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Derivation of the Unit Hydrograph of Allith Basin in the South West of Saudi Arabia

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Abstract: Most studies on unit hydrograph theory is developed for temperate regions and to the best of the authors' knowledge, there is no studies on this topic in arid regions because of the lack of runoff measurements. This paper presents the derivation of a unit hydrograph of a Allith basin and its S-curve in the south western part of Saudi Arabia to be used to predict flash flood more accurately in this region. The derivation is based on the method of stream flow data that has been collected from measured rainfall and runoff storms in the region. The study resulted in the unit hydrograph of 1 hr duration and the S-curve that is used to transfer the hydrograph to any other durations. This unit hydrograph can be used to predict flash floods in Allith basin and similar watersheds.

Key words: Arid Zones · Unit hydrograph theory · Stream flow data · Flash Flood Modeling · Hydrology

INTRODUCTION

The study of the hydrological characteristics of the basins and developing of mathematical models for rainfall and runoff relationships that bind it with topographic characteristics is a very old subject. The first study of this topic was made by Sherman in 1932 [1-3].

Since 1932, researchers are developing rainfall-runoff models for storm runoff predictions. However, it is noticeable that most researches, books and theses were considering studies in temperate regions, while arid zones are lacking such studies.

Although the presence of severe storms in arid zones, these storms happen few times a year. The rare occurrence of the severe storms in arid zones and the lack of measurements of runoff make the study of the hydrological characteristics in arid basins a difficult task.

Specialists and researches in the field of water resources are developing methods and formulas to facilitate the process of calculating the relationship between rainfall and floods, so that they can predict future storms. There are several methods to estimate runoff hydrograph [2, 3]. These are 1) derivation of unit hydrograph from Stream flow data, 2) synthetic methods, 3) statistical distribution methods and 4) geomorphological instantaneous unit hydrograph. A review of these methods are given in Albishi M [4].

This study focused on an experimental watershed in south western part of Saudi Arabia called Allith basin as shown in Figure 1.

The purpose of this paper is to derive a unit hydrograph from stream flow data for Allith basin to be applied in south west region of Saudi Arabia instead of relying on synthetic methods that are derived in temperate regions and does not suit the topographic and climatic conditions in Saudi Arabia.

Study Area: The study area is located within the Tehama escarpment of the Arabian shield; it is characterized by semi-annual flash floods [5]. Allith basin is located in the western part of the Kingdom of Saudi Arabia. Allith basin is located in Makkah Al-Mukaramah region and is about 200 km south of Jeddah City. It lies between 40°10' & 40°50' E and 20°00' & 21°15' N with an area of 3079 km^2 as shown in Figure 1.

Geologically, Allith basin is underlain by late Proterozoic plutonic, meta-volcanic and meta-sedimentary rocks in most of the basin with an area of about 86.8% of

