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ARID HYDROLOGICAL MODELING AT WADI ALAQIQ, MADINAH, SAUDI ARABIA

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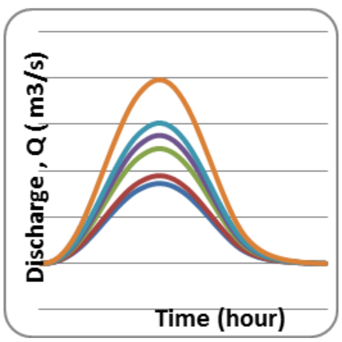
Graphical abstract



Abstract

Madinah is one of the urban centers that have experienced several devastating floods during the past 50 years. The objectives of this study are to estimate the flood hydrograph and peak discharge in the Wadi Alaqiq in Madinah and its major sub-catchments based on daily rainfall distribution. Daily annual maximum records are chosen for rainfall distribution in the study area. Wadi Alaqiq is located in the western part of the Madinah city and consists of five major sub-catchments, namely, Aqiq, Ruwawah, Reem, Al-Yutmah and Annaqi. The HEC-HMS and modified Talbot models are applied to estimate design flood for various average recurrence intervals (ARI). The analysis involves two stages, where stage one is concerned with modeling of the Wadi Alaqiq sub-catchment and comparison of the peak flow values obtained by previous studies and empirical formulae based on rainfall distribution analysis. In the second stage, the HEC-HMS is run separately for the five sub-catchments of Wadi Alaqiq. The model parameter values are then used to simulate for 25-year, 50-year and 100-year flood hydrographs. The HEC-HMS model is used to analyze the hydrologic behaviour of the wadi catchments. Initial and constant rate loss method is used to determine the hydrologic loss and the excess rainfall was transformed using the Clark's Unit Hydrograph. The peak flow simulations are very close with reported values and those derived by modified Talbot. Also, the peak discharges are applied to model discharges from the HEC-HMS and modified Talbot equations of the five sub-catchments for a set of selected return periods. The direct runoff ratio for Madinah region in wadis Al-Yutmah, Annaqi, Aqiq, Reem and Ruwawah ranged from 25% to 28% of the total rainfall. This is due to topography condition, wadi catchment area and the use of predicted maximum daily rainfall results. The model results are reasonable for rainfall-runoff application and can be used for wadi corridor management in arid region.

Keywords: Rainfall-runoff model, distributed daily rainfall, empirical formulation, Wadi Alaqiq, Madinah

Abstrak

Madinah adalah salah satu daripada pusat bandar yang telah mengalami beberapa banjir pemusnah sepanjang 50 tahun yang lalu. Objektif kajian ini adalah untuk menganggarkan hidrograf banjir dan aliran puncak di Wadi Alaqiq di Madinah dan sub-tadahan utamanya berdasarkan taburan hujan harian. Rekod maksimum tahunan harian telah dipilih untuk taburan hujan di kawasan kajian. Wadi Alaqiq terletak di bahagian barat bandar Madinah dan terdiri daripada lima sub-tadahan utama iaitu, Aqiq, Ruwawah, Reem, Al-Yutmah dan Annaqi. HEC-HMS dan model Talbot yang diubahsuai telah digunakan untuk menganggarkan reka bentuk banjir untuk pelbagai kala kembali purata (ARI). Analisis ini melibatkan dua peringkat, di mana peringkat pertama adalah berkenaan dengan model daripada sub-tadahan Wadi Alaqiq dan perbandingan antara nilai-nilai aliran puncak yang diperolehi daripada kajian sebelumnya dan formula empirik berdasarkan analisis taburan hujan. Pada peringkat kedua, HEC-HMS dijalankan secara berasingan bagi lima sub-tadahan Wadi Alaqiq. Nilai model parameter kemudiannya digunakan untuk simulasi selama 25 tahun, 50 tahun dan 100 tahun hidrograf banjir. Model HEC-HMS digunakan untuk menganalisis ciri-ciri hidrologi daripada kawasan tadahan wadi. Kaedah kadar kehilangan awalan dan tetap digunakan untuk menentukan kehilangan hidrologi dan hujan yang berlebihan menggunakan kaedah unit hidrograf Clark's. Simulasi aliran puncak sangat hampir dengan nilai yang dilaporkan dan yang diperolehi daripada Talbot yang diubahsuai. Aliran puncak digunakan untuk model aliran daripada HEC-HMS dan persamaan Talbot diubahsuai daripada lima sub-tadahan untuk satu set tempoh kala kembali yang dipilih. Nisbah air larian terus bagi kawasan Madinah di wadi Al-Yutmah, Annaqi, Aqiq, Reem dan Ruwawah adalah dari 25% kepada 28% daripada jumlah hujan. Ini adalah disebabkan oleh keadaan topografi, kawasan tadahan wadi dan hasil ramalan penggunaan hujan harian maksimum. Keputusan model adalah munasabah untuk penggunaan hujan-air larian dan boleh digunakan bagi pengurusan wadi koridor di kawasan gersang.

