GIS-BASED KW–GIUH HYDROLOGICAL MODEL OF SEMIARID CATCHMENTS: THE CASE OF FARIA CATCHMENT, PALESTINE

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الخلاصــة

يعتبر الفهم والحساب الكمي لعمليات الجريان السطحي ولمنحنى التدفق من التحديات التي تواجه دراسة الموارد المائية. في الاحواض المائية المعايرة (Gauged Catchments) فان احتساب منحنى التدفق يتم باستعمال الطرق التقليدية اعتمادا على وجود قياسات لكميات الامطار والجريان السطحي لفترة زمنية طويلة. إن استعمال النماذج الهيدرولوجية التقليدية هو موضوع جدل من حيث امكانية التطبيق في المناطق الجافة وشبه الجافة خاصة غير المعايرة منها (Ungauged Catchments). أن تطور النماذج الهيدرولوجية التي تعتمد على الخصائص الفيزيائية مثل نموذج منحنى التدفق الأحادي اللحظي الذي يعتمد على جيومورفولوجية الحوض المائي (GIUH) جاء للتغلب على مثل هذه العقبات.

في هذه الورقة هنا بدراسة وتفحص العلاقة ما بين المطر والجريان السطحي لحوض وادي الفارعة وذلك باستخدام النموذج الهيدرولوجي (KW–GIUH) وهو منحنى التدفق الأحادي المعتمد على الخصائص الجيومورفولوجية ومعادلة الحركة وكذلك بالاستعانة ببرنامج نظم المعلومات الجغرافية (GIS) يعتبر وادي الفارعة واحدا من الأحواض شبه الجافة في فلسطين، والذي تتباين فيه معدلات الأمطار السنوية من ٦٤٠ ملم في الجزء العلوي منه إلى حوالي ١٥٠ ملم في الاجزاء السفلية القريبة من نهر الاردن. وباستخدام هذا النموذج تم اشتقاق منحنى التدفق الأحادي (IUH) للأحواض الثلاثة التي يتشكل منها وادي الفارعة. منحنيات التدفق المشتقة تدل على أن النموذج الهيدرولوجي (KW–GIUH) قابل للتطبيق لنمذجة الجريان السطحي في المناطق شبه الجافة ويدلل ذلك على إمكانية استخدام وتوظيف هذا النموذج لاشتقاق منحنيات التدفق للأحواض السطحية في فلسطين.

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ABSTRACT

Among the most basic challenges of hydrology are the quantitative understanding of the processes of runoff generation and prediction of flow hydrographs. Traditional techniques have been widely applied for the estimation of runoff hydrographs of gauged catchments using historical rainfall–runoff data and unit hydrographs. Such procedures are questioned as to their reliability and their application to ungauged, arid, and semiarid catchments. To overcome such difficulties, the use of physically based rainfall–runoff estimation methods such as the Geomorphologic Instantaneous Unit Hydrograph (GIUH) approach has evolved. This paper models the rainfall–runoff process of Faria catchment using the lately developed KW–GIUH. Faria catchment, located in the northeastern part of the West Bank, Palestine, is characterized as a semiarid region with annual rainfall depths ranging on average from 150 to 640 mm at both ends of the catchment. The Geographical Information System (GIS) techniques were used to shape the geomorphological features of the catchment. A GIS-based KW–GIUH hydrological model was used to simulate the rainfall–runoff process in the three sub-catchments of Faria, namely: Al-Badan, Al-Faria, and Al-Malaqi. The simulated runoff hydrographs proved that the GIS-based KW–GIUH model is applicable to semiarid regions and can be used to estimate the unit hydrographs in the West Bank catchments.

Key words: KW–GIUH; GIS; flow hydrographs; semiarid regions

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INTRODUCTION

Hydrologists and water engineers are always concerned with discharge rates resulting from rainfall. Not only are measuring rainfall and the resulting runoff of interest, but so is the process of transforming the rainfall hyetograph into runoff hydrograph. Peak flow rate and time to peak are the two important hydrograph characteristics that need to be estimated for any catchment. Unfortunately, the classic problem of predicting these parameters is usually difficult to resolve because many rivers and streams are ungauged, especially those in developing regions or isolated areas. The high spatial variability in rainfall intensities and amounts combined with variability in soil properties makes prediction of these parameters very difficult especially for ungauged catchments. Even in cases where catchments are gauged, the period of record is often too short to allow accurate estimates of the different hydraulic parameters.

Among the most basic challenges of hydrology are the quantitative understanding of the processes of runoff generation and prediction of the flow hydrographs and their transmission to the outlet.

Traditional techniques have been widely applied for the estimation of runoff hydrographs at the outlets of gauged catchments using historical rainfall runoff data and unit hydrographs derived from them. Such procedures are of questionable reliability due to the climatic and physical changes in the catchment and their application to ungauged, arid, and semiarid catchments.