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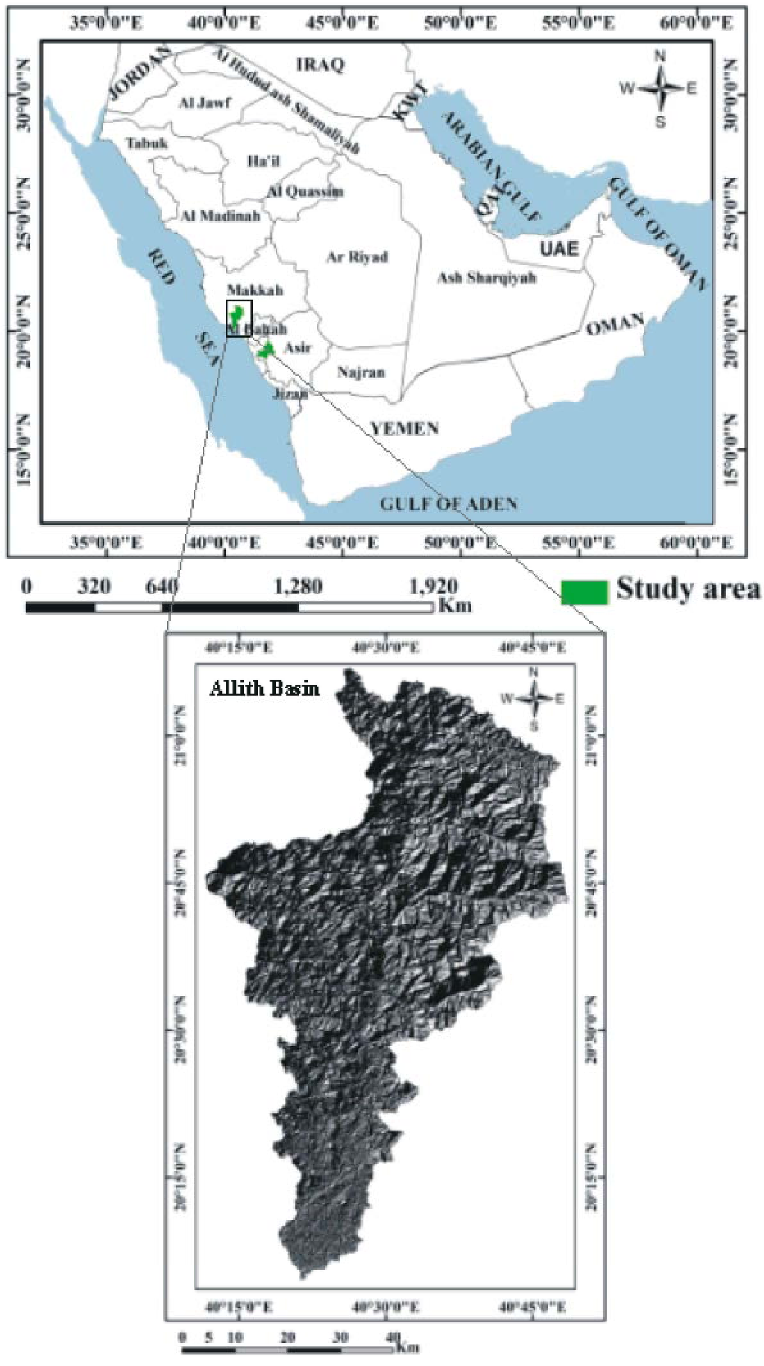

Fig. 1: Location of study area.

the total area, by chiefly Tertiary sedimentary, volcanic and plutonic rocks in and near the coastal plain and by Tertiary oceanic crust of the Red Sea offshore. The contact between continental and oceanic crust is probably 10 - 15 km onshore. Quaternary sediments of Aeolian sand, silt and pediment deposits with an area of about 11.9% of the total area blanket the coastal plain with thickness that ranges from 2 m to 10 m and fringed by coral reefs that are uplifted locally along faults parallel to the coast [6, 7].

The upstream of Allith basin is restricted between rugged mountainous terrains which get dissected by several tributaries which flow towards the main basin. The middle and the downstream of the basin is a low relief

