Drainage Analysis of Mountainous Watersheds in Ras Al Khaimah Emirate, UAE

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***Abstract*—Many Wadis in the Arab Emirates (UAE) are active during rainy periods. Geomorphologically, the UAE is composed of mountains, gravel plains, sand dunes, and coastal zones. The runoff generation in these Wadis represents a complex phenomenon because of the topography of drainage basin. Morphological parameters were estimated and analyzed for the surface runoff generation and flooding possibility of twelve catchments in Ras Al Khaimah area of UAE. Hydrologic Engineering Center-Hydrologic Modeling System model is used to estimate the water yield in Wadi Al Bih due to rainfall events. Simulated results were compared with the observed water storage data of several historical storm events for the calibration of the model. The obtained results were compared with the observed yield and are found accurate and within an average of error 10%. Rainfall-runoff/yield curves were developed based on the duration and intensity of rainfall distribution. These curves can be used for prediction of surface water runoff and water storage in dams due to different rainfall events.**

Keywords-Geomorphology, Watershed, Flood, Rainfall-runoff, United Arab Emirates.

I. INTRODUCTION

The United Arab Emirates (UAE) is void of any rivers or perennial streams. However, a number of Wadis of different categories and valley beds are present. Wadis are mostly dry but they drain the runoff to their regions only during the rainy seasons. The runoff generation from the rainfall behaves differently from one Wadi to the other according to the nature of topography and headwater catchments. In the mountains, floods are the result from heavy rainfall where small part of the rain water infiltrates in the Wadi beds and thus produce fairly large flood discharge. Most of the annual rainfall therefore reaches the plain which corresponds to a relatively high annual runoff. The mean annual runoff of major wadis in U A E is about 120 MCM [1]. In the piedmont areas, both infiltration and runoff are observed. Therefore, heavy rainfall may give rise to runoff, even in a fairly permeable zone (gravel plain). A large part of the annual rainfall in this area flows out into the dune region. In such a region where runoff is almost inexistent, the only water loss is due to evaporation. The water loss is directly proportional to the number of days of rainfall and its depth.

Morphological parameters are the main factors influencing the surface runoff generation, surface water yield, peak discharge, flooding and groundwater recharge. Therefore these parameters are necessary to estimate and analyze for the flooding and recharge aspects of the basins.

Surface water assessment is also essential for water management including flood control, recharge assessment and surface water utilization of a water basin. The drainage analysis was carried out by morphological parameters analysis as well as the application of rainfall-runoff model. In the present study, Ras Al Khaimah area of northern emirates was selected for the drainage analysis. Fig. 1 presents a location map for the study area. The biggest among other wadis, Al Bih was considered for the rainfall-runoff assessment.

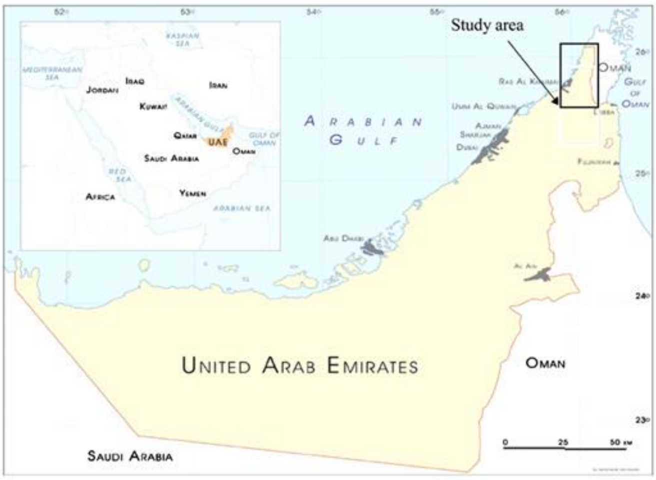

Figure 1. Location of the study area

II. CHARACTERIZATION OF MORPHOLOGICAL PARAMETERS

Every hydrologic design is different because the factors that affect the design vary with location. The important factors such as geomorphological parameters and land use of the watershed, as well as the amount of storage. The morphometric parameters have been used in various studies of geomorphology and

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surface water hydrology, such as flood characteristics and sediment yield.

