Mapping of Flash Flood Hazard Prone Areas Based on Integration Between Physiographic Features and Gis Techniques (Case Study of Wadi Fatimah, Saudi Arabia)

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Abstract: Flash floods in arid and semi-arid regions are the only recharge resource of surface water and groundwater. Forecasting flash floods in arid and semi-arid areas is very difficult because of hydrologic data scarcity. Also, flash floods are considered catastrophic phenomena posing a major hazardous threat to cities, villages and their infrastructures. This study deals with the evaluation of flash flood hazard in the ungauged Wadi Fatimah basin and its sub-basins depending on detailed physiographic features. ASTER data was used for preparing a digital elevation model (DEM) with 30 m resolution and geographical information system (GIS) was used in the evaluation of linear, areal and relief aspects of the morphometric parameters. The prevailing parameters such as basin area, flow accumulation, flow direction and stream ordering are prepared using ArcHydro Tool. Surface Tool in ArcGIS-10 software and ASTER (DEM) were used to create different thematic maps such as DEM, slope aspect, hill shade maps. Thirty five morphometric parameters were estimated and interlinked to produce nine effective parameters for evaluation of the flash flood hazard in the study area. Based on the effective morphometric parameters that control basin's hydrologic behavior and time of concentration has a direct effect on flooding prone area. Flash flood hazard of Fatimah basin and its sub-basins were identified and classified into three categories (High, medium and low hazard degree). This study provides details on flash flood prone area (Wadi Fatimah basin) and the mitigation measures. This study also helps to plan rainwater harvesting and watershed management in flash flood alert zones.

Key words: Arid Basins · Flash floods · Hydrology of ungauged catchments · Morphometric parameters · Hazard mapping.

INTRODUCTION

Drainage basins in arid and semi-arid regions are commonly subjected to sporadic storm events that usually vary in scarcity and extremely high temporal and spatial variation. Most important herein is flash flood hazard evaluation of ungauged basins through integration between physiographic features of the study basins and GIS techniques depending on, field observations, Digital Elevation Model (ASTER 30 resolution), topographic maps (1:50,000) and geologic maps (1: 250,000).

Physiography is the study of the physical features and attributes of land surface [1]. The detection of the physiographic features of a terrain is the first phase involved in the classification of various landforms of the terrain [1]. Flash floods often occur in arid regions as a consequence of heavy rainfall which occasionally causes major loss in property and life [2]. Flood hazard mapping is necessary component to appropriate land use in flooded areas. It creates easily read; prompt accessible chart and maps that mitigate their effect [3]. Flood hazard mapping in arid regions is an extremely important but

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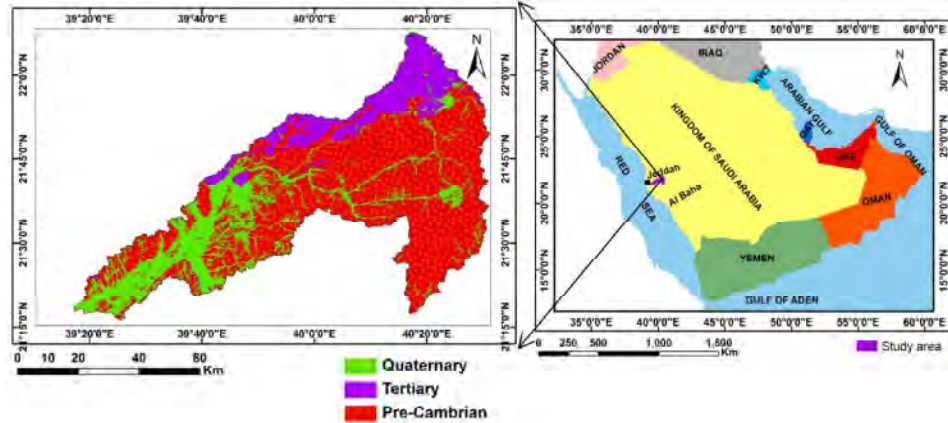P.O. Box 80208-Jeddah 21589, Saudi Arabia.

Fig. 1: Location and geology of Wadi Fatimah basin based on Geological map of Makkah quadrangle sheet 21D.

difficult task. The main reason is the scarcity of relevant data. Flood hazard mapping is very important for catchment managements (i.e. for the sustainable development of water resources and for the protection from the flood hazard and drought). Rainfall and runoff data are essential hydrological elements in the flood mapping of basin systems. Because the study area is enduring scarcity data, the flood inundation maps are made based on the topographic and geomorphic features of a Wadi [4], so, this study based on the integration between physiographic features of study area and GIS techniques.

Several studies are cited in the literature, related to flood hazard mapping and zonation using GIS [5-10]. Drainage basin characteristics in many areas of the world have been studied using conventional geomorphologic approaches [11-15]. According to [16], the morphometric characteristics of basins in many studies have been used to predict and describe flood peaks and estimation of erosion rate, underling the importance of such studies.

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 [17]. 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 [18, 19].

Location and Geology of Wadi Fatimah: Wadi Fatimah covers a large area of the south and east part of Jeddah Governorate and extends from NE to SW with 4869 km^2

area. It is located between longitudes 39° 15` and 40° 30` E and latitudes 21° 16` and 22° 15` N as shown in Fig. 1.

Geologically, the study area comprises Precambrian basement complex, Tertiary sedimentary and the Quaternary alluvial deposits (Fig. 1). The Precambrian rock units in the study area covers 63.6% of the area consisting of Late-Proterozoic basaltic to rhyolitic volcanic and volcano-clastic and epi-clastics of primitive island-arc type, that have been multiply deformed and metamorphosed and injected by intrusive bodies of different ages and compositions.

The Tertiary sedimentary succession is exposed beneath a cover of flat-lying lavas and Quaternary deposits on 13.9 % of Wadi Fatimah's area. It consists of clastic rocks dominated by sandstones, shale, mudstones, oolitic ironstones and occasionally conglomerates.