Kata kunci: Model hujan-air larian, taburan hujan harian, formula empiric, Wadi Alaqiq; Madinah

1.0 INTRODUCTION

Many major floods caused by extreme rainfall events have impacted the urban communities in different parts of the Kingdom of Saudi Arabia (KSA) resulting in significant impacts on the country's economy and social life. The arid urban areas seem to carry the brunt of most damages. Madinah City is one of the urban centers that have experienced several devastating floods during the past 50 years. The most recent flood was in 2005, which caused losses of live and destruction to properties and infrastructures.

The Madinah Province is located in western part of KSA (Figure 1). Madinah City is the holy area to Muslims and the fourth most populated area in the Kingdom. Graphically, it is arid region desert covered with wadis, mountains, rocky and residential areas. Madinah City is located at about 160 km inland from the Red Sea coast and approximately 420 km to north of Jeddah, where the city is at an elevation of about 620 meters above mean sea level (m.s.l.).

In arid regions, several studies have been conducted for estimation of rainfall, peak flood and mean annual flood discharge related to topographic, morphometric characteristics, regression and rainfall-runoff relationship of ungauged hydrological catchments for flood management issues [1-11]. Abdulrazzak *et al*. [12] reviewed different methodologies to assess the aspect of flash flood for large number of wadis in the south western region of the KSA with applications of the HEC model to develop flood zone maps. Saber *et al.* [13] presented a distributed hydrological model of the wadi system for flood control and water resources management based on homogenization method. Wheater *et al.* [14] and Abdulrazzak *et al.* [12] evaluated flood flow characteristic of different wadis in Oman and Saudi Arabia.

Empirical formulations, regression models and the SCS curve number methods have been compared for flood estimation study in Makkah City, Saudi Arabia by Gomaa *et al*. [3]. They recommended the curve number method and regression model by Al-Subai for flood estimation. Oun *et al.* [2] studied comparison of peak discharge estimation based on HEC-HMS, Rational method, modified Talbot and regional flood frequency methods in Wadi Marwan, Jeddah, in western Saudi Arabia. The root mean square error (RMSE) is used to measure the accuracy of the methods and the results are consistent with the comprehensive analyses of measured and modeled peak discharges.

The objectives of this study are to estimate the flood hydrograph, peak discharge and to evaluate flow characteristics from rainfall-runoff simulation of the Wadi Alaqiq tributaries based on distributed rainfall analysis. The analysis involves two stages, where stage one is modeling of the Wadi Alaqiq and comparison of the peak flow values obtained by previous studies and empirical formulae based on rainfall distribution data. In the second stage, the HEC-HMS software is run separately for five sub-catchments in Wadi Alaqiq based on design storm of distributed rainfall analysis. The model parameter values are then used to simulate 25-year, 50-year and 100 year flood hydrographs. The HEC-HMS model has been used to analyze the rainfall-runoff process. Therefore, simulated results are compared to determine the most appropriate model parameters and empirical formulae such as Modified Talbot equation for peak flow estimation.

