1.7 for Wadi Al Malal.

This indicates that Wadi Malal has good chance and potentiality for groundwater recharge.

4.1.7   Sinuosity (Si)

According to Gregory and Walling (1973), the sinuosity deals with the pattern of channel of a drainage basin, (Si) of Wadi Al Hamd basin is about 0.33 which indicate that this basin has good chance for groundwater recharge. (Si) of study sub-basins ranged from 0.043 for Wadi Al Aqiq to 1.03 for Wadi Khaybar as shown in Table 2. This reflects that, Wadi Al Aqiq sub-basin has the shortest travel time of water flow to the outlet, while Wadi Khaybar has the longest travel time with good chance for groundwater potentials.

4.2   Basin geometry characteristics

4.2.1   Watershed area (A)

The area of the Wadi Al Hamd and its sub-basins were determined using the ArcGIS software version 9.3. According to Horton (1945), all the areas were classified by size into the category of large basins, i.e. all of them are more than 100 Km^2. The area of the Wadi Al Hamd is about 104679 Km^2 and for its sub-basins ranged from 2182 Km^2 for Wadi Malal to 20735 Km^2 for Wadi Al Jizal as shown in Table 2.

4.2.2   The basin length (LB)

It indicates the travel time of surface runoff especially the flood waves passing through the basin. Basin length of Wadi Al Hamd is about 625 Km, and for the sub-basins, it ranges from 60-62 Km of Wadi Malal and Wadi Tirah, respectively, to 238 Km of Wadi Ash Shu`bah sub-basin as shown in Table 2. The travel time of Wadi Ash Shu`bah is the greatest one which gives good chance and potentiality of groundwater recharge than the shortest travel time of Wadi Tirah and Malal sub-basins.

4.2.3   The basin perimeter (Pr)

It is about 3436.8 Km of Wadi Al Hamd, while for the sub-basins it ranges between 372 Km for Wadi Malal to 1448.7 Km for Wadi Al Jizal as shown in Table 2.

4.2.4   Basin width (W)

According to Horton (1932), the basin width of Wadi Al Hamd is 167.5 Km, while for its sub-basins it ranges from 36.4 Km for Wadi Malal to 121 Km for Wadi Al Mukhit sub-basin. The small values of the basin width indicate to the elongated shape which led to groundwater recharge potentiality more than the larger values.

4.2.5   Circularity ratio (Rc)

According Miller (1953), the circularity ratio is influenced by the length and frequency of stream, geological structures, land use, land cover, climate, relief and slopes of the basin. The calculated values of the circularity ratio according to Strahler (1964) and Miller (1953) are ranged from 0.124 for Wadi Al

Jizal to 0.198 for Wadi Malal as shown in Table 2. This reflects that the study basin and its sub-basins have more or less circular shape and are characterized by high to moderate relief and drainage system is structurally controlled.

4.2.6   Elongation ratio (Re)

Table 2 shows the elongation ratios of the study basin and its sub-basins that are generally less than unity except Wadi Khaybar, Wadi Al Mukhit and Wadi Tirah. According to Schumm (1956), the higher the value of elongation ratio more circular shape of the basin and vice-versa. The variations of the elongated shapes the study basin and its sub-basins are due to the guiding effect of geology and structure. Thus, the elongation ratio is important for understanding the basin hydrology and for the estimation of flood hazards. Since, for a given rainfall event, the less elongated basin will generate a great peak runoff and faster travel velocities to the outlet. For example, the concentration time of flow towards the main channel is lower in circular basins than in elongated ones (Toy and Hadley, 1987). Strahler (1964) states that this ratio runs between < 0.7 and > 0.9 over a wide variety of climatic and geologic types. Wadi Khaybar, Wadi Al Mukhit and Wadi Tirah have high values of elongation ratio which reflect their high hazard degree and indicate that these Wadis are less elongated (oval) than the other sub-basins as shown in Table 2.

4.2.7   Texture ratio (Rt)

According to Horton (1945), the whole of Wadi Al Hamd basin has a texture ratio of about 4.38 Km^{-1}, while Rt ranges from 0.80 Km^{-1} for Wadi Malal sub-basin to 2.30 Km^{-1} for Wadi Al Mukhit sub-basin. Smith (1958), classified the texture ratio of the basins into coarse (<6.4 Km^{-1}), intermediate (6.4-16 Km^{-1}) and fine (>16 Km^{-1}). Table 2 shows that the Wadi Al Hamd and its sub-basins are coarse texture. According to Schumm (1965), texture ratio is an important factor in the drainage morphometric analysis which is depending on the underlying lithology, infiltration capacity and relief aspect of the terrain. The similarity of the texture ratios of the study basin and its 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 high values, where they are composed of hard rocks that have no ability for water infiltration, have a good chance to produce flash flood (Pareta, 2011a).

4.2.8   The inverse shape form (Sv)

It is also called shape factor ratio (Sf). According to Horton 1932, it is the relation between the square of the basin length and the basin area. The calculated value of Sv is about 3.73 for Wadi Al

Hamd, while it is ranged from 0.98 for Wadi Tirah sub-basin to 2.92 for Wadi Ash Shu'bah sub-basin. The higher value indicates that the basin length is high which resulted in a good chance for groundwater recharge. While the lower values indicate that the basin length is short which resulted in more flash flood hazard.

