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Hydraulic Response of Wadi Fatimah Basin, Western Province, Kingdom of Saudi Arabia

الإستجابة الهيدروليكية لحوض وادي فاطمة، المنطقة الغربية - المملكة العربية السعودية

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Abstract: A computer-based rainfall-runoff Hydrologic Modeling System (HEC-HMS) was used to determine the approximate hydrologic response of seven major sub-basins that contribute to the main channel of Wadi Fatimah watershed, situated in the western part of Saudi Arabia. The hydraulic response results, which include flood peak discharges, lag time and volumes of flood and sediment load transported by flood waters for different return periods of 10, 25, 50 and 100 years with storm duration of 1 hour are estimated. On the other hand, as an example, the hydraulic response results and resulting flood hydrographs of the seven sub-basins for the storm of 25 year return periods are presented. These results show that the largest flood volume, which is 3.2 million cubic meters would expect to be produced at Ash Shamiyyah sub-basin (SUB2) with flood peak discharge 975m^3/s and a lag time of 5.6 hours, while the smallest one (1.98 million cubic meters) with lag time of 2.7 hours and runoff peak 120m^3/s was estimated at the outlet of Wadi Azzibarah sub-basin (SUB3). The flood volume of the entire basin was 73.3 million cubic meters with runoff peak at the outlet of about 1550m^3/s and lag time of about 12.1 hours. However, the values of flood peak discharge and volumes of floods as well as sediment loads increase for storms of longer return periods. The outcome results of this work may provide valuable information that can help in water work constructions to prevent and/or reduce the flood damages that take place within the study area.

Keywords: Boilers emission, burners configuration, diffusion flames, double-burner, equivalence ratio, fumes incineration, premixed flames.

المستخلص:لإستخدم برنامج (HEC-HMS) والمعتمد في الاساس على العلاقة بين المطر - السيل لتمذجة النظام الهيدروولوجي بحوض وادي فاطمة والواقع في الجزء الغربي من المملكة العربية السعودية وذلك لتحديد الاستجابة الهيدروليكية التقريبية لافرعه السبع الرئيسية والتي تساهم بمياهها السطحية للمحراه الرئيسي. تم حساب واستخلاص نتائج الاستجابة الهيدروليكية والمتضمنة قمة تصريف السيول وزمن الارتفاع لقمة السيل وحجوم السيول والحمولة التي نقلت بفعل مياه السيول بعواصف ممطرة ذات مدد تكرار مختلفة (10, 25, 50, 100 سنة) لعاصفة مدتها ساعة واحدة. من ناحية آخرى تم طرح وكمثال نتائج الاستجابة الهيدروليكية والمنحيات المائية للسبع الافرع الرئيسية لمدة تكرار 25 سنة، اشارت النتائج ان اكبر حجم لسيل والذي يقدر بحوالي 3.2 مليون م^3 يتوقع ان يتولد عند مخرج فرع وادي الشامية مع قمة سيل 975م^3/ث وزمن ارتفاع لقمته مقدراه 5.6 ساعة، في حين اشارت ان أصغر سيل حجمه 1.98 مليون م^3 مع زمن ارتفاع لقمته حوالي 2.7 ساعة وقمته 120م^3/ث يحدث عند مخرج فرع وادي الزبارة. تم حساب حجم السيل المتولد عند مخرج حوض وادي فاطمة والذي يقدر بحوالي 73.3 مليون م^3 وقمته 1550 م^3/ث. من جانب آخر لوحظ ان قيم قمة السيول وكذلك حجوم السيول والرواسب المنقولة بواسطتها تزداه بزيادة مدد التكرار المختلفة. ان النتائج التي استخلصت من هذا العمل ربما توفر معلومات قيمة يمكن ان تساعد في الانشاءات ذات العلاقة بمياه السيول وذلك لمنع أو الأقلال من دمار السيول والتي تحدث داخل منطقة الدراسة.