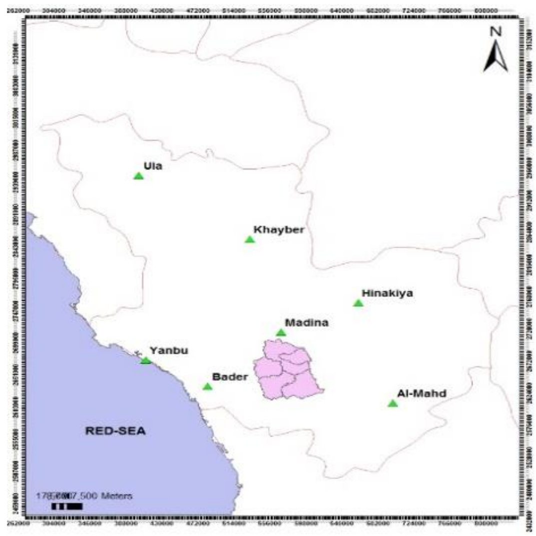


Figure 1 Location of the study area in Wadi Alaqiq, Madinah

2.0 WADI ALAQIQ AND ITS TRIBUTARIES SYSTEM

Madinah area is located in the northern extremity of the Harrat Rahat and takes place in the extreme part of the basalt plateau at the edge of the Basement Complex on which the basalts lie [15]. Many volcanic rocks are located at southern and western parts of the Madinah City. The major portion of the study area is relatively hilly with gentle and steep slopes. The soil of Madinah City is fertile originally from volcanic hills that incline towards north direction. The wadi systems greatly influence the recharge and thus the hydrogeology of the study area. The old alluvial deposits along with the basaltic lava flows (known as Harrat Rahat) constitute the groundwater aquifer in the study area, which is characterized by unconfined to semi-confined conditions [16, 17].

The study area is located in the Wadi Alaqiq, (Figure 2). Wadi Alaqiq is located in the western side of the Madinah City, where the stony formation ends. The area upstream of Wadi Alaqiq, which is about 5,138 km^2 has great influence on the hydrology of the study area. Wadi Alaqiq consists of five major sub-catchments, namely Aqiq, Ruwawah, Reem, Al-Yutmah and Annaqi (Figure 2). Wadi Alaqiq flows northward along the west before being joined by Wadi Qanat and Wadi Bathan from the east at downstream of the study area. The wadi system flows further north to Wadi Alhamd, which runs to the northwest before flowing into the Red Sea (Figure 1).

The hills are mostly rocky and barren. The total stream length of the main Wadi Alaqiq is about 152 km. The mean elevation is 971 meter above m.s.l. and the mean basin slope is 0.10. These morphometric characteristics are extracted from digital elevation model (DEM).

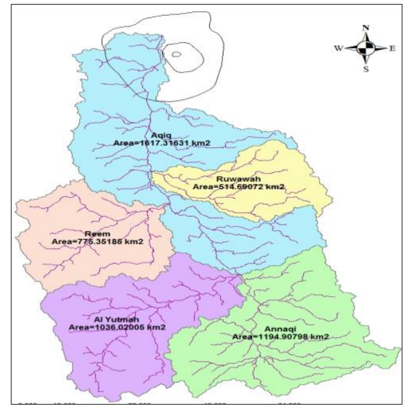


Figure 2 The sub-catchment areas in Wadi Alaqiq, Madinah

3.0 CLIMATE AND RAINFALL TRENDS

The study area receives annual rainfall between 2.5 mm and 212 mm with an average of 62 mm [18]. Only 2% to 4% of the rainfall infiltrates and percolates into the saturated zones, which is comparable with other arid and semi-arid regions [16, 19]. The annual minimum temperatures vary from 7.1°C to 11.5°C, whereas the annual maximum temperatures range from 42.4°C to 46.1°C.

Madinah area is characterized by an arid climate rainfall with high temporal and spatial variability that takes place primarily during the winter and spring seasons. The winter and spring rainfall events are caused by a combination of disturbances during the winter season from Mediterranean and the Sudan trough [20], which usually generate extreme rainfall convective events over Madinah region and its surrounding areas. Rainfall patterns in the study area are characterized by highly temporal and spatial variability due to primarily the winter and spring seasons as reported by Subyani and Al-Ahmadi [4].

4.0 HYDROLOGIC FLOOD ESTIMATION FORMULA TRENDS

The annual flood peak discharge estimates are based on the empirical method (Modified Talbot Equation) using 25-year, 50-year and 100-year return periods.