4.2.9   Basin shape index (Ish)

According to Haggett (1965), the calculated value of (Ish) of the Wadi Al Hamd is about 0.34, while it ranged from 0.44 for Wadi Ash Shu'bah sub-basin to 1.34 for Wadi Tirah sub-basin. The higher value indicates that the basin length is long which resulted in a good chance for groundwater recharge. While the lower values indicate that the basin length is short which resulted in more flash flood hazard.

4.2.10   Compactness ratio (S$_H$)

According to Horton 1945, it is used to express the relationship of hydrographic basin with that of a circular drainage basin having the same area as the hydrographic basin. A circular basin with low value of (S$_H$) is the most hazardous from a drainage stand point, because it will yield the shortest time of concentration before peak flow occurs in the basin. The values of (S$_H$) of Wadi Al Hamd is about 3, while for its sub-basins it ranged from about 2.25 for Wadi Malal and Wadi Al Mukhit sub-basins to 2.84 for Wadi Al Jizal sub-basin, showing limited variations across the sub-basins.

4.3   Drainage texture

4.3.1 Stream frequency (F)

According to Horton 1945, the basins of the structural hills have higher stream frequency and drainage density while the basins of alluvial deposits have low values. This means that the (F) is directly related to the lithological characteristics. Stream frequencies of the study basin and its sub-basins have limited variation as shown in Table 2. The limited variation is due to the similarity of lithology, rainfall, relief, infiltration rate, initial resistivity of terrain to erosion and total drainage area of the basin.

4.3.2   Drainage density (D)

The calculated values of (D) have limited variation between the Wadi Al Hamd basin and its sub-basins as shown in Table 2. A high value of basin drainage density indicates that a large amount of the rainfall resulted in runoff, while a low drainage density reflect erosion-resistant fractured hard rock of the study area and indicates that most of the rainfall infiltrates to recharge the groundwater storage.

4.3.4   Drainage intensity (Di)

Faniran (1968) reported that the (Di) is defined as the ratio of the stream frequency to the drainage density. Drainage intensity values of the studied basin and sub-basins have limited variations and ranged from 0.20 for Wadi Malal sub-basin to 0.26 for most

sub-basins. Low values of drainage intensity implies that the 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 rock types, consequently the surface runoff is not rapid removed from the basin, or those of high drainage intensity with high infiltration capacities which give good chance from groundwater recharge.

4.3.5   Length of overland flow (Lo)

According to Horton (1945), (Lo) refers to the length of surface water flow over the ground before it becomes concentrated in definite stream channels. It is an important independent variable, which greatly affect the quantity of water required to exceed a certain threshold of erosion. In the studied basin and sub-basins, (Lo) ranged from 0.728 Km for Wadi Malal sub-basin to 0.926 Km for Wadi Al Jizal sub-basin. Basins that have low values of (Lo) as Wadi Malal, indicate that the surface water is concentrated faster than the basins of high values of (Lo) as in Wadi Al Jizal sub-

4.3.6   Infiltration number (FN)

According to Faniran (1968), the (FN) is defined as the product of drainage density (Di) and stream frequency (F). It gives an idea about the infiltration characteristics of the basin which is an indication of impermeable lithology and higher relief. The higher the infiltration number will be the lower the infiltration and resulted in higher surface runoff. This resulted in the development of higher drainage density. All the calculated values of (FN) for Wadi Al Hamd and its sub-basins have lower values with limited variations as shown in Table 2.

4.3.7   Drainage pattern (Dp)

According to Howard (1967), basin drainage pattern helps in identifying the stage of the cycle of erosion and reflects the influence of slope, lithology and structure (Pareta, 2011b). Dendritic pattern is the main pattern in the study basin and its sub-basins as shown in Figure 4. This formed in a drainage basin composed of fairly homogeneity in texture and less of structural control.

4.4   Relief characteristics

Wadi Al Hamd is highly elevated basin, where the elevation ranged from 0 at the Red Sea Coast to 2350 m above mean sea level at the water divide of the basin with mean elevation about 894 m as shown in Figure 3. The study sub-basins can be grouped according the relief into two groups; moderate relief group as in Wadi Ash Shu'bah sub-basin, where its relief about 816 m and high relief group as the rest of the sub-basins as shown in Table 2.

4.4.1   Relief ratio (Rr)

According Schumm (1956), (Rr) is the relation between basin relief (Rf) and its length (LB). The high values of (Rr) in Wadi Al Aqiq, Wadi Tirah and Wadi Malal sub-basins as shown in Table 2 can be explained by the presence of highly resistant rocks of basement and Tertiary which covered the basin. The high values of (Rr) indicate steep slope and high relief, while the lower values may indicate presence of basement rocks that are exposed in the form of small ridges and mounds with lower degree of slope. Relief controls the rate of conversion of potential to kinetic energy of water draining through the basin. Runoff is generally faster in steeper basins, producing more peaked basin discharges and greater erosion process. Both (Rr) and (SI) are directly proportional to flooding and inversely to the time of concentration.