كلمات مدخلية: السيول - مسار السيل - المنحنيات المائية

Introduction

Despite the arid nature of Saudi Arabia, flash floods often take place as a consequence of excessive rainfalls. These floods occasionally cause heavy destruction to human lives and properties. This fact ranks floods among the most catastrophic phenomena in wadis that are located in the Arabian Shield in the western part of the country. Wadi Fatimah is one of these basins where flash floods frequently take place either locally within its tributaries or within the entire basin. These floods almost become a source of danger that threaten towns such as Bahrah and Hada and other small villages within the wadi as well as highways and bridges that obstruct the water course of these basins. Generally, flood discharges are not properly studied in the country. A small number of investigations concerning flood studies is available (e.g. Sorman and Abdulrazzak, 1987; Al-Turbak and Quraishi, 1987; Nouh, 1988; Sorman, *et al.* 1991; Abdulrazzak, *et al.* 1995). Their work is mostly related to regional flood frequency estimates for basins, in order to derive the frequency of peak discharges and develop regional curves to determine annual peak flows for given return periods at ungauged sites. Reliable estimates of the expected flood discharges of the sub-basins in Wadi Fatimah are essential for protection measures of areas that are often subjected to flash floods and for future development. The present work focuses on the main tributaries of Wadi Fatimah, including Ash Shamiyyah, Al-Yamaniyyah, Hawarah, Azzibarah, Alaf, Dusm, and Thalathan sub-basins. The present work is an attempt to quantify wadi sub-basin characteristics and their hydraulic responses for design rainfall of 10, 25, 50 and 100 year return periods for a storm duration of one hour.

Description of the Study Area

Wadi Fatimah basin lies within the western province of Saudi Arabia between latitudes 21° 00′ and 22° 00′ N and longitudes 39° 10′ and 40° 30′ E (Fig. 1). It has a catchment area of about 3900 km^2. It drains in a southwesterly direction from the Hijaz highlands (~ 1600 meters above sea level) towards the Red Sea.

The study area lies in a transitional zone that comes under the influence of both Mediterranean and monsoon types modified by the proximity of the Red Sea and the main escarpment. During the late autumn the southeasterly monsoon is channeled along the Red Sea trough from which it is diurnally diverted towards the land by differential heating, giving rise to orographic thunderstorms along the escarpment. During the winter months air masses of Atlantic Ocean origins pass over the middle and north of Africa across the Red Sea trough, behaving as a cold or warm air mass giving rise to widespread rain over the whole study area (Sen, 1983; Al-Ehaideb, 1985; and Alyamani and Sen, 1992). The lower part of the basin, which lies in the coastal plain, may be considered among the driest parts, where the annual rainfall does not exceed 60mm. In contrast, the upper reaches (1260 meters above sea level) often receive considerable amount of rain and the average annual rainfall is about 280mm.

Geologically, the study area is located on the rifted western margin of the Arabian Shield. It is dominated by the presence of Precambrian igneous and metamorphic rocks. In the upper parts, the basement rocks bordering the wadi form cliff walls of intrusive rocks consisting of granite, diorite and granodiorite (Moore and Al-Rehaili, 1989). These rocks are highly fractured and jointed. Harat Rahat, which is basaltic flow of Tertiary age, bounds the north and northeast corner. The Quaternary deposits that mainly derived from the weathering of the parent rocks are the most extensive of the surficial deposits, consisting of fine to coarse sands, gravels and clay. The drainage system is generally well developed and the pattern is typically dendritic (Fig.1).