The Modified Talbot empirical formulae, after Quraisi and Al-Hasoun, [11], give the peak discharge for different sizes of large watershed as follows.

$$Q_{25} = 4.985\ C\ (A)^{0.5} \quad (1)$$

$$Q_{50} = 1.2 Q_{25} \quad (2)$$

$$Q_{100} = 1.17\ Q_{50} \quad (3)$$

Parameters Q_{25}, Q_{50}, and Q_{100} are runoff discharges (m^3/s) for return periods of 25-year, 50-year and 100-year, respectively.

Parameter C is for summation of C1, C2 and C3 that depend on terrain condition, slope, width, and length of drainage area [11] - see Table 1) and A is drainage area (hectare).

The Modified Talbot method is popular for design of hydraulics structures in the KSA. Many hydrologists disagree because (i) the modification factors used are excessive (0.1 to 2.0) without clearly defined criteria, and (ii) the rainfall intensity is ignored for flash floods are estimated in urban/developed areas.

Table 1 Values of C1, C2 and C3 [21]

C1	0.30	Mountainous area
	0.20	Semi-mountainous
	0.10	Low land
C2	0.50	S> 15%
	0.40	10%<S<15%
	0.30	5%<S<10%
	0.25	2%<S<5%
	0.20	1%<S<2%
	0.15	0.5%<S<1%
	0.10	S<0.5%
C3	0.30	W=L
	0.20	W=0.4L
	0.10	W=0.2L

Note: W-width, L-length S-slope of drainage area

5.0 HEC-HMS RAINFALL-RUNOFF SIMULATION

HEC-HMS model is used to analyze the hydrologic behaviour of the present catchment characteristics together with the existing conditions. The model could not be calibrated because runoff observation data are not available due to ungauged catchments, and consequently, various other methods and approaches are used to compare the estimated peak flows prior to their use for developing flood hazard maps in the study area. The option taken to address this uncertainty due to non-calibration is to compare the study results with other studies that use different methods or approaches in establishing flow hydrographs. In this study, the simulation result for Wadi Alaqiq is compared with the results obtained by Subyani and Al-Ahmadi [4] and Modified Talbot formulae.

5.1 Application of Hydrologic Modeling (HEC-HMS)

The same model is applied to estimate design flood for various ARI's. Two stages are modeled for the catchments based on different land use types and catchment sizes. The stages include design storms based on historical data. The study area covers Wadi Alaqiq catchment, Madinah, which consists of arid ungauged catchments for obtaining runoff data. The catchment characteristics are surveyed and they help to determine the parameters for modeling time of concentration, imperviousness, initial and constant parameter and transformation parameters.

5.2 Model Representation and Data Input

This modeling exercise is meant to be as systematic as possible covering wide ranging conditions using two different stages of simulation as tabulated in Table 2. The various individual sub-catchments that make up the entire Wadi Alaqiq catchments are taken into consideration in the simulations. The point that is common to each modeling stage is imperviousness usage at 25% and 40% as indicated by the results of soil and transformation parameters plus weighted rainfall. The individual modeling stages can be described as follows.

Stage 1 is for modeling the whole Wadi Alaqiq catchment for comparison purposes,

Stage 2 is for modeling of the individual sub-catchments with similar hydrologic losses and transformation parameters as in the Stage 1 by using imperviousness at 25% and 40% levels based on Arizona formula for T_c and R parameters. The results of Stage 2 are compared with Modified Talbot formulae.

Table 2 Characteristics of individual stages of modeling

Stage	Tc and R	Remarks
1	Bransby Willians & ADOT	Comparison for Wadi Alaqiq
2	ADOT	Wadi Alaqiq and sub-catchments (Reem, Alyutmah, Annaqi, AlRuwawah, Aqiq)

(ADOT- Arizona Department and Transportation [22])

5.3 Hydrological Modeling Parameters

These parameters are obtained from the physical characteristics survey of the catchment. Some of the parameters are measurable at site, while some others are derived from approximation of the site conditions or are based on available literature information. These parameters are related to hydrologic losses and transformation, where the former is based on Initial and Constant Loss methods, and the latter on Clark Unit Hydrograph method.

(a) Initial and Constant Loss Parameters

These parameters depend on the percentage of pervious area within each catchment. Since most of the pervious areas at the site consist of hilly rock and compacted plain, small losses are expected from the catchment area. It is assumed that the only pervious area within the catchment lies along the wadi course, for which the initial loss varies depending on the type and density of vegetative plants and existing crops.