Morphometric analysis of any watershed provides an account about the topography of the area, geological condition and runoff potential. Morphometric analysis is the measurement of 3 dimensional geometry of landforms and has traditionally been applied to watershed, drainages, hill slopes, and other group of terrain features [2]. The morphometric characteristics of a watershed represent its attributes and can be helpful in synthesizing its hydrological behavior [3]. Morphometric parameters affect catchment stream flow pattern through their influence on concentration time [4].

Drainage patterns are determined by the inequalities of surface slope and rock resistance. Drainage pattern may reflect original slope and structure or successive changes. In any drainage basin, the drainage characteristics are deduced by the following morphological important parameters such as linear aspects of the drainage network: stream order, bifurcation ratio, stream length and areal aspects of the drainage basin: drainage density, stream frequency, texture ratio, elongation ratio, circularity ratio, form factor ratio of the basin.

Northern part of UAE of Ras Al Khaimah region comprising twelve catchments were analyzed for the drainage characteristics. The Fig. 2 shows the distribution of catchments and the drainage network of each catchmnet of northern region of Ras Al Khaimah area. In Ras Al Khaimah area, 12 basins namely; Shaam, Ghalilah, Rehban, Hagil, Al Bih, Ar.Rimelah, Naqab, Ghel, Al Arbain, Nihel, Khat and Al Minesib. The qualitative analysis of the morphometric characteristics of these basins (i.e., stream order, stream length, bifurcation ratio, drainage density, drainage frequency, relief ratio, elongation ratio, basin shape and form factor ratio) has been carried out. Morphometric parameters of these twelve catchments were estimated and presented in Tables 1 through 3.

TABLE I. MORPHOLOGICAL PARAMETERS

Basin	A	R.R	D.D	S.F	E.R	F.F	B.S
Shaam	38	0.08-0.19	0.0-1.5	0.94	0.77	0.47	2.14
Ghalilah	75	0.08-0.19	0.0-1.5	0.71	0.80	0.51	1.97
Rehban	13	0.08-0.19	0.0-1.5	1.23	0.61	0.29	3.45
Hagil	29	0.08-0.19	0.0-1.5	1.31	0.84	0.55	1.83
Al Bih	476	0.04-0.08	1.5-2.0	1.44	0.58	0.27	3.76
Ar.Rimela	29	0.04-0.08	2.0-2.5	0.96	0.78	0.48	2.08
Naqab	107	0.04-0.08	2.0-2.5	1.37	0.55	0.24	4.25
Ghel	49	0.04-0.08	2.5-3.6	1.58	0.64	0.32	3.14
Al Arbain	8	0.04-0.08	2.5-3.6	2.21	0.59	0.27	3.72
Nihel	3	0.08-0.19	2.5-3.6	1.18	0.34	0.09	11.3
Khat	3	0.08-0.19	2.5-3.6	2.07	0.27	0.06	17.7
Al Minesib	49	0.04-0.08	2.5-3.6	2.57	0.97	0.74	1.36

A = Area (Km^2), R.R = Relief Ratio, D.D = Drainage Density (Km/Km^2)
S.F = Stream Frequency, E.R = Elongation Ratio, F.F = Form Factor Ratio
B.S = Basin Shape

TABLE II. DETAILS OF STREAM ORDER

Catchment	Stream order					Total no. of Streams
	I	II	III	1V	V	
Shaam	24	9	2	1		36
Ghalilah	41	10	2	1		54
Rehban	9	4	2	1		16
Hagil	26	8	3	1		38
Al Bih	603	119	26	6	1	685
Ar.Rimelah	22	5	1			28
Naqab	120	22	3	1		146
Ghel	58	15	4	1		78
Al Arbain	12	4	1			17
Nihel	3	1				4
Khat	5	1				6
Al Minesib	92	25	6	2	1	126

TABLE III. BIFURCATION RATIO

Catchment	Bifurcation ratio			
	I/II	II/III	III/IV	IV/V
Shaam	2.67	4.5	2.0	
Ghalilah	4.1	5.0	2.0	
Rehban	2.25	2.0	2.0	
Hagil	3.25	2.67	3	
Al Bih	5.06	1.88	4.58	6
Ar.Rimelah	4.4	5	4.33	
Naqab	5.45	7.33	3	
Ghel	3.87	3.75	4	
Al Arbain	3	4		
Nihel	3			
Khat	5			
Al Minesib	3.68	4.17	3	2