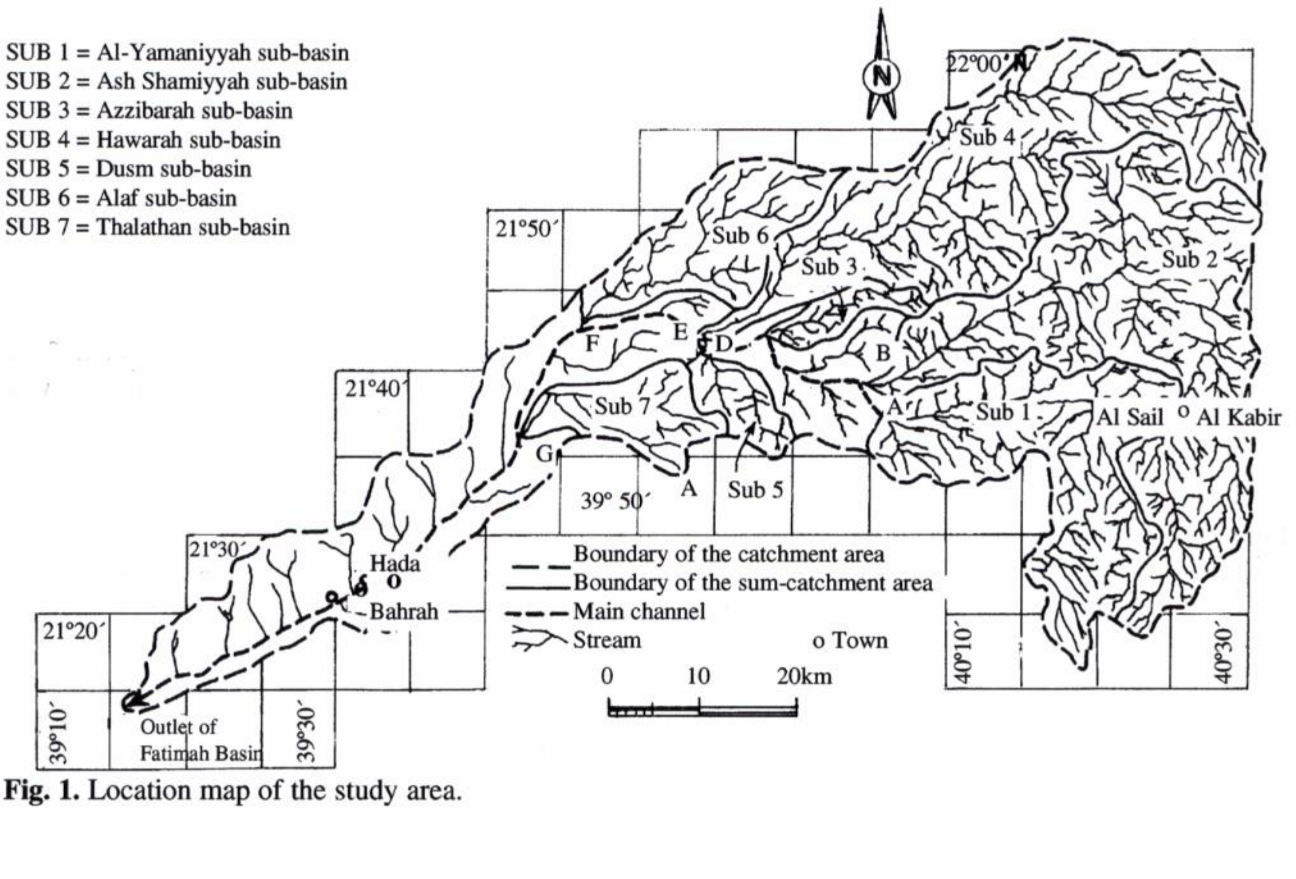

Fig. 1. Location map of the study area.

The detailed pattern of the drainage net and the topography of the wadi may in places reflect differential erodibility. It has many small and relatively large tributaries, which are deep and narrow, and their longitudinal profiles are rather gentle and in some places become irregular. Larger sub-basins such as Ash Shamiyyah and Al-Yamaniyyah are probably controlled by major structures, and smaller faults commonly control lesser drainage channels. However, the major tributaries mostly follow N-S and NE-SW directions, following the dominant faults and joint systems. The upper part of the wadi is rather narrow, where the width of the main wadi course varies from 150m to more than 1.5km further downstream, where the alluvium deposits are widespread and rather thicker.

Methodology and Data Collection

The absence of hydrologic data in the area considered usually results in no guidance on flood characteristics for the design of hydraulic structures. Predicting peak discharges and/or synthesizing complete discharge hydrographs for use in designing minor and major structures are two of the most challenging tasks in hydrology. However, advances in computer methods over the past two decades combined with larger and more extensive data monitoring efforts have allowed for the development and application of simulation models in hydrology. Such models incorporate various equations to describe hydrologic transport processes and various design and control schemes can be tested with the model. For watershed analysis, the major categories of interest include lumped parameter versus distributed parameter, event versus continuous and stochastic versus deterministic. Most of these models are simulating single storm responses for given rainfall input data.

Unity hydrograph or kinematic wave methods are used to generate storm hydrographs, which are then routed within the stream channels. In the present work, the Hydrologic Modeling System (HEC-HMS), (2001) that was introduced by the US Army Corps of Engineers, Hydrologic Engineering Center was used. The basic idea of this model is to simulate the rainfall-runoff processes of dendritic watershed systems. It is also designed to be applicable in a wide range of geographic areas for solving the widest possible range of problems. The physical representation of watersheds or basins is configured in the basin model. Hydrologic parameters are connected in a dendritic network to simulate runoff processes. Throughout the options that are offered by the model, flood computations are performed using Snyder's synthetic unit hydrograph with rainfall loss rates determined using the Soil Conservation Service (SCS) curve number method. This method defines the unit hydrograph with two basic parameters, standard lag time (t_p) and storage coefficient (C_p). These two parameters have been derived from a gauged basin in the region that has similar topographic and climatic conditions. A dimensionless method that was developed by SCS for constructing synthetic unit hydrographs based on dimensionless hydrographs was used in the present work (SCS, 1972).