The initial loss due to the type and density of plants is little or completely negligible. The constant losses can be approximated from published data or infiltration tests conducted at sites. In this analysis, Constant Loss (CL) is adapted from National Resources Conservation Services (NRCS) of the U.S. Department of Agriculture [5] for group C type of soil, which is considered appropriate for the study area. The adopted CL is 3.81 mm/hr.

(b) Design Storm

The rainfall events for simulation at Stage 1 and Stage 2 are based on Table 3, where design storm ARI-weighted rainfall distributions are given in detail. Herein, it is assumed that all the catchments would receive the same amount of design rainfall. Also, the design storm as given in Table 3 is used to simulate the 25-year, 50-year and 100-year flood hydrographs.

Table 3 Design storm ARI-weighted daily rainfall distribution (in mm)

		Design Storm ARI (year)		
Catchment	**Area (km²)**	25	50	100
Al-Yutamah	1036	65	75	85
An-Naqi	1195	61	70	79
Reem	775	58	70	83
Al-Ruwuwah	515	63	78	96
Aqiq	1617	56	68	81
Wadi Alaqiq	5138	60	70	81

Transformation parameters

The two Clark transformation parameters are time of concentration (Tc) and storage coefficient (R). For rainfall-runoff analysis of this study, ADOT formula is used to derive both parameters based on the following equations 4a and 4b. Table 4 presents parameters for Tc and R derivations in these equations for the individual sub-catchments of Wadi Alaqiq in the study area.

The regression equation as used in the study is derived from Arizona Department and Transportation (ADOT), [22] for the mountain/desert area suitable for arid regions in the ungauged catchment of Wadies Alaqiq. All inputs are physical parameters in the catchment area. The regression equations parameters T_c and R in hours can be estimated as a function of watershed and storm characteristics with the main channel length (L) as the primary characteristics, which are listed below.

$$T_c = 2.4*A^{0.1}* L^{0.25}*L_{ca}^{0.25} *S^{-0.2} \quad (4a)$$

$$R = 0.37* T_c^{1.11} *L^{0.8} * A^{-0.57} \quad (4b)$$

where,
T_c - the time of concentration in hours
L -the stream length measured along the main channel from the watershed outlet to the watershed divide, (mile)
S - the main channel slope determined from elevation at points that represent 10% and 85% of the distance along the channel from the watershed outlet to the watershed divide, (ft/mile)
A - the area in square miles
L_{ca}- the length measured from the concentration point to a point on L that is perpendicular to the watershed centroid, in miles

Table 4 Parameters for Tc and R calculation using ADOT formulation

Wadi ID	**A**	**L**	**L_{ca}**	**S**
Unit	**mile²**	**mile**	**mile**	**ft/mile**
Reem	299.3998	29.6819	13.8449	56.3675
Alyutmah	400.0560	44.4277	22.9624	85.4295
Ruwawah	198.7463	34.0066	18.2787	66.3986
Annaqi	461.4101	42.7027	21.6787	44.6794
Aqiq	624.5218	66.8713	29.0808	22.9089
Wadi Alaqiq	1983.793	100.8	46.24	46.28