4.4.2   The slope index (SI%) or main channel slope

It is an indication of the channel slope from which an assessment of the runoff volume can be evaluated. Generally, the Wadi Al Hamd and its sub-basins are characterized by low slope index except Wadi Tirah sub-basin. The (SI%) ranged from 0.002 for Wadi Ash Shu'bah to 0.27 for Wadi Tirah sub-basin. This means that Wadi Ash Shu'bah has more groundwater recharge potentiality, while Wadi Tirah has flash flood hazard potentiality.

4.4.3   Mean basin slope (Sm)

Slope is the most essential 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 (Figure 8) have created by using Surface Analysis Tool in ArcGIS-10. The mean slope of the Wadi Al Hamd is about 5.9° and for its sub-basins, it ranged between 2.5° for Wadi Ash Shu'bah and 12.1° for Wadi Malal as shown in Figure 10 and Table 2. The wide variations between the values of mean slope are due to the variation of the topography of the sub-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 it takes more time for water to infiltrate, thereby reducing the amount surface runoff reaching the stream as in Wadi Al Mukhit and Wadi Ash Shu'bah sub-basins. A steep slope produces greater velocities and allows faster removal of the runoff from the watershed; therefore, shorter concentration times to peak of hydrograph as in Wadi Jizal, Wadi Tirah and Wadi Malal sub-basins as shown in Table 2.
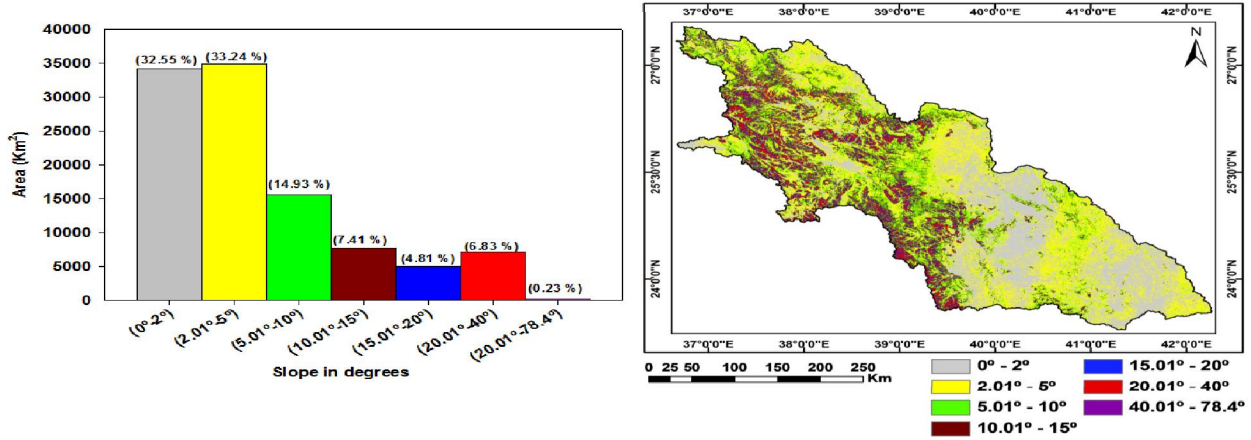
Figure 8. Slope map and histogram of Wadi Al Hamd and its sub-basins

4.4.4   Ruggedness number (Rn)

According to Melton (1965), it is a slope index that provides specialized representation of relief ruggedness within the watershed. High values of (Rn) occur when the basin of high relief ratio, steep and long slope for Wadi Al Aqiq, Wadi Tirah and Wadi Malal sub-basins as shown in Table 2.

4.4.5   Basin flow direction (BFD)

Using ArcView and ArcGIS tools, the direction of flow could be determined. The calculated main direction of Wadi Al Hamd is matching with the direction of its main channel which drains into the Red Sea with mean vector of 258.1° as shown in Figures 4 and 9 .

4.4.6   Hypsometric integral (HI)

Hypsometric curves are 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 (Herlekar and Sukhtankar, 2011). Strahler (1952, 1957, 1964) identified three types of landforms; namely, young, mature and old (monadnock) on the basis of hypsometric curve shape. 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 little erosion, which can evolve into S-shape, while concave hypsometric curves indicate a greater importance of erosion (Hurtrez *et al.*, 1999). Wadi Al Hamd shows mature S-shaped curve as shown in Figure. 10.
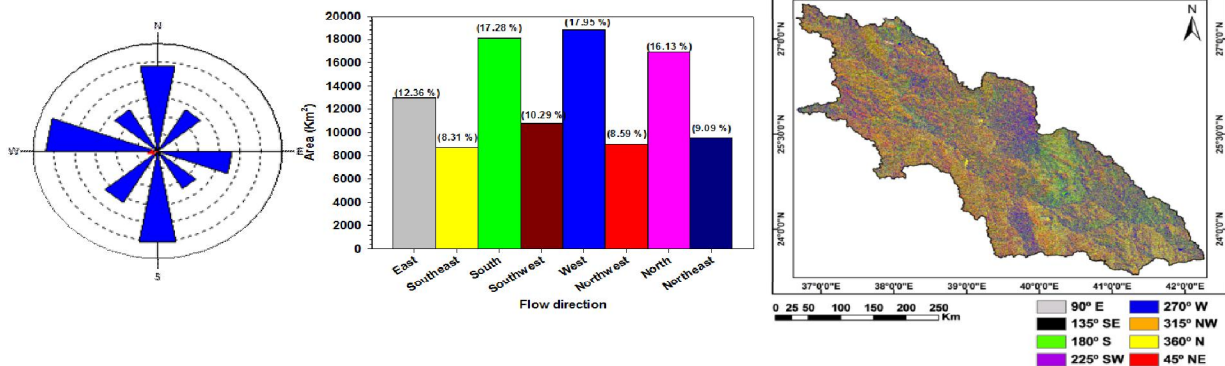