III. MORPHOLOGICAL PARAMETERS AND DISCUSSIONS

All the drainage patterns were dendritic characterized by the regular branching in all directions with tributaries joining the main stream at all angles. It generally develops where rocks offer uniform resistance in horizontal directions. Catchment area of northern region varies from 2.9km^2 to 476.4km^2 with Khat was the smallest and Al Bih represents the biggest catchment in the region. Relief ratio varies from 0.04 to 0.19 in other words it 4 to 19 per cent of slope. Highest percentage of slopes was noticed in the northern most part of the region and lower slopes were observed between Al Bih and Al Arbain catchments. Drainage is density in the range of 0.0 and 3.6. Higher drainage densities are observed in southern catchments from Rimelah to Al Minseb when compared to northern catchments from Sham to Al Bih. The estimated stream frequencies varied between 0.94 and 2.57. Elongation ratio is in the range from 0.27 to 0.96. The maximum form factor ratio was observed at Al Minseb (0.74) and minimum at Khat (0.06) catchment. Basin shape among the catchments are in the range of 1.36 and 17.73.

Drainage density measures the potential of the basin to adequately evacuate generated storm flow as fast as possible. It has an effect on hydrograph time relations such as time of concentration, time lag, time to peak and hydrograph peak.

Lower the drainage density tends to lower the flooding probability. Generally, more than 0.2 drainage densities are regarded as more prone to flooding. The drainage density varies between 1.5 km/km^2 and 3.6 km/km^2. The estimated drainage densities of all the catchments are more than 0.2 and fall under the high flooding possibilities.

The stream frequency is in the range between 0.71 and 2.57 for all the catchments. Generally, more than 0.2 stream frequency more prone to get flooded. However, these parameters are impacted and inter-related by the bifurcation ratios. High drainage density and high stream frequency in river basin indicate larger runoff from the basin.

Bifurcation ratios characteristically range between 3.0 and 5.0 for basins in which the geologic structures do not disturb the drainage pattern [5]. The value of the ratio tends to be more for elongated basins [6]. It is a useful index for hydrograph shape for watersheds similar in all other respects. The high value indicates structural complexity and low permeability [7]. It also indicates that the value of bifurcation ratio is not same from one order to next order. An elongated watershed has higher bifurcation ratio is lower capacity in moving their excess precipitation from the lower to the higher order of stream. Therefore the higher bifurcation ratios of the basins indicate the higher groundwater potentiality and low flooding possibilities. The bifurcation ratio for the selected catchments are estimated between 1.88 and 6. Part of the northern catchments from Shaam to Hagil representing comparatively lower bifurcation ratios than remaining catchments in the southern part. It is indicated that the watersheds in the northern part more circular than the southern part and would produce larger runoff. This also means that flood peak is easily achieved and the basins are liable to flooding.