Table 5 Comparison of simulation results in Wadi Alaqiq

	Subject	**Peak Discharge (Qp), m³/s**								
Assumption model	Parameters	**Imperviousness= 25 %** IL = 15 mm, CL= 3.81 mm/hr Weighted rainfall distribution			**Imperviousness= 25 %** IL = 15 mm, CL= 3.81 mm/hr Weighted rainfall distribution			**Imperviousness= 40 %** IL = 15 mm, CL= 3.81 mm/hr Weighted rainfall distribution		
Method for Tc, and R calculation		Tc (Bransby Willians) and R (ADOT)			Tc and R (ADOT)			Tc and R (ADOT)		
Tc and R	Hour	Tc= 44 , R= 5			Tc=20, R=5			Tc=20 , R=5		
ARI	Unit	25	50	100	25	50	100	25	50	100
Weighted Daily Rainfall	mm	60	70	81	60	70	81	60	70	81
1.HEC-HMS simulation	m³/s	615	675	883	862.9	946.4	1238.6	1380.6	1514.2	1981.8
2.Subyani and Al-Ahmadi, [4]	m³/s	864	989	1250	864	989	1250	864	989	1250
3.Modified Talbot	m³/s	1917	2301	2692	1917	2301	2692	1917	2301	2692
Difference of (1)&(2)	%	28.82	31.75	29.36	0.13	4.31	0.912	59.79	53.10	58.54
Difference of (3) & (2)	%	54.93	57.02	53.57	54.93	57.02	53.57	54.93	57.02	53.57
Difference of (1) & (3)	%	67.92	70.66	67.20	54.99	58.87	53.99	27.98	34.19	26.38
Qp (HEC-HMS)	m³/s	615	675	883	862.9	946.4	1238.6	1380.6	1514.2	1981.8
Volume (x 1000)	m³	79639	87346	114321	79639	87346	114320	127422	139754	182913
Runoff	mm	15.5	17	22.25	15.5	17	22.25	24.8	27.2	35.6
Runoff-rainfall ratio	%	25.83	24.29	27.47	25.83	24.29	27.25	41.33	38.8	43.9

Table 6 Peak discharge (Qp) for sub-catchments of Wadi Alaqiq

Catchment	HEC-HMS (Q m³/s) **25% imperviousness**			HEC-HMS (Q m³/s) **40% imperviousness**			Modified Talbot **(Q m³/s)**		
	25 yrs	50 yrs	100 yrs	25 yrs	50 yrs	100 yrs	25 yrs	50 yrs	100 yrs
Aqiq	271.6	297.8	389.8	434.5	476.5	623.7	954	1145	1339
Al-Yutmah	194.8	224.8	254.8	311.8	359.7	407.7	1010	1212	1418
Annaqi	224.8	242	273.2	359.6	387.3	437.1	10170	1284	1502
Reem	145.8	157	186.1	297.8	251.2	233.2	900	1080	1264
Ruwawah	98.4	116.2	163.4	157.4	186	245.1	764	917	1073

Table 7 Hydrograph characteristic of the sub-catchment of Wadi Alaqiq (25 % imperviousness)

Rainfall Contribution/Parameter	**Unit**	**W.Reem**	**W.AlYutmah**	**W.Ruwawah**	**W.Annaqi**	**W.Aqiq**
Rainfall 25 yrs	mm	58	65	63	61	56
Peak Discharge	m3/s	145.8	194.8	98.4	224.8	271.6
Volume (x1000)	m3	12594	16835	8498	19419	25063.5
Runoff	mm	16.243	16.25	16.51	16.25	15.5
Runoff-rainfall Ratio	%	28	25	26.21	26.64	27.68
Rainfall 50 yrs	mm	70	75	78	70	68
Peak Discharge	m3/s	157	224.8	116.2	242	297.8
Volume (x1000)	m3	13563	19425	10043	20913	27489
Runoff	mm	17.49	18.75	19.51	17.5	17
Runoff-rainfall Ratio	%	25	25	25	25	25
Rainfall 100 yrs	mm	83	85	96	79	81
Peak Discharge	m3/s	186.1	254.8	163.4	273.2	389.8
Volume (x1000)	m3	16081	22105	13846	23601	35978.3
Runoff	mm	20.74	21.34	26.9	19.75	22.25
Runoff-rainfall Ratio	%	25	25	28	25	27.5

6.0 RESULTS AND DISCUSSION

6.1 Stage 1

Stage 1 modeling serves as the model comparison of the hydrological parameters adopted in the study. The total catchment area of Wadi Alaqiq is about 5,138 km^2. As given in Table 3, the storm event is based on weighted rainfall distribution of the daily design storm for 25-year, 50-year and 100-year ARI. It is assumed that all the sub-catchments receive the same amount of design rainfall [6, 23]. In HEC-HMS, initial constant rate method requires adequate data for appropriate evaluation to verify the input parameters (i.e. percentage of imperviousness, soil infiltration parameters, initial and constant losses, transformation parameters, time of concentration and storage coefficient) within the catchment area.

Various modes for model inputs are set up according to the existing conditions as follows:

(i). For hydrologic losses: initial loses (IL)=15 mm, constant loses (CL)=3.81 mm/hr and impervious area =25%. On the other hand, for transformation parameters, time of concentration (Tc)=20 hours and storage coefficient (R)=5, are adapted based on Arizona formulation.