It requires only the determination of the time to peak and the peak discharge, for which the discharge is expressed as a ratio of discharge to peak discharge (Q/Q_p) and the time by a ratio of time to lag time (t/ t_p). On the other hand, the hydrographs of the sub-basin routing is performed using the Muskingum method, which is an analytical approach to flood routing. This method needs two variables; the weighting factor (X) and the storage time constant for the reach (K).

The Muskingum X has been approximated as 0.2, whereas K equals the approximate reach travel time, using length divided by the average velocity. The required morphological parameters that are used in the model were determined based on topographic maps of scale 1:50,000. More details on the theory of the proposed methods can be found in the available hydrological textbooks (e.g. Chow, *et. al.* 1988; Viessman, *et. al.* 1989). The flood discharge estimation has been designed for the storms of different return periods (10, 25, 50 and 100 years) and a storm duration of one hour.

The daily rainfall records from Alsail Alkabir rain gauge, which lies in the upper part of the basin (see Fig. 1) were selected to design rainfall for 10, 25, 50 and 100 year return periods. The method of frequency analysis used was the log-Pearson Type III probability distribution. This technique was applied to the data of the maximum daily rainfall in every year throughout the records. The maximum daily rainfall in each station was determined. These values were then employed in the model (see Table 2). A flowchart of the processes and flood hydrograph routing is illustrated in Fig. 2. The sediment loads in the wadis during flash floods were estimated as bed load transported by flood water at the main stream of each sub-basin, using the modified Meyer- Peter's formula (Garg, 1987):

$q_s = 4700 \{\tau_o [N' / N]^{3/2} - \tau_c \}^{3/2}$ (Kg/m/hr.)

where q_s is the rate of sediment transported per unit width per unit time, τ_o is the tractive stress (kg/m²), τ_c is the critical tractive stress, which is a function of the mean grain size diameter of the sediment (kg/m²), N' is the Manning's coefficient of rugosity for a plane bed and N is the actual Manning's coefficient of rugosity for a rippled bed.