Quaternary deposits cover large parts of the study area, about 22.5 %, with 2 m -20 m thickness range. These deposits basically occur in the main channels of Wadi Fatimah. The principle units of the Quaternary rocks are gravel, alluvial fan deposits, talus deposits, alluvial sands and gravels of wadi beds and some eolian edifices.

Geomorphology of Wadi Fatimah: The geomorphology of Wadi Fatimah shows a typical of Wadi system extending from western part of the escarpment ridge of the Arabian shield. It starts from eastern high mountainous slopes of the escarpment and decreases down to the west side of flat sediments of coastal plain of Tihama close to the red sea. The elevation of the Wadi Fatimah ranges from 10 m to 2314 m with a mean elevation of 753 m (amsl), as shown in Fig. 2. Wadi Fatimah and its surrounding areas exhibit different geomorphologic units (Fig. 2) as follows:
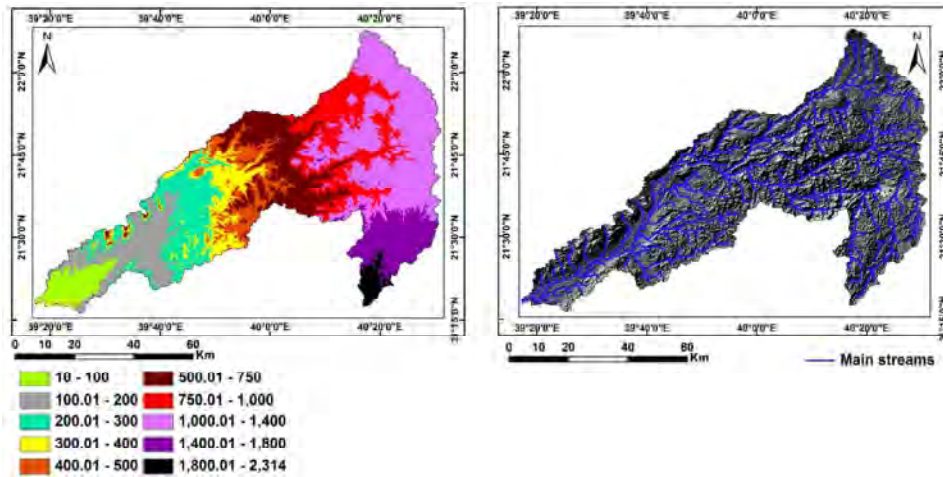
Fig. 2: Digital Elevation Map (DEM) and hillshade of Wadi Fatimah basin.

- High mountainous area is composed essentially of Proterozoic rocks with high elevation values reach 2314 m (amsl) as shown in Figs. 2 which represents the main basin's catchment. 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.

- Hilly area: The hilly area occupies the eastern and middle parts of the Wadi. This area is composed of hilly dissected and weathered rocks as shown in Fig. 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 channels of the Wadi.

Morphometric Characteristics of the Study Basin:
Morphometric analysis of the study basin and its sub-basins is based on the physiographic features and morphometric parameters mainly. These analyses were performed by tracing the drainage network using digital elevation model (30m resolution DEM) and topographic maps (1:50,000 scale). Based on Strahler method [20], streams are ordered and then hydrological parameters were measured and calculated according to [21, 11] as shown in Tables 1 and 2. The study of an ungauged basin is morphometrically evaluated to estimate the flash flood hazard based on morphometric parameters.

Drainage Network Characteristics
Stream Order: Stream ordering is the essential parameter of qualitative and quantitative analyses of any drainage basin. The stream ordering systems was first advocated by [11], but [22] 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 Wadi Fatimah basin and its sub-basins ranges from 4 to 7 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.

Stream Number (Nu): The total number of order is the outcome of stream segments which is known as stream number. Stream segments numbers of each order form an inverse geometric sequence with order number [11], Table 2.

Stream Length (Lu): Total stream lengths of the study basin and its sub-basins have various orders, which have computed with the help of topographical sheets (1: 50,000) and ArcGIS 10 software. Horton's law of stream lengths supports the theory that geometrical similarity is preserved generally in watershed of increasing order [12]. Stream length has been computed based on the law proposed by [11]. The total stream length of the Wadi Fatimah basin is 7603.9 km, while for the sub-basins it ranges from 42.6 km to 2985.6 km as shown in Table 2.

Table 1: Morphometric parameters formulas.

Morphometric Parameters			Formula	Reference
Drainage Network	1	Stream order (u)	Hierarchical Rank	[11], [22] & [12]
	2	Stream number (Nu)	Nu = N1+ N2 + N3+…..Nn	[22]
	3	Stream length (Lu)	Lu= L1+L2+...... Ln	[21]
	4	Bifurcation ratio (Rb)	$Rb = Nu/Nu+1$	[11] and [12]
	5	weighted mean bifurcation ratio (WMRb)	$WMRb = \dfrac{\sum (Rbu/Rbu + 1)(Nu + Nu + 1)}{\sum N}$	[20]
	6	Main channel Length	GIS software Analysis	
	7	Main channel index (Ci)	Ci = (Main channel length) / (Maximum straight of the main channel)	[24]
	8	Sinuosity (Si)	$Si = VL/LB$	[25]
Basin Geometry	9	Watershed Area (A)	GIS software Analysis	[27]
	10	The basin length (LB)	GIS software Analysis	[27]
	11	The basin perimeter (Pr)	GIS software Analysis	[27]
	12	Basin Width (W):	$W = A/LB$ (km)	[21]
	13	Circularity ratio (Rc)	$Rc = 4\pi A/Pr^2$	[26]
	14	Elongation ratio (Re)	$Re = (2\sqrt{A/\pi}/LB$	[27]
	15	Texture ratio (Rt):	$Rt = \sum Nu/Pr$	[11]
	16	Form factor ratio (FFR)	$FFR = A/LB^2$	[21]
	17	Inverse shape form (Sv) or Shape factor ratio (Sf)	$Sv = LB^2/A$	[21]
	18	Basin shape index (Ish)	$Ish = 1.27A/LB^2$	[33]
	19	Compactness ratio (SH)	$SH = Pr/2(\sqrt{\pi A})$	[11]
Drainage texture	20	Stream Frequency (F)	$F = \sum\limits_{i=1}^{K} Nu/A$	[21] & [11]
	21	Drainage density (D)	$D = \sum Lu/A$	[21] & [11]
	22	Drainage Intensity (Di)	Di = F/D	[36]
	23	Length of overland flow (Lo)	$Lo = 1/2D$	[11]
	24	Infiltration Number (FN)	FN = (F)(D)	[36]
	25	Drainage pattern (Dp)	Stream network using GIS software Analuysis	[21]
Relief Characterizes	26	Maximum elevation (Hmax)	GIS software Analysis using DEM	
	27	Minimum elevation (Hmin)	GIS software Analysis using DEM	
	28	Relief (Rf)	Rf = Highest elevation-Lowest elevation	[22]
	29	Internal relief (E)	E= (E85-E10)	[22]
	30	Mean Elevation (Hm)	GIS software Analysis using DEM	
	31	Relief ratio (Rr)	$Rr = (Rf/LB)100$	[27]
	32	Slope index (SI %)	$SI = (E/0.75VL)100$	[39]
	33	Mean basin slope (Sm)	GIS software Analysis using DEM	
	34	Ruggedness number (Rn)	$Rn = Rf.D$	[40]
	35	Hypsometric Integral (HI)	Elev is the mean elevation, Elevmax. is the maximum elevation and Elevmin is the minimum elevation,	[22]