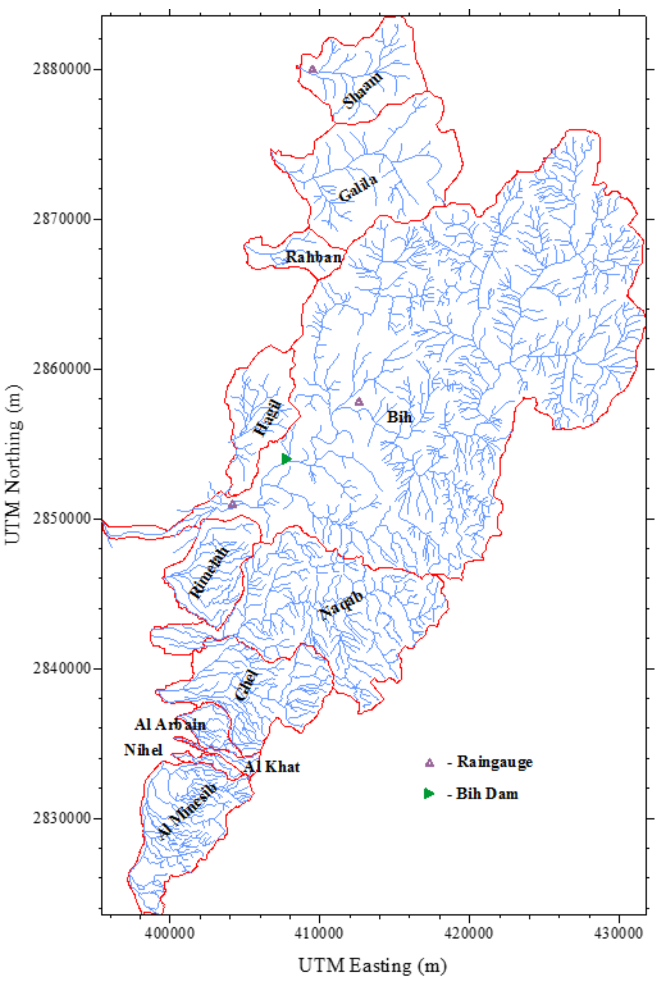

Figure 2. Selected catchments and drainage network

Relief ratio measures the overall steepness of a drainage basin and is an indicator of the intensity of erosion processes operating on the slopes of the basin. It has been found to relate to stream gradient, drainage decay, maximum slope, basin shape; etc. The basins recorded the higher relief ratio (0.04-0.19), which indicates overall slope and hence higher runoff velocity.

The elongation ratio is the significant index in the analysis of the shape of the basin which helps to give an idea about hydrological characters of a drainage basin. The value of elongation ratio generally varies from 0.6 to 1.0 associated with a wide variety of climate and geology. Values close to 1.0 are typical of regions of very low relief whereas that of 0.6 to 0.8 are associated with high relief and steep ground slope [5]. These values can be grouped into three categories, namely circular (>0.9), oval (0.8-0.9), less elongated (0.7-0.8), and elongated (< 0.7). The elongation ratios of selected catchments are varying from 0.27 to 0.96. The shape indices considered in this study indicate that basins are oval to less elongated basin where travel time and time of concentration are moderately short.

Form factor determines about the shape of the basin. Form factor is defined as the ratio of basin area to the square of the basin length [9]. For perfectly circular basin the value should be greater than 0.78. Smaller the value, more elongated will be the basin. The watershed with high form factors have high peak flows of shorter duration, whereas elongated watershed with low form factor flow for longer duration. The estimated form factors in the range between 0.06 0.74 for all the watersheds. Results indicate that all the catchments represent less elongated to elongated basin except Al Minesib. Shorter duration with high peak flow expected from the Al Minesib basin.

Basin shape determines about peak flow or flood discharge. It is the ratio of square of the basin length to the area of the basin [10]. Lesser value indicates sharply peaked water flow which may lead to the flooding. Higher the value indicates weaker flood discharge period or weaker out flow. The factor is varied from 1.36 to 17.73 for the selected basins. Nihel amd Khat basins indicated higher values while Al Minesib has the minimum value. These values indicate lower flood incidences in Nihel and Khat when compared to Al Minesib.

IV. RAINFALL-RUNOFF MODELLING

The assessment and quantification of the surface water potential is essential for planning and management of the water resources system. However, very limited work on the assessment of surface water potential was carried out in U. A. E. Therefore a suitable methodology should be selected and verified for the design of water conservation structure, the peak rate of surface runoff due to a rainstorm of a specified frequency.

Generally, existing hydrological models are complex, over-parameterized, data demanding and expensive to use. Such models are often criticized for being over parameterized [11]. When validating through comparison of observed and modelled stream flow, it is known to be statistically unsound to model hydrographs with more than about five model parameters [12]. The simple modelling approaches with a fewer model parameters is generally accepted strategy in rainfall-runoff modelling [13], [14], [12], [15] and [16]. However, the SCS methodology is widely used because it is a reliable procedure that has been used for many years in different parts of the world. It is computationally efficient, the required inputs are generally available, and it relates runoff to soil type, land use and management practices.

It was observed that no consistency was noticed between the annual rainfall and the observed storage volume on the annual basis. Effort has been made to establish relationship between the rainfall and surface runoff storage volume at Al Bih dam. Therefore, a systematic analysis of intensity and duration of storm with flooding of Wadi Al Bih was performed as the biggest catchment in the Ras Al Khaimah area. A suitable rainfall-runoff model (HEC-HMS) was used to generate yield and flood hydrographs at dam site.