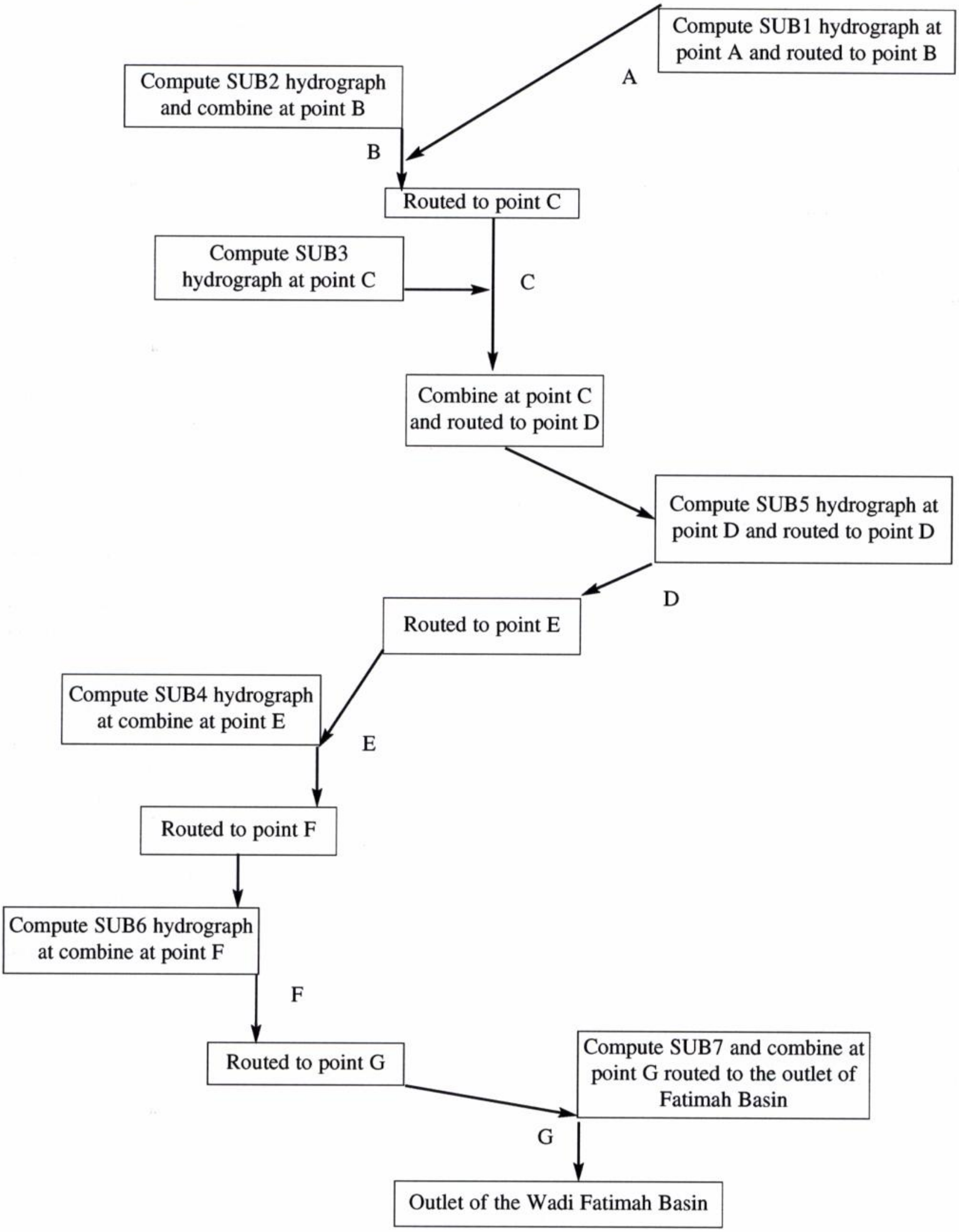

Fig. 2. Flowchart for flood routing computation.

Calibration of the Model

Since no real measurements were available in the study area, data concerning the surface runoff of Wadi Tindaha, which was provided by the Hydrology Division of the Ministry of Water and Electricity, were used for calibration of the model (HMS). Wadi Tindaha, which is a tributary of Wadi Bishah in the southwestern region, drains in a northerly direction from the Asir mountains. It has an area of about 440 Km^2. The most intense rainfall (55mm) produced a flood with a lag time of 9h and peak discharge 273m^3/s. Trial runs were made until the results relatively matched the historical data of the wadi. The comparison results obtained are illustrated in Fig. 3. The percent errors in peak flow and lag time were 7.6% and 4.3% respectively.

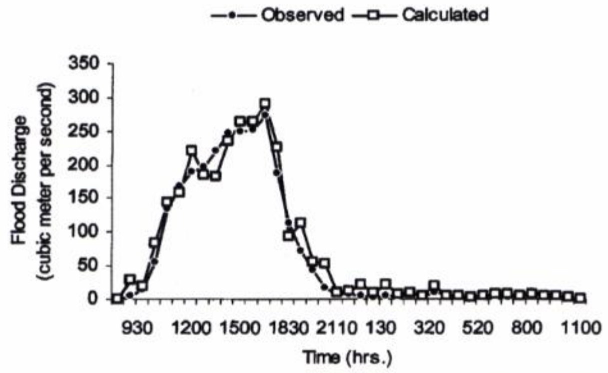

Fig. 3. Comparison between computed and observed hydrographs.

Results and Discussion

This is an approximate analysis because the model was calibrated using data from a wadi out of the study area. A summary of the existing morphometic characteristics of Fatimah watershed and its sub-catchments are presented in Table 1.

Most of the parameters presented in this table were used to estimate the hydraulic responses of the sub-basins of the Wadi Fatimah watershed. However, these morphometric parameters may control the flood hydrograph estimation in terms of lag time and peak discharges. For instance, the drainage density of the basin and sub-basins reflect the effectiveness of the overland flow. Consequently, the average length of overland flow can be estimated by 1/2D, where D is the drainage density (Orbson, 1970; Eweida and El Refeai, 1985). High drainage density, such as in Al-Yamaniyyah (SUB1) and Azzibarah (SUB3) sub-basins, reflects a highly dissected basin, which respond rapidly to rainfall input, while low drainage density indicates a poorly drained basin with slow hydrologic responses.

The overall results obtained are presented in Table 2, consisting of the lag time, flood peaks, volumes of floods and sediment loads for each sub-basin as well as their routed and combination flood hydrographs of different return periods, 10, 25, 50 and 100 years.

The results indicate that the storm of 25 year return period, for instance, produced the large flood volume of about 32.5 million cubic meters with rainfall intensity 36mm at Ash Shamiyyah sub-basin (SUB2) with a flood peak of 975m^3/s and a lag time of 5.6 hours. In contrast, the lowest flood volume (1.98 million cubic meters) during the same return period with a lag time of 2.7 hours and runoff peak 120m^3/s was estimated at the outlet of Wadi Azzibarah sub-basin (SUB3). The difference in the flood peak discharges between the two sub-basins can be attributed to the effects of the drainage basin areas on their runoff peak magnitudes. The same relationship is also depicted between the flood volume and drainage area in Fig 4a-b. In contrast, the sediment load volume does not follow the tendency observed above. It rather shows a weak relationship with the drainage area (Fig. 4c), which might be attributed to the effects of the main channel width (Table 1) of the sub-basins.