In the unit hydrograph theory, it is assumed that the potential abstractions are fully met before runoff occurs. This assumption is applicable to humid regions, but is doubtful in arid and semiarid regions. For arid and semiarid regions, the infiltration portion is higher than for humid regions due to higher infiltration rates and dry soil antecedent moisture condition. The infiltrability of the soil is high and the infiltration process will continue significantly during the rainfall event. The amount of actual infiltration may not satisfy the infiltrability of the soil. The evaporation losses are also high in arid and semiarid regions and the evaporation process may occur during the storm. Therefore the applicability of the unit hydrograph approach in semiarid regions should be investigated as to its basic assumption of satisfying the abstraction and neglecting the surface and subsurface flow interaction during the rainfall–runoff process, (Shaheen [1]).

A significant advance in the unit hydrograph approach for ungauged watersheds is the development of the GIUH (Yen and Lee [2] and Lee and Yen [3]). The GIUH approach was originated by Rodriguez-Iturbe and Valdes [4], who rationally interpreted the runoff hydrograph in the framework of travel time distribution explicitly accounting for geomorphological structure of a catchment. In the GIUH approach, excess rainfall is assumed to follow different paths on overland areas and in channels of different stream orders to reach the watershed outlet.

Geomorphology-based instantaneous unit hydrographs have been applied by several engineers to predict runoff from rainfall for ungauged catchments. They have proposed to estimate floods for ungauged streams by using the information obtainable from topographic maps or remote sensing possibly linked with the Geographic Information Systems (GIS) and Digital Elevation Models (DEM), Snell and Sivapalan [5], Jain *et al.* [6], and Hall *et al.* [7].

GIS provides a digital representation of the catchment characterization used in hydrologic modeling. GIS can also provide the basis for hydrologic modeling of ungauged catchments and for studying the hydrologic impact of physical changes within a catchment. Maidment [8] summarized the different levels of hydrological modeling in association with GIS as follows: hydrologic assessment; hydrologic parameter determinations; hydrologic modeling inside GIS; and linking GIS and hydrologic models.

In this study GIS has been employed as a tool to determine the hydrologic parameter for the Faria catchment needed to compile the KW–GIUH model. The KW–GIUH model that was developed for ungauged catchments is to be used in the modeling. The available KW–GIUH model has been developed by Kwan Tun Lee and Chin-Hisn Chang, Watershed Hydrology and Hydraulics Laboratory, Department of River and Harbor Engineering and National Taiwan Ocean University.

The West Bank is a semiarid region. In arid and semiarid regions storm water drainage and hydrological modeling is as important as in humid regions because it is not only a drainage problem but also a water resources management and planning problem. Hydrological modeling in the West Bank has not been given enough care and no intensive studies have been done. As a result of the semi-aridity and due to the Karstic nature of the rock formation of the Palestinian aquifers, a high percentage of the rainfall infiltrates. The rainfall–runoff ratio in the West Bank has a wide variation (0.1% to 16.3%) indicating that a small portion of the rainfall is converted to runoff, Shaheen [1].

The objective of this is paper is to hydrologically investigate the Faria catchment as one of the most important catchments located in the northeastern parts of the West Bank, Palestine. The main objective is to model the rainfall–runoff process of the Faria catchment, which has not been modeled so far, and to derive the unit hydrograph for the catchment. Modeling the runoff in the Faria catchment will provide basic information for the managers to understand runoff generation within the catchment and thus support the decision-making process about future development of the water resources in the area.

THE STUDY AREA

The area under consideration is the Faria catchment which is located in the northeastern part of the West Bank and extends from the ridges of Nablus Mountains down the eastern slopes to the Jordan River as shown in Figure 1. Faria watershed has a catchment area of about 334 km^2 which accounts for about 6% of the total area of the West Bank. The Faria catchment lies within the Eastern Aquifer Basin, which is one of the three major groundwater aquifers forming the West Bank groundwater resources.