Table 2: Morphometric parameters and hazard degree of the study basins.

Fatimah Basin — Name of Sub-basins

Morphometric Parameters			Whole Basin	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Drainage Network	1	(u)	7.00	6.00	6.00	5	5.00	5.00	5.00	5.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00
	2	(Nu)	7543.0	1470.0	3059.0	383	404.00	461.00	124.00	376.00	66	56.00	158.00	75.00	66.00	89.00	49.00	47.00	46.00
	3	(Lu)	7603.9	1503.2	2985.6	422.10	404.10	456.2	130.40	364.8	70.60	53.70	170.40	80.10	74.20	96.40	42.60	46.20	50.10
	4	(Rb)	4.50	4.20	4.74	4.18	4.32	4.40	3.19	4.50	3.65	3.80	5.30	4.35	4.17	4.25	3.33	3.46	3.72
	5	(WMRb)	4.90	4.60	4.44	4.25	4.96	4.80	3.63	4.65	3.58	4.62	4.30	4.73	4.08	4.88	3.68	3.84	5.40
	6	(MC)	110.00	79.50	73.00	20.20	35.40	12.50	10.00	17.10	4.90	11.90	17.00	9.30	1.00	7.00	6.00	2.80	2.40
	7	(MCi)	1.42	1.37	1.46	1.35	1.26	1.25	1.30	1.55	1.22	1.24	1.42	1.22	1.43	1.32	1.13	1.17	1.10
	8	(Si)	0.80	1.22	1.11	0.81	0.97	0.32	0.59	0.54	0.56	0.99	1.13	0.93	0.08	0.58	0.57	0.27	0.27
Basin Geometry	9	(A)	4869.00	981.00	1995.2	247.00	285.20	279.00	75.80	248.20	41.60	32.50	95.00	43.00	41.20	55.80	27.50	27.80	29.60
	10	(LB)	138.00	65.50	66.00	25.00	36.50	39.00	17.00	31.50	8.70	12.00	15.00	10.00	12.00	12.00	10.50	10.30	9.00
	11	(Pr)	776.40	338.60	435.00	128.50	145.70	170.00	65.50	130.50	47.50	46.50	64.4	45.20	44.20	52.00	39.30	42.40	36.00
	12	(W)	35.30	15.00	30.23	9.90	7.81	7.20	4.46	7.88	4.78	2.71	6.30	4.30	3.43	4.65	2.62	2.70	3.30
	13	(Rc)	0.10	0.11	0.13	0.19	0.17	0.12	0.22	0.18	0.23	0.19	0.29	0.26	0.27	0.26	0.22	0.19	0.29
	14	(Re)	0.57	0.54	0.763	0.71	0.52	0.48	0.58	0.56	0.84	0.54	0.73	0.74	0.60	0.70	0.56	0.58	0.68
	15	(Rt)	9.72	4.34	7.03	2.98	2.77	2.71	1.90	2.88	1.40	1.20	2.45	1.66	1.49	1.71	1.25	1.11	1.28
	16	(FFR)	0.26	0.23	0.46	0.40	0.21	0.18	0.26	0.25	0.55	0.23	0.42	0.43	0.29	0.39	0.25	0.26	0.37
	17	(Sv)	3.90	4.33	2.18	2.53	4.67	5.45	3.81	4.00	1.82	4.43	2.37	2.33	3.50	2.58	4.00	3.82	2.74
	18	(Ish)	0.33	0.29	0.58	0.50	0.27	0.23	0.33	0.32	0.70	0.29	0.54	0.55	0.36	0.49	0.32	0.33	0.46
	19	(SH)	3.14	3.10	2.75	2.31	2.43	2.87	2.12	2.43	2.08	2.30	1.86	1.95	1.94	1.96	2.11	2.27	1.87