Figure 9. Flow direction map, histogram and rose diagram of Wadi Al Hamd

The (HI) assists in explaining the erosion that has taken place during the geological time scale (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 basin, 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 (HI) represents the area

under the hypsometric curve and it is computed as described by Hurtez *et al.* (1999). Generally, the calculated (HI) value of Wadi Al Hamd is about 0.38, this value indicates to that Wadi Al Hamd is mature 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. The study basin has hypsometric integral of 0.38 which indicated that this Wadi is mature or stable basin.
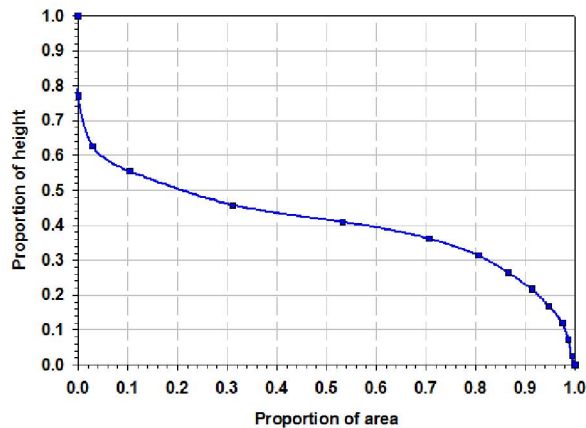

Figure 10. Hypsometric curve of Wadi Al Hamd

5   Evaluation of flash flood hazard

To evaluate the flash flood hazard of the study sub-basins of Wadi Al Hamd, nine morphometric parameters having a direct effect on flooding were chosen, and their relationship with the flash flood were 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). These parameters have a direct relationship with the hazard morphometric parameters except for the (WMRb) which shows an inverse relationship. 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 out 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 the samples points, the intermediate values can be calculated from the geometric relationship (Davis, 1975):

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

For the (WMRb) which shows an inverse relationship, the hazard degree was calculated using the following equation (Davis 1975):

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

where X is the value of the morphometric parameters to be assessed for the hazard degree for each basin, X_{min} and X_{max} are the minimum and maximum values of the morphometric parameters of all sub-basins, respectively.

The hazard degree for the study sub-basins of Wadi Al Hamd is calculated using equations (1) and (2). The summation of the hazard degrees for each basin represents the final flood hazard of that basin (Table 2). These values were ranged between 20.40 for Wadi Ash Shu'bah and 31.60 for Wadi Tirah as shown in Table 2. From the calculated values, according to their hazards degree the studied sub-basins can be classified into three groups: Basins of low hazard degree (Wadi Al Mukhit, Wadi Ash Shu'bah, and Wadi Malal); Basins of medium hazard degree (Wadi Al Jizal, Wadi Khaybar and Wadi Al Aqiq); Basins of high hazard degree (Wadi Tirah) as shown in Figure 11.
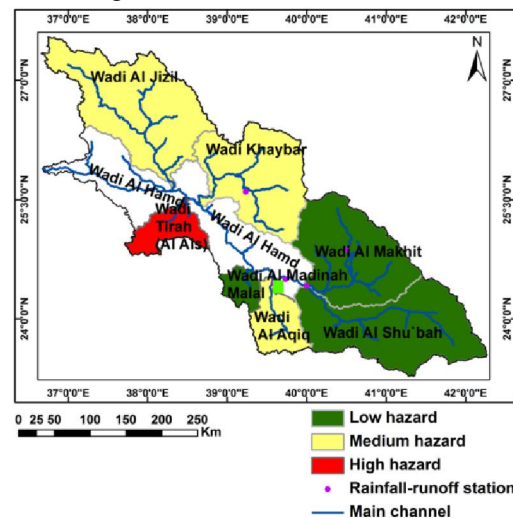

Figure 11. Map of flash flood hazard degree for Wadi Al Hamd sub-basins

6   Rainfall-runoff modeling

Rainfall-runoff relationships are very important for the catchment managements (i.e. 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. Basin systems in arid regions are commonly subjected to sporadic storm events that usually vary in scarcity and extremely high spatial and temporal variations. Usually, the application of hydrologic models in arid regions, are faced by scarcity in the required data that may not allow for the application of rainfall-runoff models.