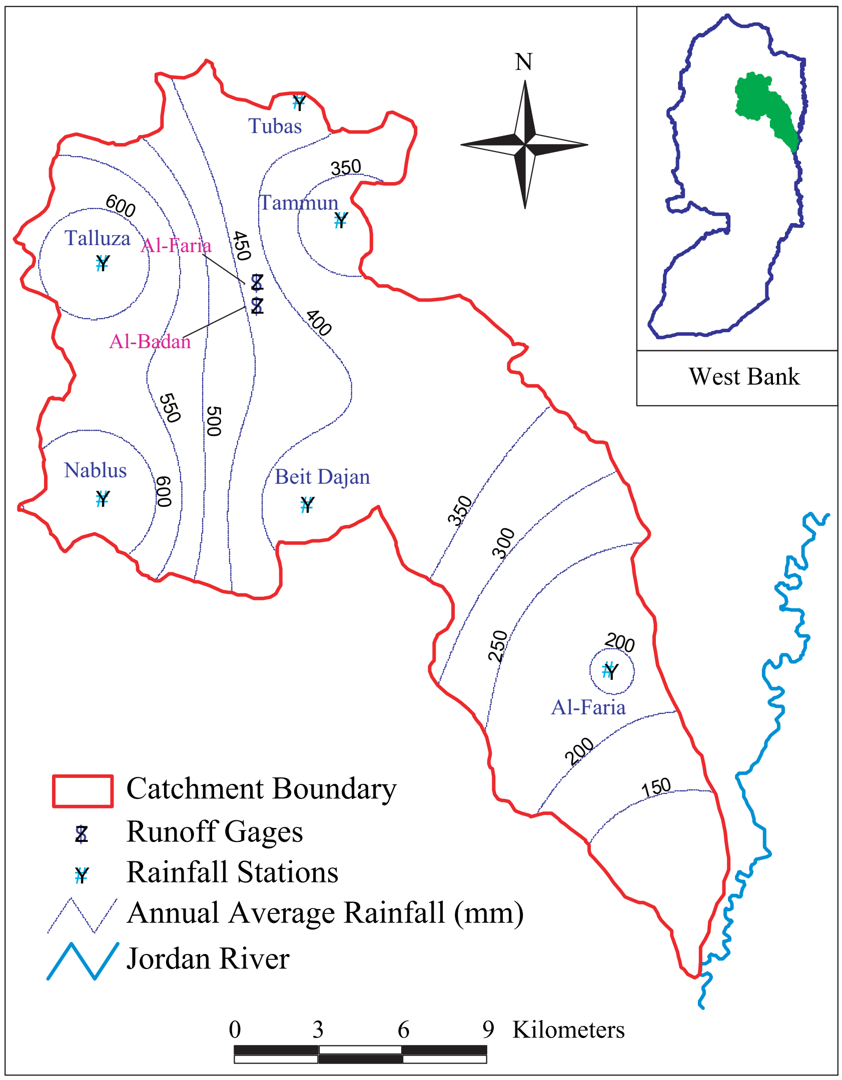

Figure 1. Rainfall distribution and location of runoff gauges and climatic stations in the Faria Catchment

Topography is a unique feature of Faria catchment which starts at an elevation of about 900 meters above mean sea level in Nablus Mountains and descends drastically to about 350 meters below mean sea level across the main surface water wadi especially in the southern parts of the catchment at the confluence where Faria wadi meets the Jordan River (Figure 2).

Faria catchment is gauged by six rainfall stations (Figure 1) and two runoff flumes. Daily rainfall is available for the six rainfall stations but for different numbers of years and not as a continuous time series except for the Nablus station. Rainfall intensity readings are available for only two stations in the Faria catchment, Nablus and Beit Dajan, and for nine and three years, respectively. In August 2004 four Tipping Bucket Rain Gauges were installed in the schools of

Taluza, Tubas, Tammon, and Beit Dajan. Data are available for the 2004 and 2005 rainy seasons from three of the four stations only, since the Taluza gauge is not functioning. A summary of the available data is presented in Table 1. X and Y coordinates of the rainfall stations are according to the Palestinian grid (local coordinate).

Table 1 shows that Nablus and Talluza stations have the largest average annual rainfall and Al-Faria station has the lowest. Rainfall isoheights were interpolated from the readings obtained from the six stations using GIS. Figure 1 shows that rainfall distribution within the Faria catchment ranges from 600 mm at the headwater to 150 mm at the outlet to the Jordan River. In general, rainfall averages decrease moving from north to south and west to east. All stations are still in working order except for the Al-Faria meteorological station, which has been stopped since 1989. Al-Faria station has an elevation of 237 m below the sea level, Shadeed [9].