Fatimah Basin — Name of Sub-basins

Morphometric Parameters			Whole Basin	1	2	3	4	5	6	7	8
Drainage texture	20	(F)	1.55	1.5	1.53	1.55	1.42	1.65	1.64	1.51	1.59
	21	(D)	1.56	1.53	1.5	1.71	1.42	1.64	1.72	1.47	1.7
	22	(Di)	0.99	0.98	1.02	0.91	0.99	1.01	0.95	1.03	0.94
	23	(Lo)	0.32	0.33	0.33	0.29	0.35	0.31	0.29	0.34	0.29
	24	(FN)	2.42	2.3	2.29	2.65	2.01	2.7	2.81	2.22	2.69
	25	(Dp)	Dendritic	Dendritic	Dendritic	Dendritic	Dendritic	Dendritic	Dendritic	Dendritic	Dendritic
Relief Characterizes	26	Hmax	2314	1600	2300	718	716	643	306	760	390
	27	Hmin	10	306	305	165	134	121	37	245	179
	28	(Rf)	2304	1294	1995	553	582	522	269	515	211
	29	(E)	1075	550	1050	125	175	240	55	350	160
	30	(Hm)	753	941	1115	300	333	262	87	525	249
	31	(Rr)	0.017	0.02	0.03	0.022	0.016	0.013	0.016	0.016	0.02
	32	(SI %)	0.013	0.009	0.019	0.008	0.007	0.026	0.007	0.027	0.044
	33	(Sm)	9.1°	8.90°	12.40°	6.10°	8.50°	6.40°	2.70°	7.30°	3.50°
	34	(Rn)	3.6	1.98	2.99	0.95	0.82	0.85	0.46	0.76	0.36
	35	(HI)	0.32	0.49	0.41	0.24	0.34	0.27	0.19	0.54	0.33
Summation of Hazard degree				20.52	29.9	21.49	13.09	17.87	20.15	16.07	23.41
Hazard degree				3	5	3	1	2	3	1	4

Fatimah Basin — Name of Sub-basins

Morphometric Parameters			Whole Basin	9	10	11	12	13	14	15	16
Drainage texture	20	(F)	1.55	1.72	1.66	1.74	1.6	1.6	1.78	1.69	1.55
	21	(D)	1.56	1.65	1.8	1.86	1.8	1.73	1.55	1.66	1.69
	22	(Di)	0.99	1.04	0.93	0.94	0.89	0.92	1.15	1.02	0.92
	23	(Lo)	0.32	0.3	0.28	0.27	0.28	0.29	0.32	0.3	0.3
	24	(FN)	2.42	2.85	2.98	3.25	2.89	2.76	2.76	2.81	2.63
	25	(Dp)	Dendritic	Dendritic	Dendritic	Dendritic	Dendritic	Dendritic	Dendritic	Dendritic	Dendritic
Relief Characterizes	26	Hmax	2314	714	743	739	720	515	227	232	383
	27	Hmin	10	88	99	148	96	65	44	20	75
	28	(Rf)	2304	626	644	591	624	450	183	212	308
	29	(E)	1075	100	60	30	120	100	90	40	80
	30	(Hm)	753	247	190	218	267	163	116	72	126
	31	(Rr)	0.017	0.052	0.043	0.059	0.052	0.038	0.017	0.021	0.034
	32	(SI %)	0.013	0.011	0.005	0.004	0.16	0.019	0.02	0.019	0.044
	33	(Sm)	9.1°	10.00°	5.40°	5.90°	10.30°	6.40°	4.50°	3.40°	4.40°
	34	(Rn)	3.6	1.03	1.16	1.1	1.12	0.78	0.28	0.35	0.52
	35	(HI)	0.32	0.25	0.14	0.12	0.27	0.22	0.39	0.25	0.17
Summation of Hazard degree				21.4	25.15	26.36	27.38	20.93	19.58	19.65	18.18
Hazard degree				3	4	5	5	3	2	2	2

Sub-basin 1: Wadi Huwarah, sub-bsin 2: Wadi Ash Shamiyah and Al Yamaniyah, sub-basin 3: Ayn Shams, sub-basin 4: Jibal Al Lahat, sub-basin 5: Wadi Makkah, sub-basin 6: Jibal Al Malas, sub-basin 7: Jabal Al Afayqim, sub-basin 8: Abu Urwah, sub-basin 9: Jibal Ash Shu`bah, sub-basin 10: As Samad, sub-basin 11: Jabal Mikassar, sub-basin 12: Jabal Ad Daymarah, sub-basin 13: Bahra1, sub-basin 14: Umm As Salam, sub-basin 15: Abar Abu Ja`alah, sub-basin 16: Bahra 2.
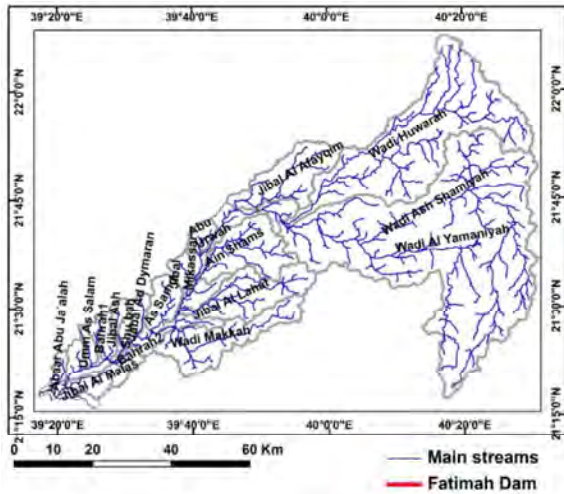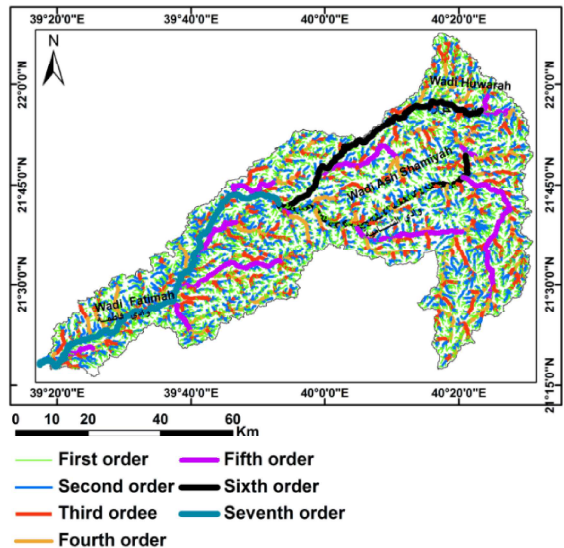
Fig. 3: Sub-basins map of Wadi Fatimah.
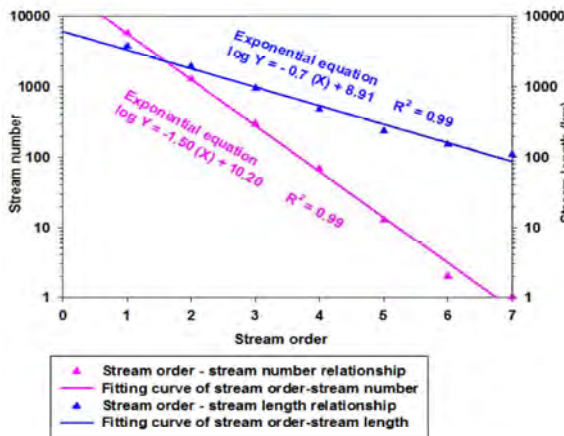