V. Application of HEC-HMS model

The Hydrologic Modeling System is designed to simulate the precipitation-runoff processes of dendritic watershed systems. HEC-HMS provides a variety of options for simulating precipitation-runoff processes. In addition to unit hydrograph and hydrologic routing options, the model capabilities include a quasi-distributed runoff transformation that can be applied with gridded (e.g., radar) rainfall data, and a simple "moisture depletion" option that can be used for continuous simulation. It is designed to be applicable for a wide range of geographic areas for solving the various possible ranges of problems. This includes large river basin water supply and flood hydrology, and small urban or natural watershed runoff. Hydrographs produced by the program can be used for studies of water availability, urban drainage, flow forecasting, future urbanization impact, reservoir spillway design, flood damage reduction, floodplain regulation, and others.

The execution of the programme requires specification of three sets of data. The first, labeled Basin Model, contains parameters and connectivity data for hydrologic elements. Types of element are sub-basin, routing reach, junction, reservoir, source, sink, and diversion. The second set, Precipitation Model, consists of meteorological data and information required to process it. The model may represent historical or hypothetical conditions. The third set, Control Specifications, specifies time-related information for a simulation.

A. Basin Model

The basin model contains pertinent information regarding the hydrologic system connectivity and other physical data describing the basin. It is the sub-model within which the watershed schematic is constructed and manipulated. Subbasins represent the physical areas within the basin and produce a discharge hydrograph at the outlet of their respective areas. The hydrograph produced is calculated from the precipitation data minus the losses. The resulting precipitation excess is transformed using empirical models (UH models) or conceptual model (kinetic-wave model) to compute runoff at the outlet.

Loss rate can be simulated by one of several methods, however, the SCS curve number considered to be simple, predictable and stable method and well established and widely accepted for use in US and abroad [17]. It relies on only one parameter which varies as a function of soil group, land use and treatment, surface condition and antecedent moisture condition which can be readily grasped and also well-documented environmental input. Therefore SCS curve number method was selected for the Wadi considered in the present study.

The transform which convert rainfall excess into surface runoff, can be simulated using unit hydrograph techniques apart from ModClark or kinematic wave method. The Snyder UH method was developed based on the study of mountainous watersheds and also uses watershed characteristics for estimating UH parameters. Therefore in the present study Syder synthetic hydrograph theory was used in the transform routine for the Wadi Bih.

Baseflow takes into account normal flow through a channel or the effects of groundwater. HEC-HMS has recession, and constant monthly methods for baseflow calculations. However, in the present study no baseflow was considered as no baseflow was observed in the Wadi.

Flood routing in HEC-HMS offers many options for the reaches such as simple lag, Modified-Plus, Muskingum, Muskingum-Cunge, and Muskingum-Cunge 8 point methods. Due to the non-availability of data, the simple lag method was adopted for the routing of reaches. Lag model is the simplest one and the outflow hydrograph is simply the inflow hydrograph. This model is widely used, especially in urban drainage channels [18].

In the basin model, basin elements like intermittent reservoir, sources and sinks, and diversions are omitted from the present basin models as there are no such elements present in the Wadi.

The models of Bih contain only 3 of 7 elements in the basin model. There are 13 hydrologic elements in the Wadi Bih model, made up of 7 subbasins, 3 river reaches, and 3 junctions. As before junction-3 is considered at the wadi Bih reservoir (Fig. 3).

B. Meteorological Model

The meteorological model contains the precipitation data, either historical or hypothetical for the HEC-HMS model. The options in historical precipitation inputs include hyetographs, gauge weighting, and inverse-gauge weighting and capable of handling unlimited number of recording and non-recording gauges. Hypothetical precipitation data can be derived from

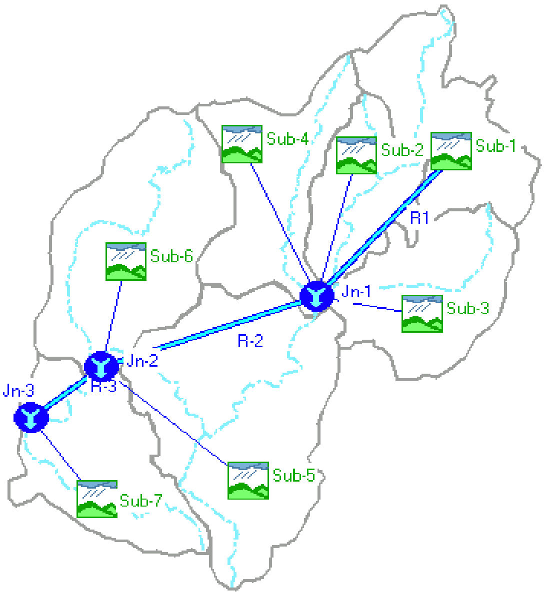

Figure 3. Schematic basin model of Wadi Bih

frequency storm and standard project storm (SPS) models. In the present study, user gauge weighting method has been selected with recording (Bih) and non-recording rain gauges (Shaam, Buryrat). The number of rain gauges and its Thiessen weights considered for the subbasins are presented in Table 4 for the Wadi.