Table 1. Results of quantitative analysis of the drainage net of Wadi Fatimah basin and its major tributaries.

Basin and Sub-Basin name	Drainage Area (km^2)	Drainage Density (km^{-1})	Stream Frequency	Average Slope (m/km)	Main Trunk Length (km)	Average Channel Width (m)
Fatimah Basin	3900	0.59	0.32	7.84	144.3	250
Ash Shamiyyah Sub-Basin	903.2	0.65	0.43	11.9	82.90	155
Alyamaniyyah Sub-Basin	497.8	0.93	0.53	12.5	61.9	193
Hawarah Sub-Basin	736.9	0.47	0.27	10.0	87.2	171
Dusm Sub-Basin	67.8	0.54	0.25	15.6	14.71	90
Alaf Sub-Basin	216.2	0.43	0.16	19.5	38.8	143
Thalathan Sub-Basin	122.9	0.50	0.16	13.7	22.0	123
Azzibarah Sub-Basin	55.1	0.93	0.64	16.0	21.0	109

Table 2. Summary of flood peaks and flood and sediment load volumes of different return periods at points A through G to the outlet of Fatimah basin.

				Return period (years)											
				10			25			50			100		
				Design rainfall with different return periods in mm											
				19			36			54			76		
Step	Description	Point	Lag Time (hrs.)	Flood peak (m^3/s)	Flood volume (m^3) x10^6	Volume of sediment Load (Tonnes) x10^6	Flood peak (m^3/s)	Flood volume (m^3/s)	Volume of sediment (Tonnes) x10^6	Flood peak (m^3/s)	Flood volume (m^3) x10^6	Volume of sediment (Tonnes) x10^6	Flood peak (m^3 /s)	Flood volume (m^3) x10^6	Volume of sediment (Tonnes) x10^6
1	Computed SUB1 hydrograph at	A	4.9	321	9.40	0.083575	608	17.9	0.098645	913	26.9	0.109144	1285	37.8	0.118617
2	Routed SUB1 hydrograph to	B	4.1	284	8.90	0.077387	538	17.4	0.090479	807	26.4	0.099159	1137	37.2	0.109397
3	Computed SUB2 hydrograph at	B	5.6	515	17.2	0.063001	975	32.5	0.074212	1463	48.8	0.081409	2059	68.6	0.088825
4	Combined (steps 2+3) at	B	-	781	25.1	0.140388	1480	49.9	0.164691	2221	75.2	0.180568	3126	105.8	0.198222
5	Routed (step 4) to	C	5.2	624	23.5	0.095376	1183	48.2	0.113524	1775	73.3	0.118900	2498	103.8	0.129897
6	Computed SUB3 hydrograph at	C	2.7	64	1.05	0.022829	120	1.98	0.026893	180	2.97	0.030204	254	4.20	0.032648
7	Combined (steps 5+6) at	C	-	665	24.5	0.118205	1261	50.2	0.140417	1892	76.3	0.149104	2663	108.0	0.162545
8	Routed (step 7) to	D	2.1	646	23.6	0.108783	1224	49.1	0.127623	1837	75.1	0.141242	2585	106.8	0.155313
9	Computed SUB5 hydrograph at	D	2.4	91	1.30	0.019205	172	2.45	0.022823	258	3.76	0.025092	363	5.17	0.029028
10	Combined (steps 8+9) at	D	-	687	24.9	0.127988	1301	51.6	0.150446	1952	78.9	0.166334	2717	111.9	0.184341
11	Routed (step 10) to	E	1.1	681	24.6	0.022438	1290	51.2	0.026336	1935	78.5	0.029473	2724	111.6	0.031737
12	Computed SUB4 hydrograph at	E	6.0	386	14.0	0.061626	732	26.5	0.072345	1098	39.8	0.080752	1545	56.0	0.087500
13	Combined (steps 11+12) at	E	-	883	38.6	0.084064	1673	77.7	0.098681	2509	118.3	0.110225	3532	167.6	0.119237
14	Routed (step 13) to	F	3.2	828	36.7	0.032471	1496	75.6	0.038780	2244	116.0	0.041850	3159	165.2	0.045910
15	Computed SUB6 hydrograph at	F	3.9	177	4.10	0.032309	336	7.80	0.038210	504	11.70	0.042133	709	16.4	0.046182
16	Combined (steps 14+15) at	F	-	901	40.8	0.064780	1707	83.4	0.076990	2561	127.2	0.083983	3604	181.6	0.092092
17	Routed (step 16) to	G	3.1	867	37.7	0.042715	1642	79.9	0.050440	2464	123.6	0.055627	3468	177.7	0.060378
18	Computed SUB7 hydrograph at	G	2.9	135	2.34	0.028087	256	4.43	0.032987	383	6.64	0.035533	539	9.35	0.039737
19	Combined (steps 17+18) at	G	-	891	40.0	0.078020	1689	84.3	0.083427	2533	130.2	0.091160	3565	187.1	0.100115
20	Routed (step 19) to	Outlet of basin	12.1	818	30.1	0.027316	1550	73.3	0.032362	2325	118.2	0.036522	3272	164.3	0.040446