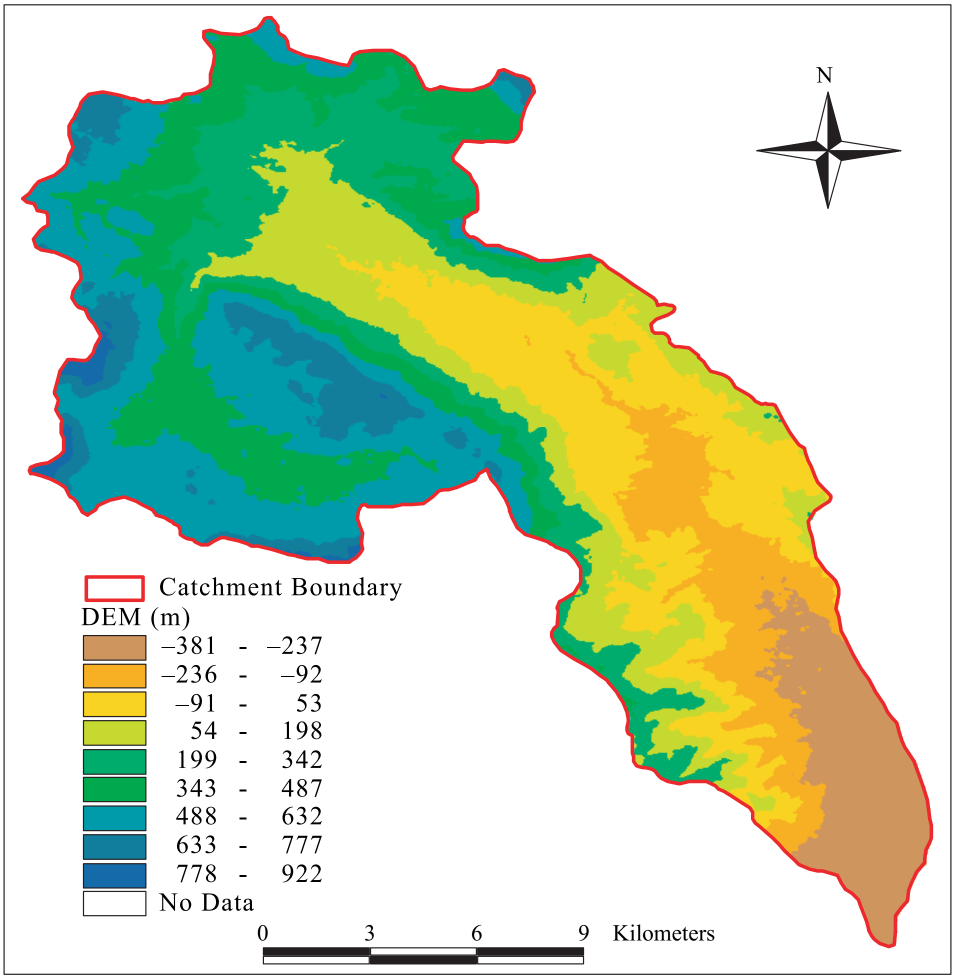

Figure 2. Digital Elevations Model (DEM) for the Faria Catchment

Table 1. Available Rainfall Stations within the Faria Catchment

Station Name	X Coord. (km)	Y Coord. (km)	Elev. (m)	Records Period	Max. (mm)	Min. (mm)	Avg. (mm)
Nablus Meteorological Station	178.0	178.0	570	1946–2005	1388	316	643.4
Talluza Primary School Station	178.0	186.3	500	1963–2005	1303	292	631.2
Tubas Secondary School Station	185.0	192.0	375	1967–2005	890	202	415.7
Beit Dajan Rainfall Station	185.3	177.8	520	1952–2005	777	141	379.6
Tammun Primary School Station	186.5	187.8	340	1966–2005	616	124	322.7
Al Faria Meteorological Station	196.0	172.0	–237	1952–1989	424	30	198.6

Not enough runoff data are recorded for the Faria catchment. Most of the data available are monthly data estimated using direct measurements of the runoff at selected locations and periods of the year. Therefore, to collect the rainfall–runoff data necessary for the detailed modeling of storm events, the Water and Environmental Studies Institute (WESI) of An-Najah National University constructed, on August 2003, two Parshall Flumes to measure the flows at the two main streams of the upper Faria catchment, Al-Faria and Al-Badan. The flumes were constructed in the context of the GLOWA project (Impacts of global changes on surface water resources in wadis contributing to the lower Jordan River basin). Maximum and minimum flows that were measured by the flumes at Al-Faria and Al-Badan were 15 m^3/s, 0.19 m^3/s, and 25 m^3/s, 0.23 m^3/s, respectively. There are two reading gauges at each flume to measure the flow depths at the critical sections, which are converted into flow rates using the designed empirical formulas. The constructed flumes are working and the records were available for the two hydrological years 2003–2004 and 2004–2005. The flumes did not have automatic recorders during the first year. The automatic recorders were constructed later and are available since the second year, Shadeed [9]. Selected rainstorm events and corresponding runoff records were chosen from the available rainfall and runoff data and used to test the KW–GIUH model.

The Geographical Information System (GIS) techniques were used to shape the geomorphological features of the catchment. In this study, GIS ArcView 3.2 software was used for geomorphological parameter determinations. The available 1:50 000 topographic maps of the catchment were scanned and the catchment was subdivided into sub-catchments. Drainage lines and divides were digitized using GIS techniques. A Digital Elevations Model (DEM) with a 20-m resolution has been used to derive flow directions and stream slopes (Figure 2).

STRUCTURE OF THE KW–GIUH MODEL

Overland flow over a permeable soil surface can occur when the rainfall rate is greater than the infiltration capacity or when surface saturation exists in regions near the stream, Lee and Chang [10]. When a unit depth of rain excess falls uniformly and instantaneously onto a catchment, the unit rainfall excess is assumed to consist of a large number of independent, noninteraction raindrops. Thus, the whole rainfall–runoff process can be represented by tracing the rainfall excess moving along different paths towards the catchment outlet to produce the outflow hydrograph, Lee and Yen [3].