Fig. 4: Stream order of Wadi Fatimah.

Fig. 5: Stream order, number and length relationship of Wadi Fatimah basin.

When the logarithm of the stream number is plotted against the stream order, most drainage networks show linear relationship (Fig. 5), with only a small deviation from a straight line [23].

Bifurcation Ratio (Rb) and Weighted Mean Bifurcation Ratio (WMRB): According to [11] the bifurcation ratio is considered as the index of relief and distortion. Bifurcation ratios show a small range of variation for different regions or for different environment except where the powerful geological control dominates [20]. 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 [12]. The bifurcation ratio is a dimensionless property and generally ranges from 3.0 to 5.0. According to [12], the lower value of Rb is a characteristic of the watersheds, which have less structural disturbances and drainage pattern have been distorted [24]. 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; which reflect high mountainous dissected areas and elongated basins as shown in Table 2. Higher value of Rb indicates high effect of structural control on the drainage pattern, while lower value indicates that the basins are less affected by structural disturbances (Table 2).

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 Fatimah basin is about 110 Km, while for the sub-basins, it ranges from 1 Km to 79.5 Km as shown in Table 2. The large variations between the main channel lengths of the study basins are due to the variation of the geological features of the study area.

Main Channel Index (Ci): According to [25], the main channel index (Ci) is an index of sinuosity characteristic which measures the deviation of the main channel from its geometric path. The main channel index of Wadi Fatimah basin is about 1.42, while for the sub-basins it ranges from 1.10 to 1.55. This indicates that sub-basin of long main channel has a greater chance and potentiality for groundwater recharge.

Sinuosity (Si): According to [26], sinuosity (Si) deals with the pattern of channel of a drainage basin. The value of Si for Wadi Fatimah basin is about 0.80 which indicates that this basin has high potential for groundwater recharge. The Si value for study sub-basins ranges from 0.08 to 1.22 as shown in Table 2. This reflects that, sub-basins of low values of Si have the shortest travel time of water flow to the outlet, while the sub-basins of high values of Si have the longest travel time with high for groundwater potentiality.

Basin Geometry Characteristics

Watershed Area (A): The area of the Wadi Fatimah and its sub-basins were determined using the ArcGIS 10. Based on Horton's methodology, all sub basins were classified by size into three categories indicating large basins (>100 km^2), medium basins (50-100 km^2) and small basins (0-50 km^2), i.e. all of them are more than 100 Km^2. The area of the Wadi Fatimah is about 4869 Km^2 and for its sub-basins ranges from 27.5 Km^2 to 1995.2 Km^2 as shown in Table 2.

The Basin Length (LB): Basin length indicates the travel times of surface runoff especially flood waves passing through the basin. Basin length of Wadi Fatimah is about 138 Km and for the sub-basins, it ranges from 9 Km to 66 Km as shown in Table 2. The travel time of the sub-basins of large length is the highest which indicate greater potentiality of groundwater recharge than the shorter travel time of the sub-basins of short length.

The Basin Perimeter (Pr): The basin perimeter of wadi Fatima is about 776.4 Km, while it ranges between 36 Km to 435 Km as shown in Table 2.

Basin Width (W): Based on the methodology of [21], basin width of Wadi Fatimah is about 35.3 Km, while it ranges from 2.62 km to 30.23 km. The small value of the basin width indicates the elongated shape which leads to greater groundwater recharge potentiality.

Circularity Ratio (Rc): According to [27], the circularity ratio is influenced by the length and frequency of the stream, geological structures, land use, land cover, climate, relief and slopes of the basin. Calculated values of the circularity ratio for study basins, according to [12, 27], range from 0.10 to 0.29 as shown in Table 2. This reflects that the study basin and its sub-basins have small

to moderate circular shape and are characterized by high to moderate relief as well as the drainage system is structurally controlled.

Elongation Ratio (Re): Table 2 shows the elongation ratios of the study basin and its sub-basins which are less than unity. According to [28], the higher the value of the elongation ratio the more circular the shape of the basin and vice-versa. The variations of the elongated ratio values of 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 basin's hydrology and for estimating flood hazards. This is because for a given rainfall event, the less elongated basin will generate a great peak runoff and higher travel velocities to the outlet. Thus, the concentration time of flow towards the main channel is lower in circular basins than in elongated ones [29].

Texture Ratio (Rt): According to the methodology of [11], Wadi Fatimah basin has a texture ratio of about 9.72 Km^{-1}, while it ranges from 1.11 Km^{-1} to 7.03 km^{-1}. According to [30], texture ratio of the basins is classified into coarse (<6.4 Km^{-1}), intermediate (6.4-16 km^{-1}) and fine (>16 km^{-1}). Table 2 shows that the whole basin of Wadi Fatimah within the intermediate texture class, while all the sub-basins are in the coarse texture class except for Wadi Ash Shamiyah and Al Yamaniyah sub-basin which are intermediate texture class. According to [31], 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 higher values indicate this basin, are composed of hard rocks that are less capable of water infiltration which means more likely to encourage the onset of flash floods [32].