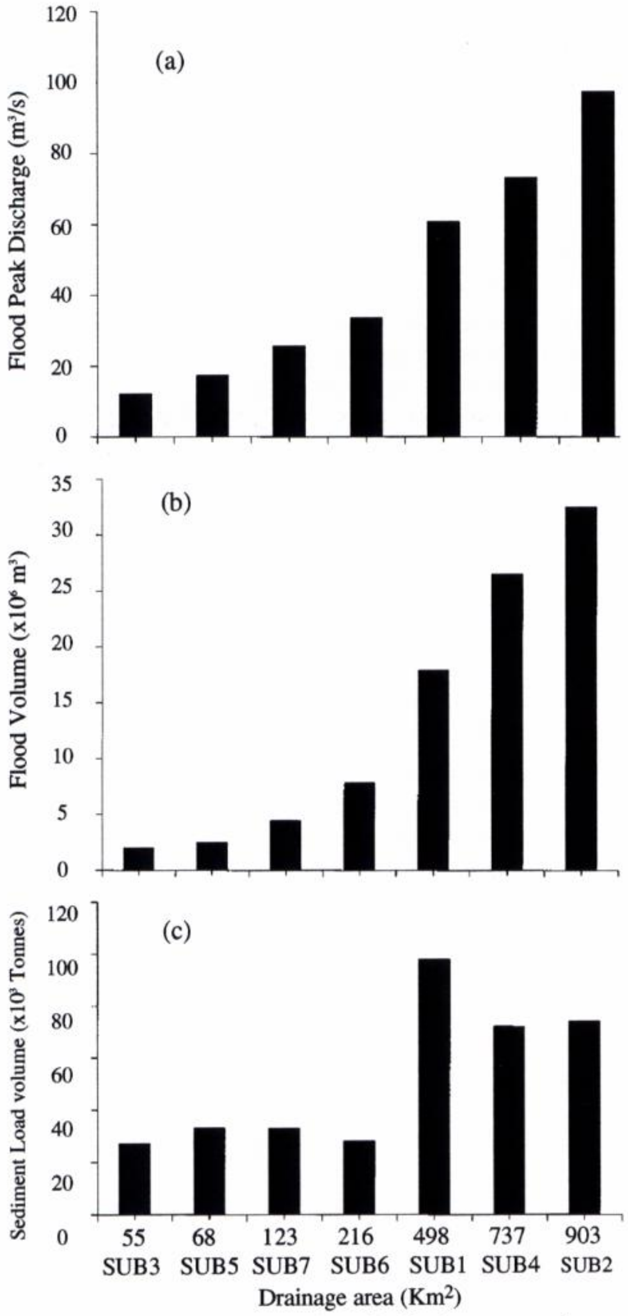

Fig. 4. The relationships of peak discharges, volume of floods and volume of sediment load with drainage area.

The resulting flood peak hydrographs for the storms of the 25 year return period at the outlets of the relatively larger sub-basins (e.g. SUB1, SUB2, SUB4 and SUB6), including their routed and combination hydrographs to the outlet of the entire basin are shown in Figures 5 and 6. The output hydrographs show that the flows are characterized by relatively steep rising limbs and gentle recessions to zero baseflow. This pattern of hydrographs generally represents the flood flows that commonly take place in arid regions (Walters, 1989). The routed and combination hydrographs of the sub-basins at the points A throughout G to the outlet of the basin (see Fig. 2) indicate that the peaks often decrease in their magnitude at the end of the reach lengths and increase when augmented by tributary inflows. For instance, the flood peak discharge for SUB1 under existing conditions is 608m³/s with a lag time of 4.9 hours, but when it is routed to point B, it reduces to 538m³/s with a lag time of 4.1 hours, as a result of the channel reach storage. On the other hand, the flood peak at the outlet of SUB2 is 975 m³/s and when the routed flood of SUB1 joins, it becomes 1480m³/s. The results also indicate that the flood volume of the entire basin is 73.3 million cubic meters with a flood peak discharge at the outlet of about 1550m³/s and a lag time of 12.1 hours.