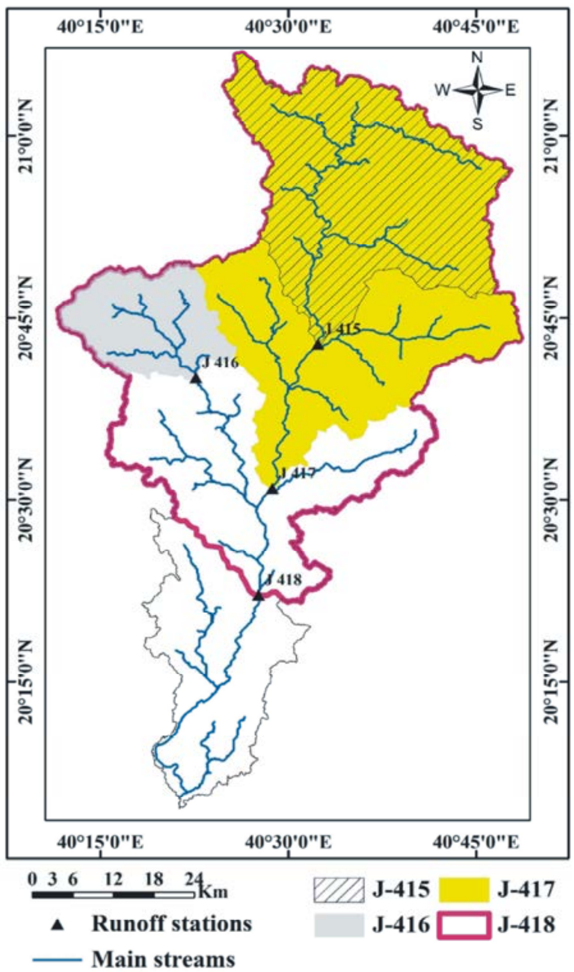

Fig. 2: Allith basin and its sub catchments.

area covered by several types of Quaternary deposits including alluvium, sand plains, gravel, silt and Aeolian sand dune fields, while the upstream has complicated relief covered by a relatively thin alluvium layer composed of sand and gravel [6, 7].

Proterozoic age layered and intrusive rocks, which are composed of gabbro, tonalite, granodiorite basalt and andesite, rhyolite and green schist, surround the upper part of the basin. These hard rocks are characterized by a weathered surface covered with angular blocky fragments. Unconsolidated quaternary deposits comprise the main alluvium deposits in the main channel and its tributaries [6, 7].

The geomorphology of Allith basin shows a typical basin system flowing from the west part of the escarpment ridge of the Arabian shield. It starts from the eastern high mountainous slopes of the escarpment and decreases down to the west of flat sediments of the Tehama coastal plain close to the Red Sea. The elevation of Allith basin ranges from 0 to 2,620 m with mean elevation of 824 m (above mean sea level, amsl). Allith basin and its surrounding areas exhibit different geomorphologic units as follows: (A) High mountainous area is composed essentially of Proterozoic rocks with high elevation values that reach to 2,620 m (amsl) which is representing the main catchment of the basin. The high mountainous area of the study area plays an important role in the rainfall intensity. (B) The hilly area occupies the north eastern and middle parts of the basin. This area is composed of hilly dissected and weathered zone as shown in Figure 1 and (C) The coastal plain occupies the low land area between the mountainous area and the Red Sea. It comprises morph tectonic depressions and the main channel of the basin. Allith basin has been divided to 4 sub catchments. These sub catchments have runoff stations numbered as J-415, J-416, J-417 and J-418. Figure 2 shows locations of Allith basin and its sub catchments. Arc GIS has been used to calculate the morphometric characteristics for Allith basin and its sub catchments. The morphometric parameters are tabulated in Table 1.

Methodology: The procedure to derive the unit hydrograph is based on the stream flow data and has the following steps:

- Strom data are collected and transferred into a digital form to be used on the computer.
- The hydrograph from the original data (digitized) and the interpolated over 0.1 hr interval.
- Phi (Ô) index method is used to determine the effective rainfall (excess rainfall).
- The unit hydrograph is calculated by dividing each value in the hydrograph on the value of effective rainfall depth. $Q = x\left(1 - e^{-bt}\right)$
- An S-curve is constricted which is the hydrograph of direct runoff that would result from a continuous succession of unit storms producing 1-unit depth in the duration of the unit hydrograph. It is created for each storm to derive unit hydrograph of different durations from all storms.
- It is necessary to synthesis a mathematical model to represent an acceptable S-curve. It has been assumed an exponential equation in the form below for that purpose:

$$Q = x\left(1 - e^{-bt}\right) \quad (1)$$

where:

Q: the discharge (m^3/s),

Table 1: The morphometric parameters for Allith basin and its sub catchments at runoff station