Form Factor Ratio (FFR): According to [21] the form factor ratio is defined as a numerical index that shows shape of the basin [32]. The FFR value for Wadi Fatimah is 0.26, while it shows a wide variation for sub-basin's range from 0.18 to 0.55. Basins of low values of form factor are more elongated, have less intense rainfall and also have lower peak runoff of longer duration over its entire

area than an area of equal size with a large form factor [33]. The basins with high values of form factor have a high peak runoff of longer duration. According to [34], the form factor is the governing factor of the water courses which enter the main streams

The Inverse Shape Form (Sv): It is also called shape factor ratio (Sf). According to [21], it is the relation between the square of the basin length and the basin area. Calculated value of Sv is about 3.9 for Wadi Fatimah, while it is ranges from 1.82 to 5.45. The higher value indicates that the basin length is high which predicts a greater likelihood for groundwater recharge. While the lower values indicate that the basin length is short which resulted in more flash flood hazard.

Basin Shape Index (Ish): According to [35], calculated value of (Ish) for Wadi Fatimah is about 0.33, while it ranges from 0.23 to 0.70. The higher value indicates that the basin length is long which predicts a greater potential for groundwater recharge. While lower value indicates that the basin length is short which resulted in more flash flood hazard.

Compactness Ratio (SH): According to [11], compactness ratio (SH) 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 SH is the most hazardous from drainage stand point; because it will yield the shortest time of concentration before the occurrence of the peak flow in the basin. The value of SH for Wadi Fatimah is about 3.14, while it ranges from about 1.86 to 3.10, showing wide variations across the sub-basins.

Drainage Texture
Stream Frequency (F): According to [11], basins of the structural hills have higher stream frequency and drainage density while basins of alluvial deposits have low values. This means the (F) is directly related to the lithological characteristics. Stream frequencies of the study basin and its sub-basins have a small variation, ranges from 1.42 km^{-2} to 1.72 km^{-2}, as shown in Table 2. The small 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.

Drainage Density (D): Calculated values of (D) have a small variation between Wadi Fatimah basin and its sub-basins, ranges from 1.42 km^{-1} to 1.86 km^{-1}, 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.

Drainage Intensity (Di): The drainage intensity (Di) is defined as the ratio of the stream frequency to the drainage density [36]. Drainage intensity values of the studied basin and sub-basins have limited variations that range from 0.89 to 1.15 as shown in table 2. Low values of Di imply 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 rapidly removed from the basin, or those of high drainage intensity with high infiltration capacities which give better chance from groundwater recharge.

Length of Overland Flow (Lo): Length of overland flow (Lo) refers to the length of the surface that water flow over the ground before it becomes concentrated in definite stream channels [11]. Lo is an important independent variable that greatly affects the quantity of water required to exceed a certain threshold of erosion. In study basin and sub-basins, Lo ranged from 0.27 Km to 0.35 km as shown in Table 2. A low value of Lo indicates that surface water is concentrated faster than that of basins with higher Lo values.

Infiltration Number (Fn): The infiltration number (FN) is defined as the product of drainage density (Di) and stream frequency (F) [36]. 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, the lower the infiltration resulting in higher surface runoff. This causes the development of higher drainage density. FN value for Wadi Fatimah is 2.42 while, the FN ranges from 2.01 to 3.25 as shown in Table 2.

Drainage Pattern (Dp): According to [37], basin drainage pattern helps in identifying the stage of the cycle of erosion and reflects the influence of slope, lithology and structure [38]. Dendritic pattern is the main pattern in the study basin and its sub-basins as shown in Figure 4. This results in a drainage basin with homogeneous in texture and less effect of structural control.

Relief Characteristics: Wadi Fatimah is a basin with wide variation in elevations. Elevations in this basin range from 10 at the Red Sea coast to 2314 m above mean sea level at basin's water divide with mean elevation of 753 m as shown in Figure 3. Sub-basins under study have wide variation relief ranges from 183 m to 1995 m as shown in Table 2. These sub-basins can be grouped according to the relief into three groups including; low relief group which its relief less than 500 m (Jabal Al Malas, Abu Urwah, Bahra 1, Umm As Salam, Abar Abu Ja`alah and Bahra 2 sub-basins) moderate relief group which has relief ranges from 500 - 1000 (Ayn Shams, Jibal Al Lahat, Wadi Makkah, Jabal Al Afayqim, Jibal Ash Shu`bah, As Samad, Jabal Mikassar and Jabal Ad Daymarah sub-basins) and high relief group which has relief more than 1000 m (Wadi Huwarah and Wadi Ash Shamiyah and Al Yamaniyah sub-basins).

Relief Ratio (Rr): According to [28], relief ratio (Rr) is the relation between basin relief (Rf) and its length (LB). The high values of Rr in as shown in Table 2 can be explained by the presence of highly resistant rocks of Pre-Cambrian 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.

The Slope Index (SI %) or Main Channel Slope: It is an indication of the channel slope from which an assessment of runoff volume can be evaluated [39]. Generally, Wadi Fatimah and its sub-basins are characterized by low to medium slope index except for Abu Urwah and Bahra 2 sub-basins of high slope index. The SI % ranges from 0.004 to 0.044. This means that Jabal Mikassar sub-basin (SI % = 0.004) has more groundwater recharge potentiality, while Abu Urwah and Bahra 2 sub-basins (SI % = 0.044) have greater flash flood hazard potentiality. Both (Rr) and (SI) are directly proportional to flooding and inversely to the time of concentration.

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 map of the study basin and its sub-basins (Figure 6) were created using Surface Analysis Tool in ArcGIS-10. The mean slope of Wadi Fatimah is about 9.1° and for its sub-basins, it ranging between 2.7° and 12.4° as shown in Figure 6 and Table 2. The wide variations between values of the mean slope are due to the variation of sub-basins? topography. Generally, slope of the terrain affects the total runoff volume and time of concentration to the peak of hydrograph. Basins with gentle slope produce less runoff volume and smaller peaks of runoff hydrograph. In gentle slope basins, the velocity of overland flow will be low which means more time for water to stay on ground surface. In other words, more infiltration rate resulting in reduced runoff reaching the stream. A steep slope produces greater velocities and allows faster removal of runoff from watershed. Therefore, shorter concentration time to peak of hydrograph as shown in Table 2.