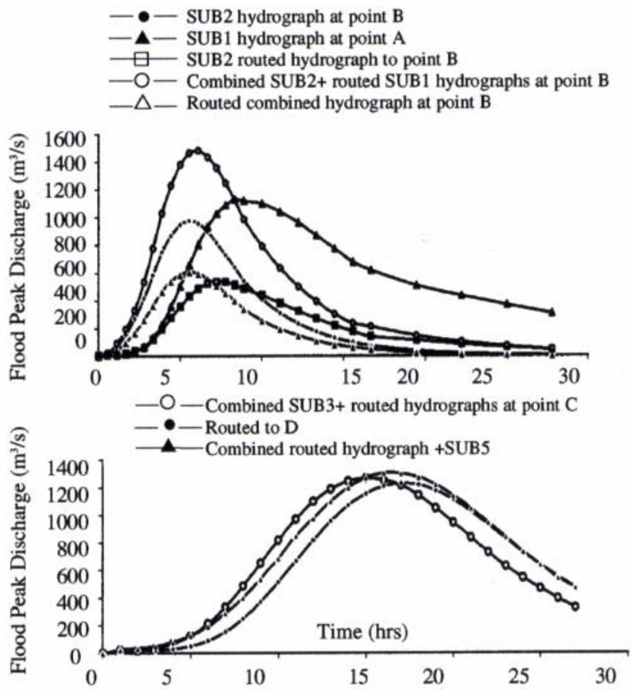

Fig. 5. Runoff hydrographs for SUB1 and SUB2, combined and routed hydrographs.

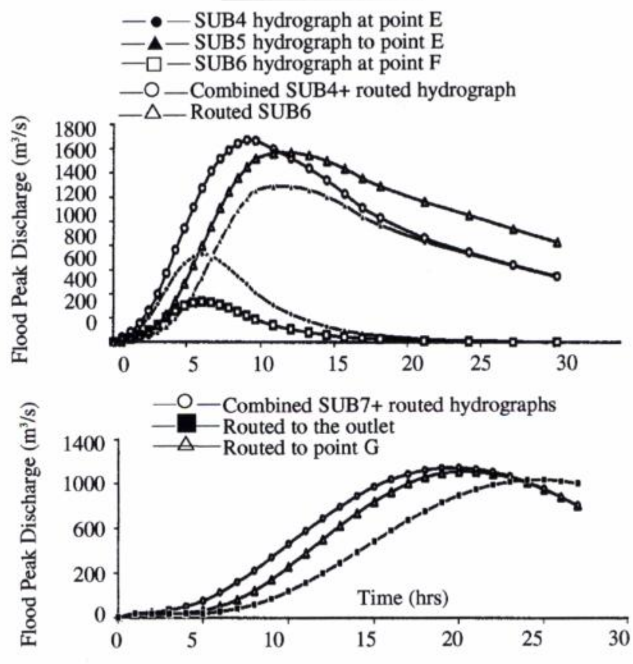

Fig. 6. Runoff hydrographs for SUB4 and SUB6, combined and routed hydrographs.

Conclusions

With the help of a computer-based Hydrologic Modeling System (HEC-HMS), flood peak discharges and the routed and combinations hydrographs were determined for seven major tributaries of the Wadi Fatimah watershed. The study was repeated for storms of 10, 25, 50 and 100 year return periods and storm duration of one hour. The hydraulic response results of the 25 year return period indicate that the largest flood peak discharge of $975 m^3/s$ and a lag time of 5.6 hours is expected to take place at the outlet of Ash Shamiyyah sub-basin. The smallest runoff peak of $120 m^3/s$ with a lag time of 2.7 hours was estimated at Azzibarah sub-basin outlet. Values of flood peak, sediment load and flood volumes indicate an increasing trend with the storms of longer return periods. The results, such as peak discharges and flood volumes, may provide valuable information in designing flood control works and protection measures.

On the other hand, the sediment load results may provide data that can be used in the design of any proposed dam in the area in terms of dam capacity determination since these sediments that are carried and transported by flood waters often occupy a part of the dam storage capacity.

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