Based on the Strahler ordering scheme, a catchment of order Ω can be divided into different states. Most of the surface flow occurs on the low portions of the catchment; after that, it goes into the adjacent channel and then flows through the stream network to the outlet. Each raindrop falling on the overland region will move successively from lower to higher order channels until it reaches the outlet. The catchment geomorphology is represented probabilistically based on the stream order, instead of simulating the overland surfaces and channels by their individually actual geometry as in the deterministic modeling. The ith-order overland regions is denoted by x_{oi} and x_i represents the ith-order channel, in which $i = 1, 2,\ldots, \Omega$. If w denotes a specified runoff path $x_{oi} \rightarrow x_i \rightarrow x_j \rightarrow \ldots.. \rightarrow x_\Omega$, the probability of a drop of rainfall excess adopting this path can be expressed as

$P(w) = P_{OA_i}.P_{x_{oi}x_i}\ldots P_{x_ix_j}\ldots P_{x_kx\Omega}$,where $P_{x_{oi}x_i}$ is the transitional probability of the raindrop moving from the ith-order overland region to the ith-order channel and $P_{x_ix_j}$ is the transitional probability of the raindrop moving from an ith-order channel to a jth-order channel and is computed as

$$P_{x_ix_j} = \frac{N_{i,j}}{N_i} \tag{1}$$

where N_{ij} is the number of ith-order channels contributing to the jth-order channels and P_{OA_i} is the ratio of ith-order overland area to the total catchment and is computed as

$$P_{OA_i} = \frac{1}{A}\left(N_i\bar{A}_i - \sum_{i=1}^{i-1} N\bar{A}_i P_{x_ix_j}\right) \tag{2}$$

where $\overline{A}_i$ is the mean of the drainage area of order i. and is estimated as

$$\overline{A}_i = \frac{1}{N_i} \sum_{j=1}^{N_i} A_{ji} \,. \tag{3}$$

It should be noted that A_{ji} denotes not only the areas of the overland flow regions that drains directly into the jth channel of order i, but it also includes overland areas draining into the lower order channels tributary to this jth channel of order i.

The travel time for the overland flow region and for the storage component of a channel are assumed to follow an exponential distribution, but the translation component of a channel is assumed to follow a uniform distribution. For the state x_k, the travel time for the channel storage component and channel translation component are $T_{x_{rk}}$ and $T_{x_{ck}}$, respectively, and the total travel time is $T_{x_k} = T_{x_{rk}} + T_{x_{ck}}$.

The IUH can be represented by the convolution of two groups of the probability density functions and is given by:

$$u(t) = \sum \{[f_{x_{oi}}(t) * f_{x_{ri}}(t) * f_{x_{rj}}(t) * \ldots.. * f_{x_{r\Omega}}(t)] * [f_{x_{ci}}(t) * f_{x_{cj}}(t) * \ldots.. * f_{x_{c\Omega}}(t)]\}_w . P(w). \tag{4}$$

The first part of Equation (4) represents the overland flow region (x_{ok}) and the channel storage component (x_{rk}). The exponential distribution with a mean travel time of T_{x_k} is

$$f_{x_k}(t) = \frac{1}{T_{x_k}} \exp\left(\frac{-t}{T_{x_k}}\right), \text{ for all } t. \tag{5}$$

The second part of Equation (4) represents the channel translation component (x_{ck}). The uniform distribution with a mean travel time of T_{x_k} over an interval (0, 2 T_{x_k}) is

$$f_{x_k}(t) = \left\{ \begin{array}{cc} \dfrac{1}{2T_{x_k}}; & 0 \le t \le 2T_{x_k} \\ 0; & \text{otherwise} \end{array} \right\}. \tag{6}$$

The distribution function bound is set to be from 0 to 2 T_{x_k} because the definition of the mean travel time. Substituting in the previous equation, the IUH can be expressed analytically as:

$$u(t) = \sum_{w \in W} \left\{ \frac{1}{T_M} \left[G(t) + \sum_{k=1}^{N_w} (-1)^k U_{2T_{x_M}}(t).G(t - 2T_{x_M}) \right] \right\}_w . P(w), \tag{7}$$

where $U_c(t)$ is a unit step function [$U_c(t) = 1$ for $t \ge c$, and $U_c(t) = 0$ for $t < c$]; N_w = total number of different order channels in the path w; and

$$T_m = T_{x_{oi}} . T_{x_{ri}} . T_{x_{rj}} \ldots T_{x_{r\Omega}} .(2T_{x_{ci}}).(2T_{x_{cj}}) \ldots (2T_{x_{r\Omega}}) \tag{8}$$

$$\begin{aligned} G(t) = \; & a_1 + a_2 t + \ldots + \frac{1}{(N_w - 1)!} a_{N_w} t^{N_w - 1} + b_{oi} \exp\left(\frac{-t}{T_{x_{oi}}}\right) \\ & + c_i \exp\left(\frac{-t}{T_{x_{ri}}}\right) + c_j \exp\left(\frac{-t}{T_{x_{rj}}}\right) + \ldots + c_\Omega \exp\left(\frac{-t}{T_{x_{r\Omega}}}\right) \end{aligned} \tag{9}$$

$$X_M = \{x_{ci}, x_{cj}, \ldots., x_{ck}\} \in \{x_{ci}, x_{cj}, \ldots., x_{ck}, \ldots.., x_{c\Omega}\} \tag{10}$$

$$T_{x_M} = \sum_{i=1}^{M} T_{x_{ci}}, \tag{11}$$

where M denotes the size of X_M; and $a_1, a_2, \ldots, a_{N_w}, b_{oi}, c_i, c_j, \ldots c_\Omega$ = coefficients.