		Allith				
Parameter		J-415	J-416	J-417	J-418	Allith
Area (A)	(km^2)	960.09	293.62	1692.75	2726.10	3079.00
Basin Perimeter (B_P)	(km)	221.73	92.88	302.60	432.68	586.57
Main order		6	5	6	7	7
Sum. Of stream numbers		1397	460	2502	4063	4944
Sum. Of stream lengths	(km)	1283.35	395.22	2262.76	3672.70	4514.54
Basin length (L_B)	(km)	39.88	21.00	60.56	80.00	113.00
Valley length (L_V)	(km)	45.64	17.23	73.75	15.72	60.78
Relief (R)	(km)	2.19	1.47	2.45	2.54	2.62
Basin slope (S)		0.0548	0.0700	0.0404	0.0317	0.0232
Main stream slope		0.0154	0.0090	0.0122	0.0060	0.0033
Internal relief (I_R)	(m)	1000	350	850	1100	1800
Bifurcation ratio (R_B)		4.11	4.44	4.56	3.97	4.11
Weighted mean bifurcation ratio (WMR_B)		4.42	4.31	4.48	4.33	4.36
Stream frequency (F)	(km^{-2})	1.46	1.57	1.48	1.49	1.61
Drainage density (D)	(km^{-1})	1.34	1.35	1.34	1.35	1.47
Length of overland flow (L_{OF})	(km)	0.37	0.37	0.37	0.37	0.34
shape factor (f)		0.77	0.85	0.59	0.54	0.31
Circularity ratio (R_C)		0.25	0.43	0.23	0.18	0.11
Elongation ratio (R_E)		0.88	0.92	0.77	0.74	0.55
Sinuosity (S_i)		1.15	0.82	1.22	0.20	0.54
Ruggedness number (N_R)		2.92	1.98	3.27	3.42	3.85
Drainage texture ratio (DR_T)	(km^{-1})	6.3	4.95	8.27	9.39	8.43
Compactness ratio (R_{CC})		2.02	1.53	2.08	2.34	2.98
Basin width (W_B)	(km)	24.07	13.98	27.95	34.08	27.25

x: It is a fitting parameter estimated from the variance of the data,

e: The base of the natural logarithms,

b: It is another fitting parameter related to the steepness of the curve at the origin and

t: Time (hr).

- In order to derive a unit hydrograph of specific duration, the S-curve has to be shifted with the required duration.
- Estimation of the unit hydrograph of various durations is made by applying the following equation:

$$Q = \frac{D\left(S_{C_0} - S_{C_1}\right)}{t} \quad (2)$$

where:

Q: The discharge (m^3/s),

D: The original duration of the unit hydrograph (hr),

S_{C0}: The S-curve without shifting,

S_{C1}: The S-curve after shifting and

t: The desirable duration (hr).

RESULTS AND DISCUSSIONS

The number of storms that has been studied at the runoff station (J-415) are two storms. Figure 3(a) shows that the peak discharge occurs after about 10 minutes of the beginning of the flood, estimated by more than 150 $m^3/s/mm$ and continues to flood for 6 hours almost, casing 942,000 m^3 flash flood volume. In view of the morphometric parameters for station J-415 (Table 1), can be argued that the floods of this station are very serious.

It is worth mentioning that the S-curve resulting from this station is shown in Figure 3(b).

The unit hydrograph and S-curve for station (J-416) is also estimated. The number of storms that studied in this station are two storms also. Unlike the previous station, the peak discharge happens after about half an hour of the beginning of the flood, as shown in Figure 4(a) and this time should be enough for warning and evacuation. The peak discharge value is estimated at about 70 $m^3/s/mm$. The flood takes about 3 hours since beginning to end, causing 276,000 m3 flash flood volume.

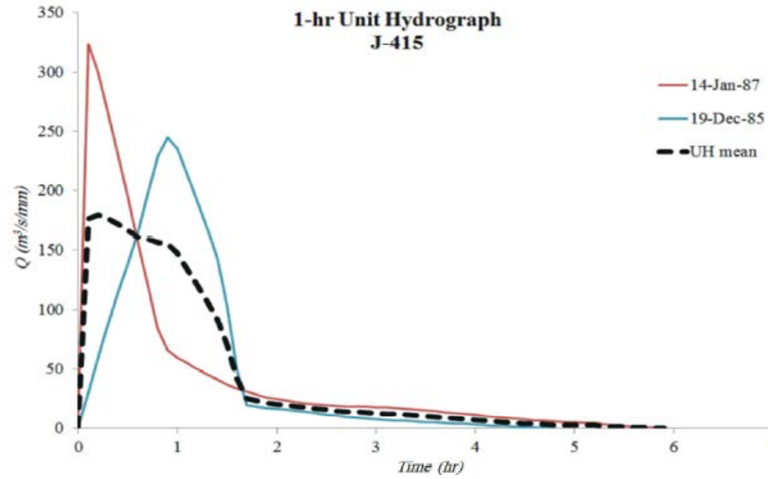

Fig. 3(a): 1-hr unit hydrograph of station J-415.