Rainfall-runoff modeling in this study depends on the integration between morphometric parameters, GIS techniques, Storm water Management and Design Aid software (SMADA 6) and the available scarcity data of some rainfall events and the corresponding maximum flow rate. The required input of this study is shown in Table 3.

6.1   Infiltration characteristics

The infiltration characteristics in this program depends on the type of curve number used in the SCS (1972, 1985) formula. The curve number was developed by SCS (1972, 1985) to assist in the estimation of infiltration during rainfall events. The curve number is always less than 100. High curve numbers (>90) represent little or no infiltration, while low curve numbers (<50) represent pervious surfaces. The SCS (1972, 1985) combines infiltration losses with initial abstraction and estimates rainfall excess or equivalently the runoff volume by the following relationship:

$$R = \frac{(P - I_a)^2}{P - I_a + Sn} \qquad P > 0.2Sn \qquad (3)$$

where (R) is the accumulated runoff depth or rainfall excess, (P) is the accumulated rainfall, (I_a) is the initial abstraction and (Sn) is a parameter in mm, called the potential maximum retention capacity of a soil at the beginning of a storm or the maximum amount of water that will be absorbed after runoff begins. The initial abstraction (I_a) equals to *0.2Sn*, hence equation 3 can be equalised to equation 4 and *Sn* is given by equation 5.

$$R = \frac{(P - 0.2Sn)^2}{P + 0.8Sn} \qquad P > 0.2Sn \qquad (4)$$

$$Sn = \frac{25400}{CN} - 254 \qquad (5)$$

where *CN* is known as the curve number. Tables of curve number are available from many sources. Equation (4) indicates that (P) must exceed 0.2S

before any runoff is generated. It should be noted that equation (4) is a runoff equation and not an infiltration equation, hence using it as an infiltration equation can lead to errors (Haan *et al*., 1994).

Originally, the *CN* values were assigned by plotting observed runoff versus measured rainfall for a number of experimental plots scattered throughout the U.S. The *CNs* were then correlated with land use. The term "good conditions" or "poor conditions" in *CN* tables refers to the relative runoff potential. An area in good hydrologic condition would has higher infiltration rates and lower runoff rates than an area in poor condition.

The curve number is a function of the antecedent moisture condition, the land use, the hydrologic condition and the soil type. The antecedent moisture content is a function of the total rainfall in the 5-day period preceding a storm (Gheith and Sultan, 2002). Since the rain events in the study area are very rare, the moisture content can be neglected. The land use type and hydrologic conditions were classified as natural desert landscape and desert shrub (poor coverage, <30% ground cover). Three substrates crop out in the study area: Quaternary channel deposits, Tertiary fractured rocks with Lava and fractured basements. According to the SCS (1986), the classification of hydrologic soils is as following: the Quaternary deposits in the study area were classified as type 'A' soils with a curve number of 64, Tertiary fractured rocks with Lava as type 'B' and 'C' with a curve number 80 while the fractured basement was classified as type 'C' and 'D' with curve number equal to 87 (Table 4). The weighted *CN* for mixed land uses can be computed using table 4 as follows:

$$CN = \sum_{i=1}^{k} AiCNi \bigg/ \sum_{i=1}^{k} Ai \qquad (6)$$

where CN_i corresponds to the appropriate *CN* for the part of the watershed that has an area A_i. Once the proper *CN* is obtained, equations (5) and (6) can be used to estimate the accumulated runoff as a function of total accumulated rainfall. The respective assignments of the curve numbers for the Wadi Al Hamd basin based on Equation (6) are summarised in Table 4.

6.2   Initial abstraction factor (I_a);

The initial abstraction factor I_a is empirically derived from the maximum soil water retention (Sn), which is related to the soil drainage characteristics (e.g. *CN* values). I_a accounts normally for losses due to evaporation, plant uptake, and water retained in surface depressions during the rainfall event. Sn accounts for the total amount of water retained in the drainage basin during the rainfall event, essentially I_a and infiltration. Using equations (3-5) the initial