C. Control Specification

The control specifications contain all the timing information for the model, including the start time date, stop time and date, and computational time step of the simulation. Control specifications were given based on the rainfall depth and its distribution for the wadis.

To perform a hydrologic analysis, a basin model is prepared for the wadi separately. Raw geometric data such as length, slope, area, centroid location, and information such as soil types and landuse/land cover description which are used to characterize the abstractions are manually processed and presented in the Table 5. However, other parameters like Ct = basin coefficient, Cp = UH peaking coefficient were selected based on the previous study [19] in which Ct typically ranges from 1.8 to 2.2 although it has been found to vary from 0.4 in mountainous areas to 8.0 along the Gulf of Mexico. It is also reported that Cp ranges from 0.4 to 0.8, where larger values of Cp are associated with smaller values of Ct. The initial SCS curve numbers (CN) have been selected on the basis of experience and the values quoted in the literature elsewhere [20] based on the hydrologic soil groups and antecedent soil moisture conditions of the Wadi. However, CN values were readjusted by trial and error method to achieve best possible results comparable with the observed storage/flow values. The curve number was selected from 63 to 66 for the Bih catchment considering the presence of limestone and wider wadi course.

VI. Results and Discussions

The storm events and corresponding yields were identified and used for calibration of the model. The calibration process for the wadi is achieved when the average absolute relative error of all storm events is minimum. After calibration, the model is used to estimate the storage at the dam site. The rainfall depths and intensity over the catchment as well as the storage estimated for the 7 storm events, listed in Table 6.

The percentage of error between estimated results and the actual measurements are varies between 0.3 and 24 per cent. The above results indicate that the difference of simulated and observed storage/yields is within the allowable limit. The difference may be attributed to the error in some of the input values such as precipitation and its distribution, storage/yield information and initial abstraction coefficients (0.2) and SCS curve numbers which may be varied on soil moisture conditions.

The runoff coefficients were estimated by the simulated storage/yield and mean rainfall over the catchment. The developed regression fitting is presented in Fig. 4. The variation of runoff coefficient with rainfall between 50mm and 150mm is tabulated in the Table 7. The runoff coefficient is in the range of 5 and 50 per cent for the rainfall ranging from 50 to 150 mm. The better productivity of runoff expected for the higher rainfall values. The relationship between rainfall and direct runoff were also established and presented in Fig. 5. It can also be noticed from these figures that runoff will generate at around 30 mm of rainfall in the area. The relationship between Rainfall and runoff is non-linear from 0 to 60 mm and afterwards it becomes linear in nature.

Different scenarios of incidence of rainfall over the catchment area were considered to simulate the storage at the dam sites using the calibrated parameters for the future predictions. The simulated storage values for different rainfall incidences were used to develop a relationship curve between rainfall and storage. The developed curve is presented in Fig. 6. The curve presented in Fig. 6 can be used to estimate storage by known rainfall depths in the catchment area. Actual rainfall depth (D) for the wadi could be derived from the following relationship, which is developed using weight coefficients of rain gauges for each sub-basin:

$$\sum \quad \sum$$

where C_b = estimated weight coefficients for any sub-basin (*b*) (Table 8); *n*=number of sub-basin; R_{gb} = rainfall depth recorded at gauge station (g_b) in the sub-basin (*b*); T_{gb} = Thiessen weight for the gauge station (g_b) in the sub-basin (*b*) (Table 4) and m_b = number of gauge stations in the sub-basin (b).

The developed curve between rainfall depth and water storages behind the dam (Fig. 6), was verified using recorded measurements of rainfall depths and water storages of subsequent storm events. For example, the calculated rainfall depth using Eq. 1 for a storm event from 26th to 29th of December 2004 in wadi Bih was 42 mm, which corresponds to a water storage of 0.75 M m^3 at dam site (Fig. 6), while the observed water storage was 1.0 M m3.