The coefficients are determined by comparing coefficients in partial fractions after applying the Laplace transformation.

KW–GIUH MODEL INPUT PARAMETERS

The Geographical Information System (GIS) techniques were used to shape the geomorphological features of the Faria catchment. In this study, GIS ArcView 3.2 software was used for geomorphological parameter determinations. The catchment was studied delineating all possible flow paths and streams and was divided into two parts, the upper and lower Faria catchments. The upper part is composed of two sub-catchments which are Al-Badan sub-catchment and Al-Faria sub-catchment. The areas of the sub-catchments are 85 km^2 and 64 km^2 respectively. The lower part of the catchment is named Al-Malaqi sub-catchment and has an area of about 185 km^2. Strahler's stream ordering system has been applied and has indicated that the Al-Faria and Al-Badan sub-catchments are both of fourth order, while Al-Malaqi sub-catchment is of third order.

Figure 3 shows the drainage network map and the stream orders of the three sub-catchments. The map in their digital forms has been used to estimate the input parameters needed for the application of the KW–GIUH model. These input parameters for the application of the model on the three sub-catchments are listed in Tables 2 and 3, which give the stream network transitional probability and the input parameters of the KW–GIUH model for the three sub-catchments respectively.

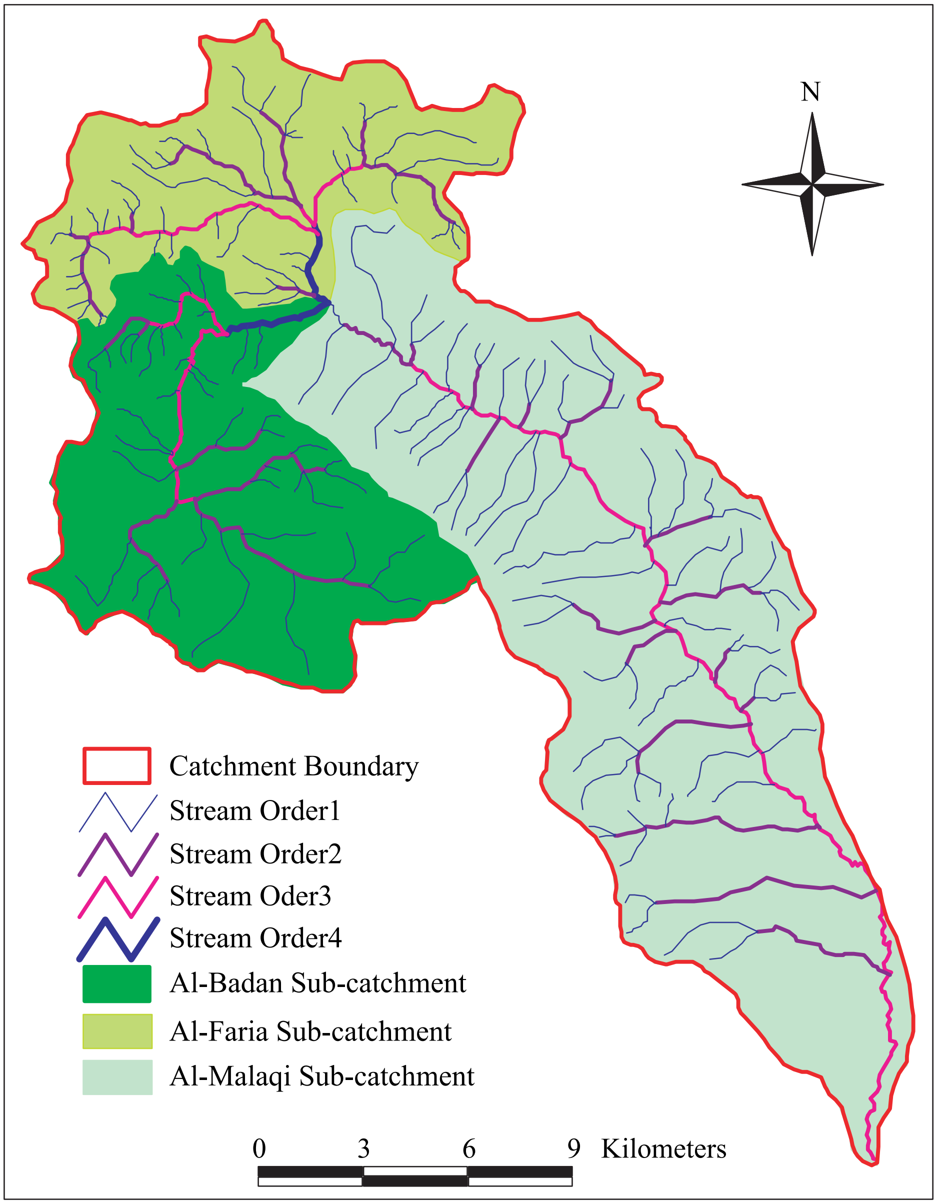

Figure 3. Stream Orders Network for the three sub-catchments of Faria Catchment

Table 2. $P_{x_i x_j}$ for the Three Sub-catchments

Description	$P_{1,2}$	$P_{1,3}$	$P_{1,4}$	$P_{2,3}$	$P_{2,4}$	$P_{3,4}$
Al-Badan	25/14	14/41	2/41	6/6	0/6	2/2
Al-Faria	36/49	11/49	2/49	7/8	1/8	3/3
Al-Malaqi	45/62	17/62	0	1	0	0