abstraction is calculated to be about 13 mm which it matches with the mean value of the evaporation of the study area.
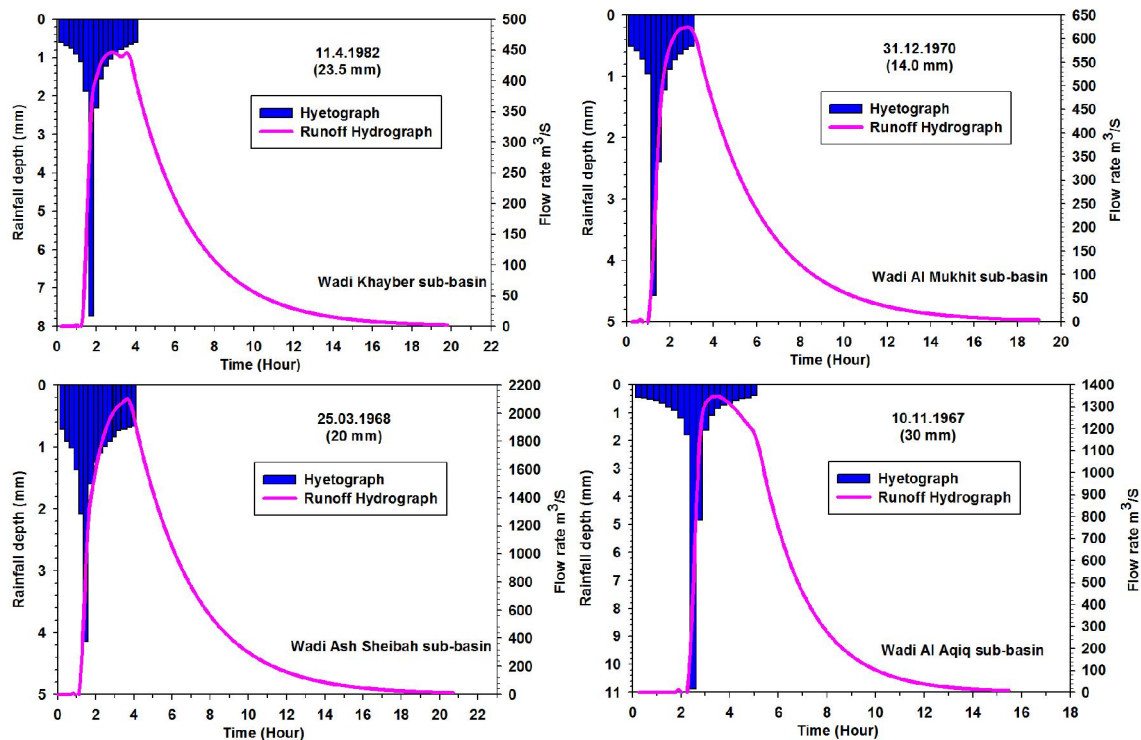
6.3 Time of concentration (T_c);

The time of concentration (T_c) is a fundamental basin parameter. It is used to compute the peak discharge for a basin. The peak discharge itself is a function of the rainfall intensity, which is based on the time of concentration. Time of concentration is the longest time required for a particle to travel from the basin water divide to the basin outlet. Equation 7 of Izzard's formula (1946) is one of many equations which are used to calculate the time of concentration of basin. In the present study, the Izzard's formula was used, where the obtained results were found reasonable and matching with the literature:

$$T_C = \frac{41(0.0007i + R)L^{1/3}}{(i^{2/3})(s^{1/3})} \qquad (7)$$

where T_c is the time of concentration, i is the rainfall intensity, R is the retardance coefficient, L is the flow length for sheet flow over surface (overland flow) and s is the average land slope for the sheet flow over the surface. The calculated results for the time of concentration of the study sub-basins using Izzard's formula are shown in Table 3.

7 Hydrograph generation

The final step carried out in the modelling process is the generation of hydrograph using SMADA 6. It contains a number of hydrograph generation routines, as follows: Santa Barbara Urban Hydrograph method (SBUH), SCS method, Unit Hydrograph method, Clark method.. However, SBUH method was selected in the present work among the other methods for hydrograph generation. SBUH was presented first by Stubchaer (1975). It has been shown that the SBUH method was found to be the most suitable method for the study area as the hydrograph results that agree with those of measured rainfall events and their corresponding maximum flow rate of flash flood. The calibration parameters for SMADA 6 were based on the available measured of four events of rainfall and the corresponding maximum flow rate as shown in Table 3 and Figure 12. Most of the physical characteristics of the basins are relatively well known from the field visits and DEM analysis; the other control parameters (Retardance coefficient, initial abstraction and additional abstraction), had to be assumed in this study to reach the hydrograph with maximum flow rate matches with the measured event.

Figure 12 Hyetograph based on the SCS distribution and final synthetic hydrographs of Wadi Al Hamd with different events

8: Results and discussion

Wadi Al Hamd and its sub-basins have an area that exceeds 100 Km^2; therefore all of these sub-basins can be grouped as large size basin which gives good opportunity to collect more water than the small sub-basins. The drainage patterns of the studied basins are dendritic; this indicates less percolation and maximum runoff especially in the elevated areas. It is noticed that the stream orders of each drainage network show that the courses of the main channels and their tributaries may be affected by the lineament structures and lithology, where many of these main channels and their tributaries are parallel to the lineament structures. Most of the segments up to the 4th order traverse areas of high altitudinal zones, forming steep slopes, while the other stream segments (5th –8th order) occur in relatively low altitudinal zones. Also, the stream lengths are directly proportional to the number of streams, basin area, basin length and perimeter. Basin length is an important parameter for the travel time of water, especially for the flash floods where the long basin has more travel time, consequently good opportunity for groundwater recharge than the short basin. All the studied sub-basins have values of Rb and WMRb greater than 3; this reflects high mountainous dissected areas and elongated basins.