Ruggedness Number (RN): According to [40], ruggedness number (Rn) 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 as shown in Table 2.

Hypsometric Integral (HI): Hypsometric curves are non-dimensional measure of the proportion of the drainage area above a given elevation. Hypsometric curves are related to geomorphic and tectonic evolution of drainage basins in terms of their forms and processes [28, 12, 41- 43]. Three types of landforms were identified ; namely, young, mature and old (monadnock) on the basis of hypsometric curve shape [22, 20, 12]. The hypsometric curves can be interpreted as young (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 [42]. Wadi Fatimah shows peneplain or distorted curve as shown in Fig. 7.

The (HI) assists in explaining the erosion that has taken place during the geological time scale [44]. 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 a selected basin, the range of basin altitude was divided into equal intervals. For each interval, the proportion of the basin area is calculated. Elevations and areas were then divided by relief and total basin area, so HI ranges from 0 - 1.
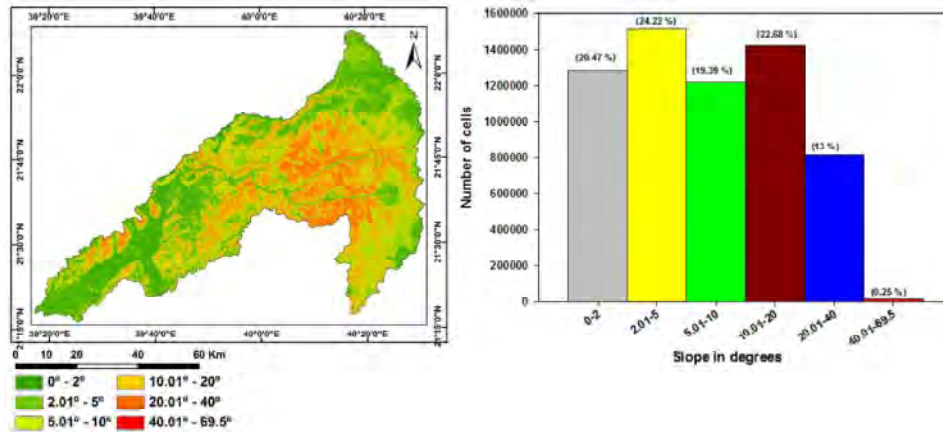
Fig. 6: Slope map of Wadi Fatimah basin and its histogram percentage.
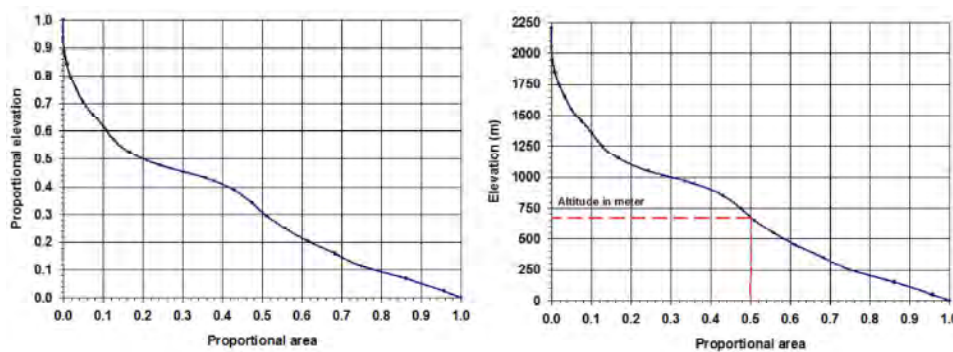

Fig. 7: Hypsometric curve and altitude value of Wadi Fatimah basin

The HI represents the area under the hypsometric curve and it is computed as described by [42]. Generally, the calculated HI value of Wadi Fatimah is about 0.32. This value indicates that Wadi Fatimah is a mature basin [45, 46, 47, 48] 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 are classified as old or Monadnock. Mature stage catchments have HI values range from 0.3 to 0.6. The study basin has hypsometric integral of 0.32 which indicates that this Wadi is of early mature to old stage.

Evaluation of Flash Flood Hazard: To evaluate the flash flood hazard of the study sub-basins of Wadi Fatimah, nine morphometric parameters with direct effect on flooding were chosen and their relationship with the flash flood were analyzed. These nine 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 that ranges from 1 to 5 is set for 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 samples points and intermediate values of hazard degree can be calculated from the geometric relationship according to [49]:
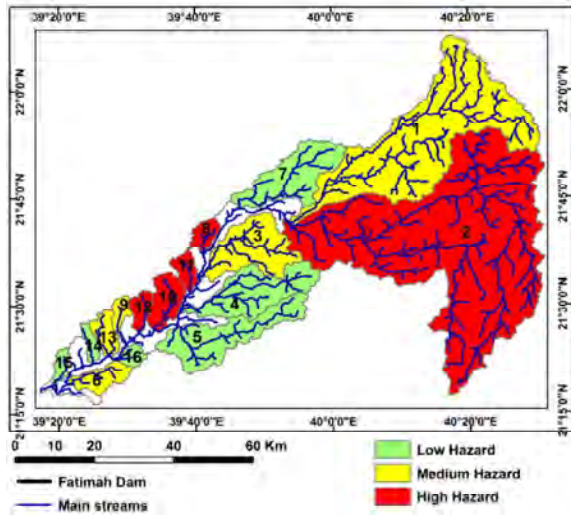
Fig. 8: Map of flash flood hazard degree for Wadi Fatimah sub-basins.