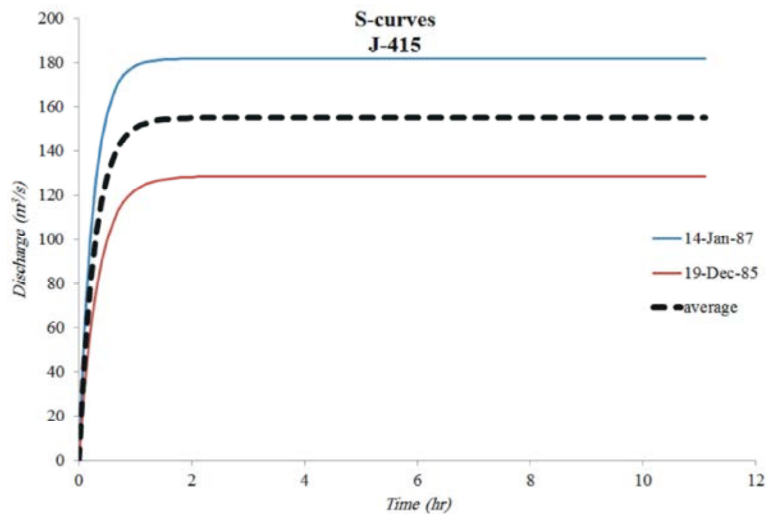

Fig. 3(b): S-curve of station J-415.

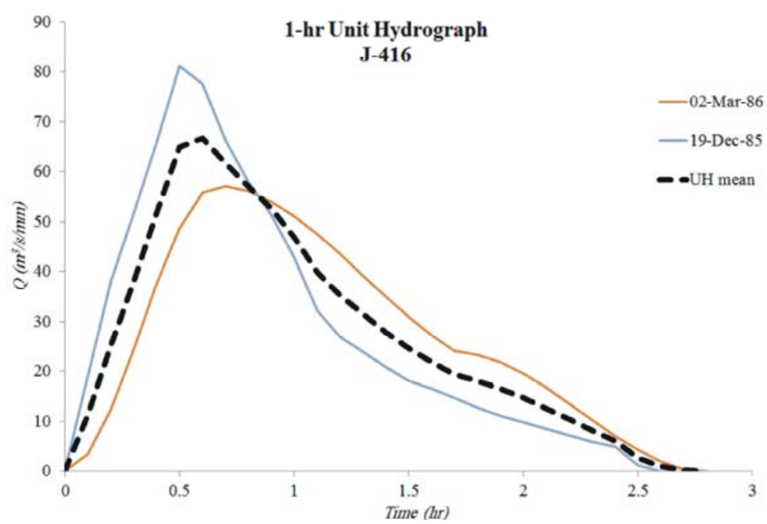

Fig. 4(a): 1-hr unit hydrograph of station J-416.