(ii). Using similar model input parameters for hydrologic losses as initial loses (IL)=15 mm, constant loses (CL) =3.81 mm/hr and impervious area=40%; while maintaining the same transformation parameters requiring that time of concentration (Tc)=20 hours and storage coefficient (R)=5.

(iii). Use of different transformation parameters and maintaining similar input parameters for hydrologic losses (imperviousness=25%). Tc is obtained from Bransby Willians and R from Arizona formula, just only for comparison purposes.

The modeling result of the study is compared with other researchers' works, who have used different approaches. Table 5 includes the results of the HEC-HMS simulation peak flows for Wadi Alaqiq as compared to the method by Subyani and Al-Ahmadi [4] and Modified Talbot. Subyani and Al-Ahmadi [4] used the US Soil Conservation Service (SCS) to predict flow hydrograph for different return periods for Wadi Alaqiq by considering composite curve number (CCN) 85. Comparisons of HEC-HMS with Subyani and Al-Ahmadi [4] for 25% imperviousness show that the difference is small (less than ±5%) for the 25-year, 50-year and 100-year return periods. However for 40% imperviousness, the difference slightly increased to 53-60%.

On the other hand, comparison of empirical formulation with Modified Talbot gives the difference between the two approaches as 54–57% as compared to Subyani and Al-Ahmadi [4]. Comparison of HEC-HMS with Modified Talbot yields different percentages as 54-55% and 26-28%, respectively, for the 25% and 40% imperviousness values. Additionally for the runoff-rainfall ratios, the difference in the results is 24-27% and 39-44% respectively for the 25% and 40% imperviousness.

The Modified Talbot method seems straight forward in application producing always higher values compared to HEC-HMS. Other points worth discussing on Modified Talbot are as follows.

a) The same straight-line is used to derive the 25-year return period discharge as $Q_{25}=Q_{basis}$ S, where S is the slope of wadi. This implies that as long as the slopes and the wadi drainage areas are the same, the discharge value can be obtained irrespective of location anywhere in the world, however, this cannot hold true for all location. It has already been stated that there should be some difference in the discharge between arid and humid regions [6].

b) The 25-year return period discharge is converted to discharges for other periods (50-year, 100-year, etc.) using the same constant multiplications. These constants can be derived at least from the rainfall records in a particular area according to some suitable theoretical probability distribution (PDF) function, such as the extreme value PDFs. These constants cannot be adopted by taking the same value for use in different areas of the KSA.

c) Modified Talbot formulation does not take into consideration the rainfall intensity/design storm based on return period or ARI.

d) Runoff coefficient (C) has maximum value of 0.9 by taking into consideration bedrock nature, channel slope, and some topographic factors. Coefficient factors, C1, C2 and C3, are not mathematical expressions and thus cannot be adapted as constants for the whole catchment. The reason for this is that any catchment may have mixed land-use, which varies with topography and mountainous areas, vegetation cover, low lands, urban areas, rural areas, and residential areas. Talbot approach has limited choice of land-use types and this makes its application questionable particularly in arid regions with mountainous settings as the KSA.

e) Modified Talbot formulation does not take into consideration the percentage of imperviousness, soil infiltration parameters (i.e. initial and constant losses) and transformation parameters (i.e. time of concentration and storage coefficient) within the catchment.

For 25% imperviousness, use of Tc from Bransby Williams and R from Arizona formula, provides different discharge results that vary, respectively, around 29%–32% and 67%–7% as compared with those of HEC-HMS and Modified Talbot approaches. Therefore, the modeling parameters can be considered acceptable by using the Arizona Department of Transportation (ADOT) formula with 25% and 40% imperviousness. The results may be extrapolated for use with other catchment stages in the study area.

Figure 3 shows simulation hydrographs for both 25% and 40% imperviousness for Wadi Alaqiq catchments. The results show higher percentage of imperviousness giving higher discharge as shown in the hydrograph for 40% imperviousness.