Table 3. KW–GIUH Input Parameters for the Three Sub-catchments

Parameter	Al-Badan Sub-catchment				Al-Faria Sub-catchment				Al-Malaqi Sub-catchment		
	Order				Order				Order		
	1	2	3	4	1	2	3	4	1	2	3
N_i	41	6	2	1	49	8	3	1	62	16	1
$\overline{L}_{c_i}$ (m)	1379	3202	5027	3172	1031	2120	3496	2621	1920	2611	32084
$\overline{A}_i$ (km^2)	1.370	10.12	40.73	85.0	0.937	6.099	19.369	64.0	1.81	5.83	185.0
P_{OA_i}	0.66	0.186	0.126	0.028	0.717	0.153	0.102	0.028	0.606	0.319	0.075
$\overline{S}_{o_i}$ (m/m)	0.14	0.062	0.051	0.029	0.117	0.058	0.033	0.031	0.14	0.063	0.01
$\overline{S}_{c_i}$ (m/m)	0.17	0.092	0.14	0.135	0.154	0.085	0.161	0.125	0.146	0.122	0.081
Area (km^2)	85				64				185		
$B\Omega$ (m)	4.57				3.66				10		
n_o	0.3										
n_c	0.03										

KW–GIUH UNIT HYDROGRAPH DERIVATION

The above input parameters are incorporated to KW–GIUH model to derive 1-hr unit hydrographs of 1 mm/hr, rainfall intensity for Al-Badan, Al-Faria, and Al-Malaqi sub-catchments, the following are assumed. From the outputs the 1 mm-GIUH hydrographs for the three sub-catchments are plotted as shown in the Figures 4 and 5.

Several excess rainfall intensities were applied to Al-Badan sub-catchment, so as to study the effect of excess rainfall amount on the generation of the GIUH. The results are illustrated in Figure 6. From the figure it is clear that the GIUH of a catchment is a function of the excess rainfall and there is a set of GIUHs instead of just one for a certain catchment. The peak value increases with increasing excess rainfall, whereas the time to peak decreases with increasing excess rainfall.