The relationship between stream number and stream order of the study basin shows a perfect negative correlation with coefficient of correlation about 0.99 as shown in Figure 6. This matches with many studies for humid and arid regions. The relationship between the stream length and stream order for the study basin show also negative direct relationship with coefficient of correlation about 0.99, this doesn't match with many studies which are positive linear relationship as reported, (Schmidt, 1984; UNESCO/WHO/UNEP, 1992; White *et al.*, 2004). Therefore, the stream length is an indicator of the relation between the climate, vegetation, and the resistance rock and soil to erosion. Arid and semi-arid regions show higher drainage densities than humid regions having the same geology, because of the flash flood and scarce vegetation in the former case. It is noticed that, there is a proportional linear relationship between the sub-basin areas and both stream number and the corresponding stream length for the study basin and its sub-basins as shown in Figure 7.

The shape characteristics of the study basin and its sub-basins (circularity, elongation and compactness ratios), reflect the dominance of moderate (All Wadi Al Hamd basin) to high elongation with limited variation for the individual sub-basins. The elongation ratio is an important parameter for the basin hydrology and for the estimation of flood hazard. For a given rainfall event, the less elongated basins will generate a greater peak runoff and faster travel velocities to the outlet as shown in hydrographs of Wadi Khaybar, Wadi Al Mukhit, Wadi Ash Shu'bah and Wadi Al Aqiq sub-basins (Figure 11). The difference between the peak values are due to the total rainfall and the type of rock exposures.

Based on the elevation, Wadi Al Hamd is highly elevated basin, and its sub-basins can be grouped according the relief into two groups: moderate relief group as in Wadi Ash Shu'bah sub-basin, where its relief is about 816 m; high relief group as the rest of the sub-basins as shown in Table 2.

Wadi Al Hamd and its sub-basins are coarse texture. According to Schumm (1965), texture ratio is an important factor in the drainage morphometric analysis which is depending on the underlying lithology, infiltration capacity and relief aspect of the terrain. The lower values of texture ratio indicate that the has good chance for groundwater recharge, while the basins of high value ,where it is composed of hard rocks that have no ability for water infiltration and consequently it has good opportunity to produce flash flood.

Wadi Al Hamd shows mature (S-shape) stage of landscape evolution hypsometric curve shape with hypsometric integral of 0.38 which indicated that this Wadi is stable sub-basin.

According to hazard degrees, the study sub-basins can be grouped into three groups: basins of low hazard degree (Wadi Al Mukhit, Wadi Ash Shu'bah and Wadi Malal); basins of medium hazard degree (Wadi Al Jizal, Wadi Khaybar and Wadi Al Aqiq) and basins of high hazard degree (Wadi Tirah) as shown in Figure 10.

Evaporation losses (initial losses) cannot be neglected, the calculated value of the initial abstraction using equations (3-5) matches with the daily mean evaporation (14 mm/day). Since the rainfall in the study is usually takes place at night in winter, hence actually the evaporation should be less than the calculated value; evaporation value which applied in these models range between 2 mm to 7.1 mm as shown in Table 3. From the archival data and from oral information from the inhabitants, the time of concentration in of Wadi Al Hamd and its sub-basins ranges from 2-6 hours depending on the area of sub-basin and rainfall intensity, this matches with calculated and modeled value which is about 2-3.5 hours.

The calculated infiltration quantities ranged from10.7 mm to 18.8 mm resulting in recharge of groundwater during flood event. Since the study area is characterized by hyper-arid conditions with scarcely vegetated and shows a high hydraulic

conductivity of the Quaternary deposits in the delta of basin and along the basin channels. Hence, it is assumed that recharge of the Quaternary aquifer could be approximated by the additional transmission water losses that arise from the infiltration through the channel. The transmission losses were controlled by the basin and channel physical characteristics (geometry, shape, slope, etc), type of soil, depth to bed rock, temperature and duration of flow.

The rainfall events which applied for the studied sub-basins ranged from 14 mm to 30 mm with duration of 3-5 h. The return period of the rainfall events (14 mm and 30 mm) are ranged from 1.5 to 2 years with probability 63% to 44%, respectively. Results of the model applied at Wadi Al Hamd sub-basins are tabulated in Table 3. The results obtained from the applied mathematical models are considerably matching with those done by Subyani and Al-Ahmdi (2011) and Gutub (2013). The estimated runoff volume of Wadi Al Aqiq is about 140 m³×10⁶ which is resulted from 60 mm of rainfall event. Subyani and Al-Ahmdi (2011) and Gutub (2013) reported that the maximum peak discharge of Wadi Al Aqiq is about 2502 m³/sec.

Table 3 Input and output parameters of the studied basin for hydrograph generation using SMADA 6 based on SBUH method