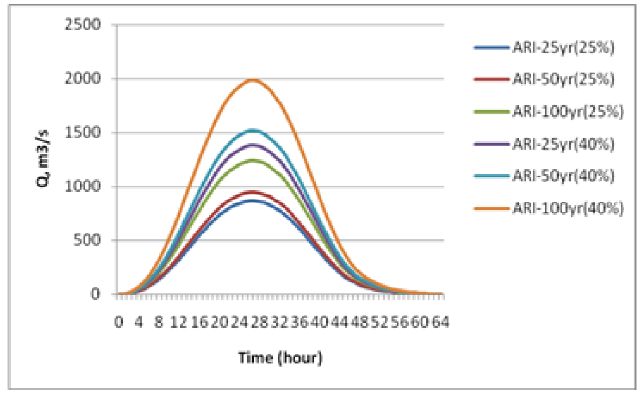


Figure 3 Generated hydrograph for Wadi Alaqiq for 25% and 40% imperviousness using Arizona formula

6.2 Stage 2

The hydrological analyses of rainfall-runoff event are important to estimate the flood volume and peak discharge around the wadi basin in Stage 2, for Wadi Alaqiq sub-catchment (Annaqi, Alyutmah, Reem, Ruwawah and Aqiq) in HEC-HMS. The storm event for the modeling is based on the weighted distribution daily design storm of 25-year, 50-year, 100-year ARI (Table 3). The model input parameters for hydrologic losses are similar with Stage 1.

Table 6 includes estimations of the flood hydrographs of five sub-catchments in Wadi Alaqiq (i.e. Wadi Yutmah, Wadi Annaqi, Wadi Aqiq, Wadi Reem and Wadi Ruwawah) for different return periods of annual maximum daily rainfall based on the application of the HEC-HMS model. Also, Table 6 presents peak discharge calculation from HEC-HMS simulation based on 25% and 40% compared with Modified Talbot with 25-year, 50-year and 100-year return periods. Peak discharge (Qp) from HEC-HMS of 40% imperviousness simulation results presented 1.6 times higher discharge value to 25% imperviousness, accordingly. However, Modified Talbot show higher values compared to both of HEC-HMS results.

Information related to generated storm hydrographs of the five wadis/catchments in Wadi Alaqiq for different return periods of 25-year, 50-year and 100-year are given in Table 6 for 25% imperviousness**.** Wadi Reem (runoff-rainfall ratio, 25%) is used as a comparison to Wadi Ruwawah (runoff-rainfall ratio, 28%) for defined runoff characteristics within 100 years return period. Also, Table 6 exposes that the direct runoff ratio for Al-Madinah region in Wadi Yutamah, Wadi Annaqi, Wadi Aqiq, Wadi Reem and Wadi Ruwawah range from 25% to 28% of the total rainfall.

From the study it is shown that rainfall patterns and runoff in the wadis are characterized by extremely high temporal and spatial variability. This is due mostly to topography condition, catchment area and the use of maximum daily rainfall prediction results. Figure 4 shows hydrograph for 25% imperviousness for 50-year and 100-year.

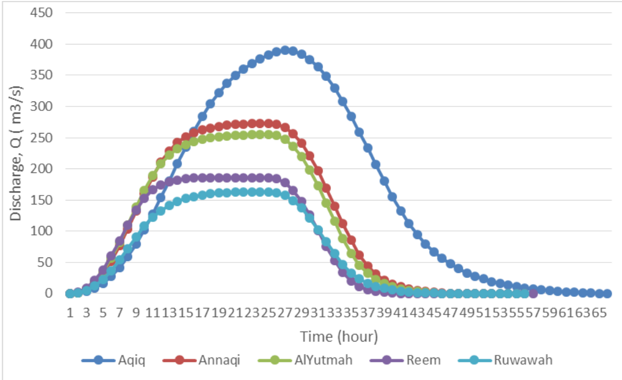


Figure 4 Simulated hydrograph for 100 years at sub-catchment of Wadi Alaqiq (25% imperviousness)

7.0 CONCLUSION

The HEC-HMS model is used in this study to analyze the hydrologic behaviour of the Wadi Alaqiq catchment characteristics. Initial and constant rate loss methods are used to determine the hydrologic losses from the study area and Clark Unit Hydrograph was used for effective rainfall transformation. Simulation results comparisons are compared with published models and empirical formulation (Modified Talbot equation) to address uncertainty of flow hydrograph. The model results comparisons are reasonable for hydrologic application and can be used in arid region for wadi corridor management.

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