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

For the (WMRb) which shows an inverse relationship, the hazard degree was calculated using the following equation according to [49]:

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

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 Fatimah is calculated using equations (1) and (2). The summation of the hazard degrees for each basin represents the flood hazard degree of that basin (Table 2). The values range from 13.09 to 29.90 as shown in Table 2. From calculated values study sub-basins can be classified into three groups: Basins of high hazard degree (Wadi Ash Shamiyah and Al Yamaniyah, Abu Urwah, As Samad, Jabal Mikassar and Jabal Ad daymarah sub-basins); Basins of medium hazard degree (Wadi Huwarah, Ayn Shams, Jibal Al Malas, Jibal Ash Shu`bah and Bahra1 sub-basins); Basins of low hazard degree (Jibal Al Lahat, Wadi Makkah, Jabal Al Afayqim, Umm As Salam, Abar Abu Ja`alah and Bahra 2) as shown in Table 2 and Figure 8.

RESULTS AND DISCUSSION

Wadi Fatimah has an area that exceeds 100 km^2; therefore it can be grouped as large size basin which means it has greater chance of collecting more water than the smaller basins. In the study area, the drainage patterns are dendritic which indicates less percolation and maximum run-off especially in the highly areas. It is noticed that the stream orders of each drainage network show that the courses of the main channels and their tributaries are affected by lithology. Most of the segments up to the 3rd order traverse parts of high altitudinal zones, forming steep slopes, while other stream segments (4th-7th order) occur in relatively low altitudinal zones. Lower order streams mostly dominate the basin. The development of the stream segments in the basin area is more or less affected by rainfall. 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 and consequently greater chance for groundwater recharge than the short basin. Wadi Fatimah and its sub-basins have values of weighted mean bifurcation ratio greater than 3; this reflects high mountainous dissected areas and elongated basins.

Based on the elevation of the study basins, it is concluded that the complex topography of the study area plays a major factor affecting the areal characteristics of those watersheds and three main groups can be distinguished:

- Eastern group which includes Wadi Huwarah and Wadi Ash Shamiyah and Al Yamaniyah sub-basins with high elevations ranging from 1600 m to 2000 m
- Western group which includes Jibal Al Malas, Abu Urwah, Umm As Salam and Abar Ja`alah sub-basins which have elevations ranging from 0 m to 500 m.
- Central group which includes the other sub-basins having moderate elevations of 500 m and 1600.

Flash floods generally occur in upland areas of moderate to high topographic relief in a drainage basin as shown in eastern and central groups, whereas wadi floods have the characteristics of lowland areas of a drainage basin as shown in western group which means a greater likelihood for recharging the groundwater shallow aquifer. Thus, some dams and dikes are very important to construct for erection of the runoff water to infiltrate and recharge the shallow aquifer at the crossing point between the fourth stream order and fifth stream order.

All the sub-basins have values of bifurcation ratio and weighted mean bifurcation ratios greater than 3, which reveal that the drainage network in the study area is in a well-developed stage. They can hence grouped as high mountainous dissected areas and elongated basins.

The shape characteristics of the Wadi Fatimah and its sub-basins (circularity, elongation and compactness ratios), reflect the dominance of moderate to high elongation characters. 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 run-off and faster travel velocities to the outlet.

Whole Wadi Fatimah basin and Wadi Ash Shamiyah and Al Yamaniyah sub-basin is intermediate drainage texture ratio due to the presence of high relief in eastern and middle parts, while the other sub-basins are of coarse textures. The drainage textures of the investigated basin and its sub-basins indicate massive and resistant rocks cause intermediate coarse texture.

From the shape of hypsometric curve and the value of hypsometric integral, Wadi Fatimah can be described as mature to old stage and subjected to more erosion. This means that this Wadi needs less minimum mechanical and vegetative measures to arrest sediment loss, but may need more water harvesting type structures to keep surface water runoff at suitable locations for groundwater recharge.

Based on the hazard degree the sub-basins of Wadi Fatimah can be grouped into three groups as follow:

Basins of high hazard degree as for Wadi Ash Shamiyah and Al Yamaniyah, Abu Urwah, As Samad, Jabal Mikassar and Jabal Ad daymarah sub-basins. This means that there is no chance for recharging the groundwater. So, some dams and dikes are very important to construct for erection of the runoff water to infiltrate and recharge the shallow aquifer at the crossing point between the fourth stream order and fifth stream order. *Basins of medium hazard degree* (Wadi Huwarah, Ayn Shams, Jibal Al Malas, Jibal Ash Shu`bah and Bahra1 sub-basins), this group has the possibility of groundwater recharge.; *Basins of low hazard degree* (Jibal Al Lahat, Wadi Makkah, Jabal Al Afayqim, Umm As Salam, Abar Abu Ja`alah and Bahra2), this group has a good potentiality of groundwater recharge where it has low elevation and composed mainly of Quaternary deposits which permit with infiltration of water.

CONCLUSIONS

Wadi Fatimah is located in the western region of the Kingdom of Saudi Arabia is a frequent victim of flash floods due to excessive high rainfall intensity in addition to other factors relating to the geographical characteristics of the Wadi. Flood hazard mapping 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. Flash floods can be intensified by many factors such as topography and catchment area, where topography is the result of geology and climate that determine landforms, slopes and local of micro-topography. In this study the topography is considered as the important controlling factor on the hydrological response to flash flood because the study area is suffering from the scarcity of data. The flood inundation maps are based on the topographic and geomorphic features of Wadi Fatimah basin. The results showed that Wadi Fatimah can be classified into three groups according the hazard degree where 5 sub-basins have high hazard degree, six sub-basins have low hazard degree and five sub-basins has medium hazard degree. It is recommended that some dams and dikes are very important to construct for erection of the runoff water to infiltrate and recharge the shallow aquifer at the crossing point between the fourth stream order and fifth stream order. In conclusion, this study provides in-depth analysis of the flash flood prone areas of Wadi Fatimah basin and its sub-basins and the mitigation measures. This study will help to plan rainwater harvesting and watershed management in the flash flood alert zones for the future.

ACKNOWLEDGMENTS

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