Using the established relationships between rainfall and runoff, a family of rainfall intensity-duration-direct runoff curves was developed (Fig. 7). These set of curves could be used to predict the direct runoff from the known intensity and duration of any rainfall event. Curves were developed for a wide range of rainfall intensities 0–100 mm/h and durations 2–50 h of rainfall to enable the prediction with significant variation in rainfall patterns. For example, a 20-mm/h intensity of rainfall with a 5-h duration will yield direct runoffs of about 10.3 MCM at wadi Bih dam.

TABLE IV. RAINGAUGES AND WEIGHTS CONSIDERED FOR THE EACH SUB-BASIN

Sub-basin	Area (Km^2)	Rain gauges and Thiessen weight			
		Rain gauge	Thiessen Weight	Rain gauge	Thiessen Weight
1	53.01	Bih	0.50	Sham	0.50
2	36.42	Bih	1.00	-	-
3	55.34	Bih	1.00	-	-
4	56.18	Bih	0.80	Sham	0.20
5	110.27	Bih	1.00	-	-
6	86.34	Bih	1.00	-	-
7	60.67	Bih	0.60	Burayrat	0.40

TABLE V. BASIN MODEL PARAMETERS

Reach (R1) = 9.4 km			Reach (R2) = 23.2 km			Reach (R3) = 9.2 km	
Sub-basin	Area (Km^2)	CN	C_t	C_p	L (km)	L_c (km)	Snyder lag (hr)
1	53.01	63	0.6	0.7	10.1	2.5	1.19
2	36.42	63	0.6	0.7	12.6	6	1.63
3	55.34	63	0.6	0.7	13.9	5	1.61
4	56.18	63	0.6	0.7	15.7	7	1.84
5	110.27	66	0.6	0.7	19.9	9	2.14
6	86.34	63	0.6	0.7	20.8	8.5	2.13
7	60.67	63	0.6	0.7	15.0	6	1.73

CN = SCS Curve number, C_t = Basin coefficient, C_p= UH peaking coefficient,
L = Length of the main stream from the outlet to the divide,
L_c = Length along the main stream from the outlet to a point nearest the watershed centroid

TABLE VI. ESTIMATED AND OBSERVED STORAGE WITH RAINFALL

Date	Rainfall depth (mm)			D	I	E.S	O.S	P.E
	Sham	Buryrat	Bih					
9.2.90	78	50	50	26	2.0	1.428	1.15	24.2
23.2.95	40	37	53	9	4.7	0.489	0.55	11.1
13.3.95	95	36	55	33	1.8	2.086	2.00	4.3
26.3.87	41	32	37	12	3.1	0.182	2.26	18.9
29.3.87	68	46	60	33	1.8	2.380		
5.2.92	81	39	60	80	0.8	2.503	2.65	5.6
3.3.98	93	94	73	48	1.6	5.014	5.00	0.3

D = Duration (h), I = Intensity (mm/hr), E.S = Estimated Storage (MCM), O.S = Observed Storage (MCM), P.E = Percentage of Error (%)

TABLE VII. ESTIMATED RUNOFF COEFFICIENTS FROM THE FITTED MODEL

Wadi	Rainfall (mm)	Runoff coefficient (%)
Bih	50	5
	75	15
	100	30
	125	50
	150	75

TABLE VIII. ESTIMATED WEIGHT COEFFICIENTS OF SUB-BASIN

Sub-basin Number	Weight coefficient
1	0.116
2	0.079
3	0.121
4	0.123
5	0.241
6	0.118
7	0.132