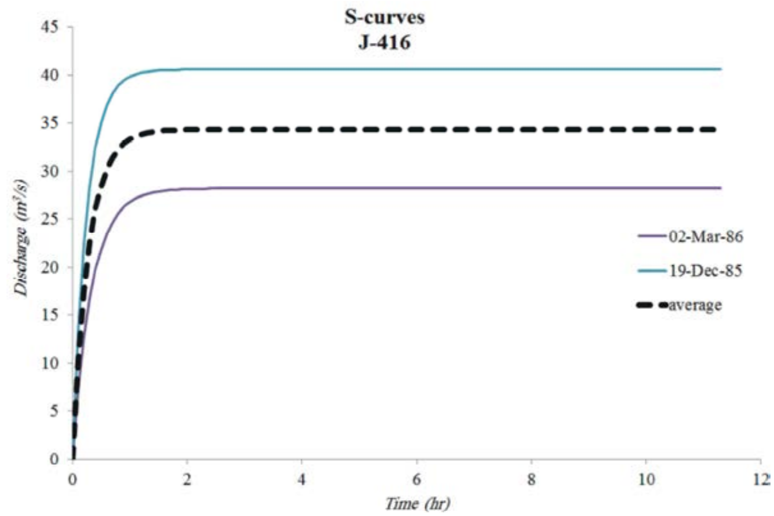

Fig. 4(b): S-curve of station J-416.

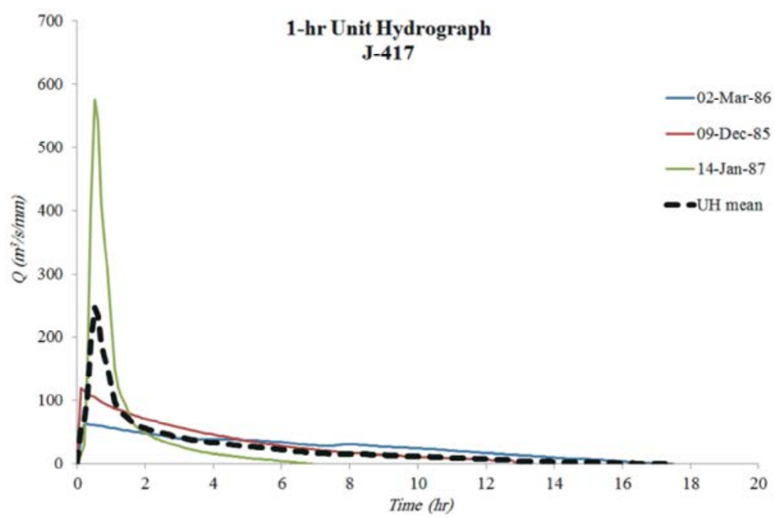

Fig. 5(a): 1-hr unit hydrograph of station J-417.

In view of the morphometric parameters for station J-416 (Table 1), it can be argued that the floods of this station can be managed well and the S-curve resulting from this station is shown in Figure 4(b).

The unit hydrograph and S-curve for station (J-417) is also estimated. The number of storms that studied in this station are three storms. The peak discharge occurs during the first half hour of flood, estimated by more than 200 m^3/s/mm and lasted for 17 hours approximately, as shown in Figure 5(a), causing more than 1,657,000 m3 flash flood volume. In view of the morphometric parameters for station J-417 (Table 1), it can be argued that the floods of this station are devastating.

Figure 5(b) shows the S-curve resulting from this station.

The unit hydrograph and S-curve for Allith basin as a whole is obtained from the previous sub basins. Overview of Allith basin, the number of storms that studied in this basin are seven storms. These storms are the previously mentioned in Figures 3, 4 and 5.

Figure 6(a) represents the average of Allith basin which resulted from the averages of the stations. The peak discharge occurs during the first half hour of the flood, estimated by more than 150 m^3/s/mm and lasted for more than 17 hours approximately, causing more than 958,000 m3 flash flood volume.

In view of the morphometric parameters for Allith basin (Table 1), it can be argued that the floods of this basin are very dangerous. Figure 6(b) shows the S-curve resulting for Allith basin.