parameters	Description of the parameters	Type of parameters	Al Hamd sub-basins			
			2	3	4	5
Area (km²)	The area of the studied basin in km²	Input parameters	15600.6	16583	19422.7	5133
Overland flow (m)	The flow length for sheet flow over surface		869	896	903	871
Slope (m/m)	The average land slope		0.003	0.004	0.002	0.0085
Retardance coefficient	The resistance of the bed of a channel to the flow of water in it (Manning's *n)*		0.0159	0.016	0.015	0.016
Pervious area (km²)	The area that allows relatively free passage of water		7800.3	11608	11653.7	3080
Impervious area (km²)	The land which allows for abstraction but upon which no infiltration takes place. Rain which fall onto this type of the land will either be abstracted, flow directly to the outlet of the watershed or flow onto the pervious watershed regions.		7800.3	4975	7769	2053
Percentage of impervious directly connected (%)	These are regions of the basin from which the water flows directly to the watershed outlet.		50	20	40	40
Weighted curve number	See the text		80	80	80	80
Initial abstraction factor	See the text		0.2	0.2	0.2	0.2
Additional abstraction on pervious (mm)	Water from rainfall which is retained on the watershed by infiltration.		10.16	7.9	10.4	10.7
Additional abstraction on impervious	Water from rainfall which is retained on the watershed on the surface. Additional abstraction on such type of lands cannot go to infiltration or become runoff.		5.0	2.8	4.8	8.1
Total rainfall (mm)	Total rainfall (mm) for a series of time increments		23.5	14.0	20	30
Total rainfall duration (h)	Event duration in hour		4.0	3.0	4	5
Rainfall intensity (mm/h)	Rainfall intensity (mm/h)		5.8	4.7	5	6
Historical Maximum flow rate (peak discharge) m³/s			450	600	2100	1500
Type of rainfall distribution (hyetograph)	Type of rainfall distribution (hyetograph)		SCS	SCS	SCS	SCS
Calculated time of concentration (minute)	See the text		207	180	207	120
Infiltration (mm)		Out put parameters	15.16	10.7	15.2	18.8
Initial losses (mm)			5.5	2.0	3.0	7.1
Rainfall excess (mm)			4.9	1.5	1.8	4.1
Calculated maximum flow rate (peak discharge) m³/s			440	620	1980	1346
Runoff volume (m³)			15.4×10⁶ m³	4.9×10⁶ m³	85 ×10⁶ m³	37.5 ×10⁶ m³

Table 4 The respective assignments of the curve numbers for the Wadi Al Hamd basin

Name of basin	Total Area (Km^2)	Substrate (Km^2)		Type of soil group	Value of CN	Weighted CN
Al Hamd	104678	Fractured Basement	57573	C and D	87	80
		Fractured Cambrian and Lava	34542	B and C	76	
		Quaternary	12563	A	62	

9　Conclusions

Flood hazard evaluation is very important for the catchment managements especially for the sustainable development of the water resources and for the protection from the flood hazard and drought. From the integrated analysis of the results on the morphometric characteristics of the study basins, it is concluded that the hydrological behavior of the study basin have a direct function of the geomorphology, the topography and the existing vegetation conditions.

In the present study, the topography and geology are considered as the important controlling factor on the hydrological response to flash flood. This study is proved that the hydrological characteristics of the basin are controlled with the basin physiographic features. The flash flood and groundwater recharge is the main results which express about the hydrological characteristics of basin.

Due to lack of measured data (rainfall and runoff) and due to that the flood assessment and rainfall-runoff relationship are dependent on the physiographic features of basins, therefore, this study was based on the integration between physiographic features of the study basin and GIS techniques. All the effective morphometric parameters of study basins were measured and calculated. According to the hazard degree, the sub-basins of the study area can be classified into the following three groups: high hazard degree (Wadi Tirah), medium hazard degree (Wadi Al Jizal, Wadi Khaybar and Wadi Al Aqiq), and low hazard degree (Wadi Al Mukhit, Wadi Ash Shu'bah and Wadi Malal). It is recommended that to construct some dikes for mitigation the runoff water and to recharge the shallow aquifer at the crossing point between the fourth stream order and fifth stream order of Wadi Tirah.

Climatic and morphometric data of the study area as one of the Red Sea Coastal areas were used to estimate the rainfall–runoff relationship for Wadi Al Hamd basin and its sub-basins. Such data were used by the application of GIS and SMADA 6 models. The results obtained by the proposed models were calibrated and verified.

Application of SMADA 6 model resulted in a synthetic hydrograph of Wadi Al Hamd sub-basins with a maximum flow peak ranges from 440 m^3/s to 1980 m^3/s. This synthetic hydrographs based on measured parameters (e.g. weighted slope, length of overland flow, sub-basin area and percentage directly connected of impervious area, rainfall intensity) and assumed data (e.g. weighted curve number, infiltration, evaporation). The volumes of surface runoff for Wadi Al Hamd sub-basins were estimated for different four storms (23.5 mm, 14 mm, 20 mm and 30 mm) which have return periods of 1.5 to 2 years with probability 63% to 44%. The resulted runoff volumes of Wadi Khaybar, Wadi Al Mukhit, Wadi Ash Shu'bah and Wadi Al Aqiq sub-basins are 15.4×10^6 m^3, 4.9×10^6 m^3, 85×10^6 m^3 and 37.5×10^6 m^3, respectively. The groundwater recharge of Wadi Al Hamd sub-basins through the transmission losses (infiltration losses) ranged from 72% to 76%, while the direct runoff ranges from 9% to 24% of the total rainfall.

On the other hand, the installation of telemetric meteorological stations on the top of the mountains along the Red Sea Series will help a lot for water resource studies, since there is a great lack of meteorological data in the area especially on the water divide line.

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