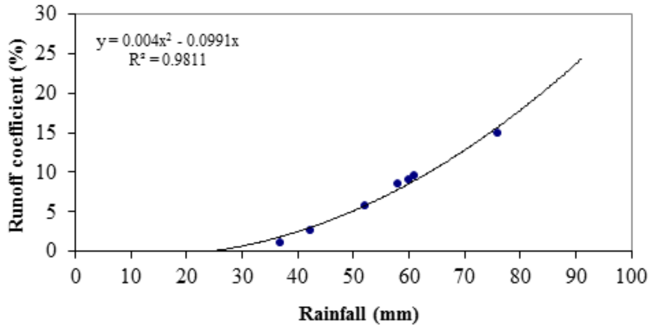

Figure 4. Estimated runoff coefficient

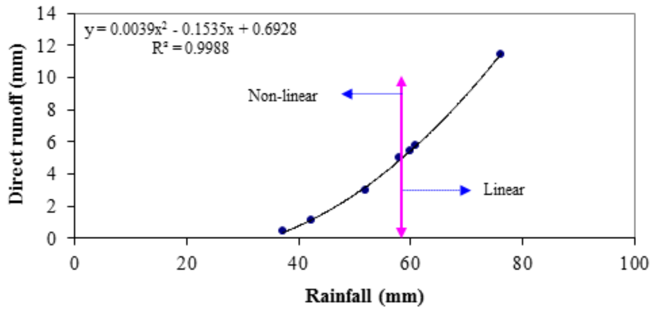

Figure 5. Simulated direct runoff

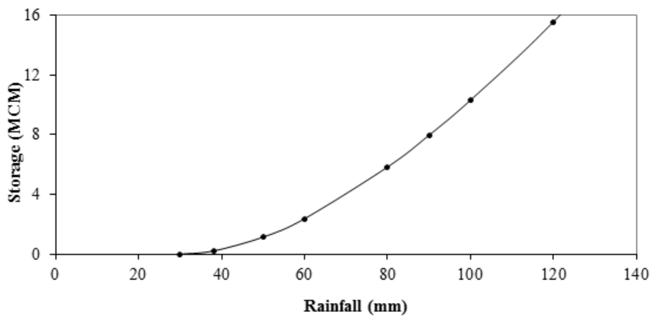

Figure 6. Simulated storage at the dam

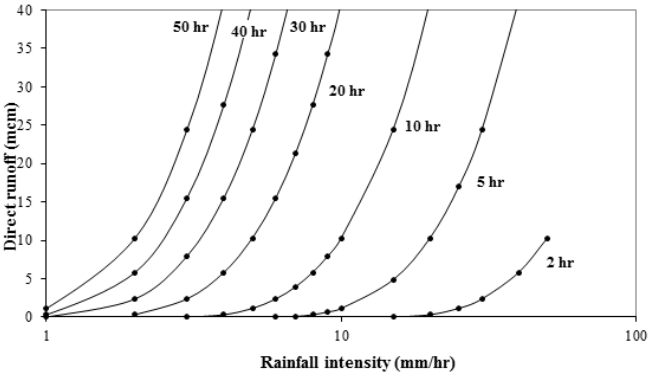

Figure 7. Intensity-duration-direct runoff curves

VII. CONCLUSION

The shape indices in this study indicate that basins are relatively oval to less elongated basin coupled with moderate to high drainage density values reflect a higher efficiency in discharging the rainwater by channel flow, thus increase the possibility of flooding in the area. The basins recorded the higher relief ratio, which indicates overall slope and hence high runoff velocity. The relatively high drainage density and stream frequency suggest the high efficiency in carrying their excess precipitation. The value of bifurcation ratio is not same from one order to next order. It also indicates the flood risk for parts of the basin. Watersheds in the northern part more circular than the southern part except Al Minesib and would produce larger runoff. This also means that flood peak is easily achieved and the basins are liable to flooding. Overall northern part of basins are relatively higher in surface water drainage potential when compared to the southern basins. These characteristics are indicated by all the deduced morphometric parameters. All deduced morphological parameters are consistent in characterize the drainage process of the catchments.

The HEC-HMS was calibrated and developed through the comparison between simulated and observed water storage values for 7 different storm events. Water storage due to rainfall events behind the dam of wadi Bih is estimated by the developed model. The estimated average absolute error is 10% for the wadi Bih. The calibrated model was also used to develop sets of rainfall-runoff/storage curves. These curves can be used to predict the storage in the dam of wadi Bih for any rainfall events. Relationship between rainfall and direct runoff for the wadi was established using the developed model. The model is also used to estimate the runoff coefficients for the wadi for the range of rainfall depths. A family of curves developed to predict the direct runoff from the intensity and duration of any rainfall event to enable the prediction with significant variation in rainfall patterns. Qualitative and quantitative assessment of these catchments have established higher runoff generation potential and higher incidence of floods with peak flows.

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