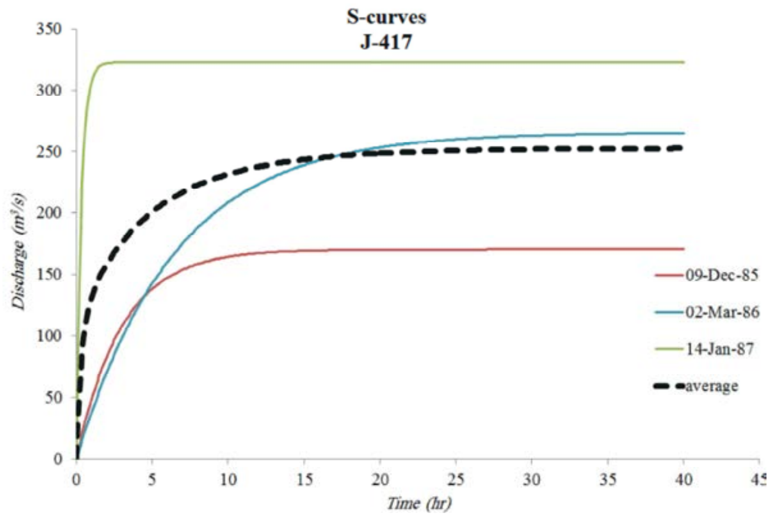

Fig. 5(b): S-curve of station J-417.

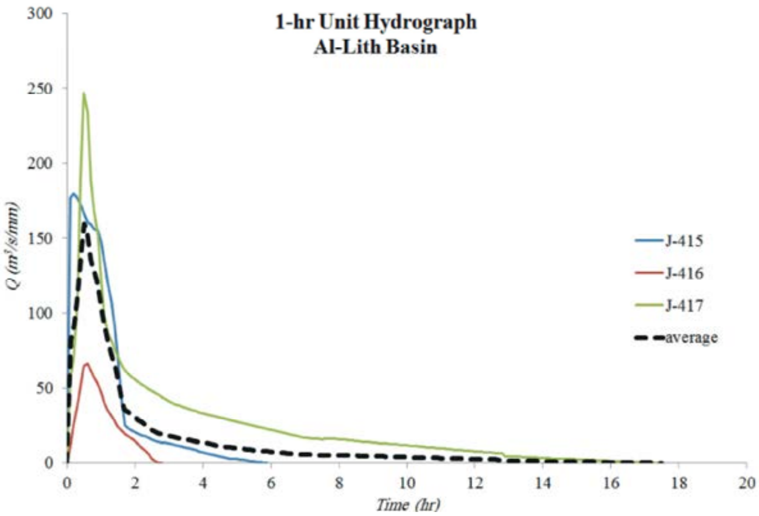

Fig. 6(a): 1-hr unit hydrograph of Allith basin.

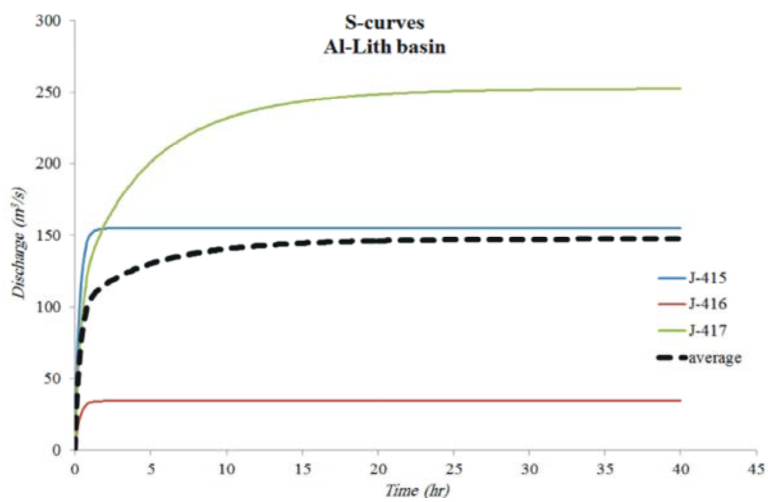

Fig. 6(b): S-curve of Allith basin.

CONCLUSIONS

This paper presents the application of the stream flow data method to derive a unit hydrograph of a Allith basin and its S-curve in the south western part of Saudi Arabia to be used to predict flash flood more accurately in this region. Most studies on unit hydrograph theory is developed for temperate regions and to the best of the authors' knowledge, there is no studies on this topic in arid regions. The study resulted in unit hydrograph of 1 hr duration and the S-curve that is used to transfer the hydrograph to any other duration. This unit hydrograph can be used to predict flash floods in Allith basin and similar watersheds.

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