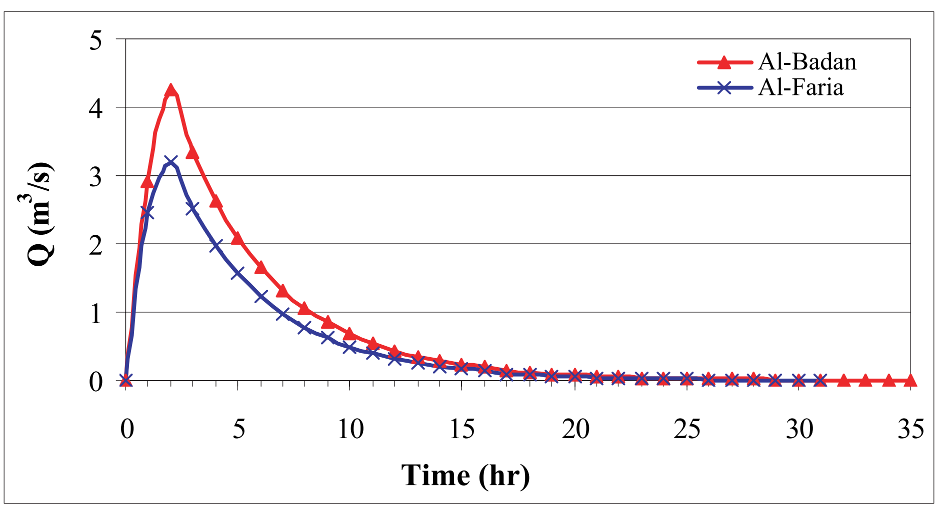

Figure 4. 1 mm-GIUH for Al-Faria and Al-Badan Sub-catchments

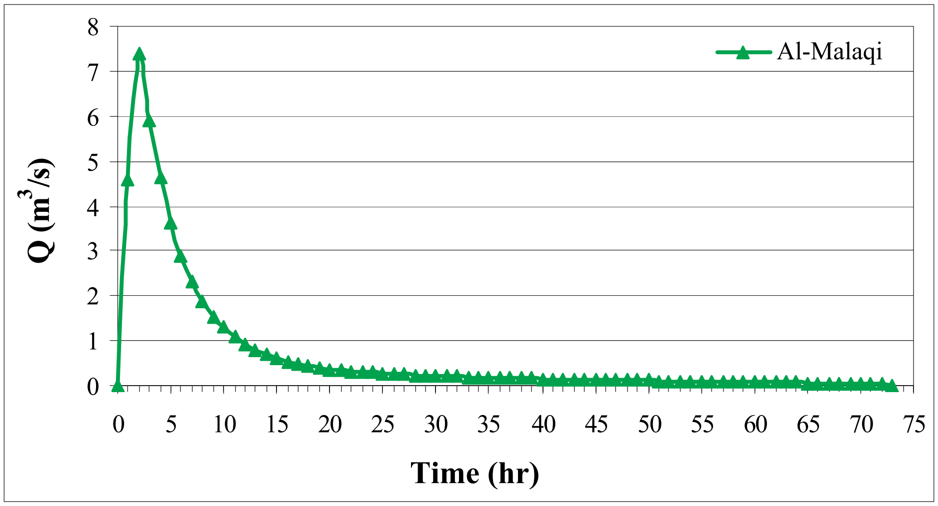

Figure 5. 1 mm-GIUH for Al-Malaqi Sub-catchments

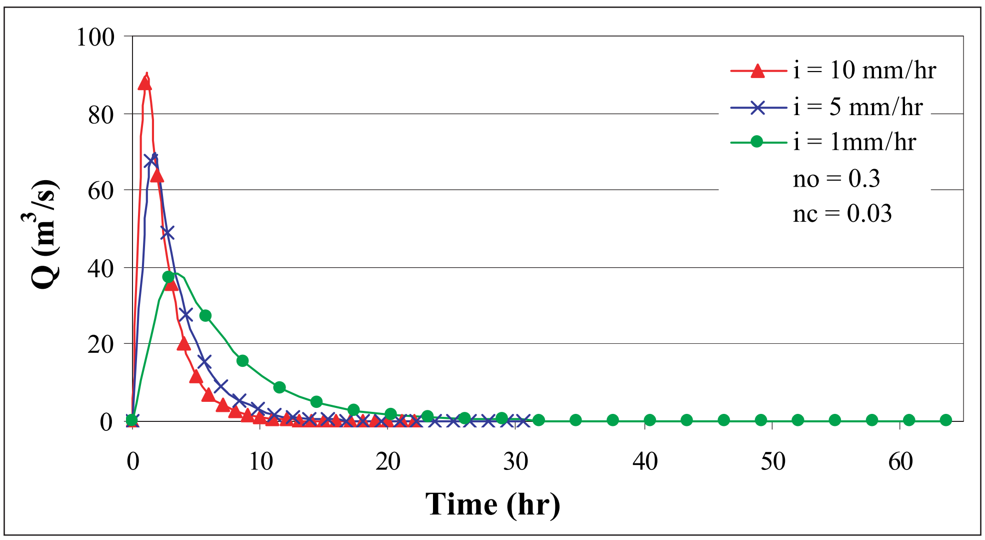

Figure 6. Variation of GIUH with excess rainfall

MODEL APPLICATION

The primary goal of developing the IUH of a catchment is to apply it to hydrograph generation for design of project storms [2]. Selected rainstorms on Al-Badan sub-catchment have been chosen to test the applicability of the KW–GIUH model to produce the runoff hydrograph of a given rain event and to verify the model output by comparison with observed data for the Al-Badan sub-catchment (Figure 3). Two selected rainstorms have been chosen from the last two rainy seasons, 2004–2005. The first event occurred on 14/2/2004 and the second occurred on 5/2/2005.

Event 1, 14/2/2004

During the rainy season of 2004, only one considerable double peak storm was recorded at the fourteen of February which was simulated using the KW–GIUH model. This storm was chosen from the records of the 2004 rainy season, where clear peak of the recorded discharge is obtained. The point rainfall recorded at Nablus meteorological station located near the headwater of Al-Badan sub-catchment was areally averaged over the sub-catchment. This averaging is necessary because the unit hydrograph theory assumed uniform rainfall over the catchment. The total rainfall of this simulated event is about 40 mm and it lasted for 16 hours. The rainfall excess hyetograph was determined by deducting the abstractions from the rainfall using the Horton infiltration equation, Patra [11].

$$f_t = f_c + (f_o - f_c)e^{-kt}, \tag{12}$$

where f_t is the infiltration capacity at any time t from the beginning of the storm in mm/h, f_c is the infiltration rate in mm/h at the final steady stage when the soil profile becomes fully saturated, f_o is the maximum initial value when $t = 0$ in mm/h at the beginning of the storm, k is an empirical constant depending on soil cover complex, vegetation and other factors, and t is the time lapse from the onset of the storm.

Values of f_o, f_c, and k are dependent on a number of factors such as soil characteristics and climatic conditions. In this study, f_c and f_o are taken as 4 mm/h and 15 mm/h respectively. These figures are reported by an experimental field study done under similar catchment characteristics near the village of Deir Ibzei, 10 km west of the city of Ramallah, West Bank (Lange *et al.* [12]). This assumption is reliable since the two locations are located in a semiarid region and have nearly the same features and soil characterizations.

The recorded and estimated peaks occur at about the same time. Two peaks have been observed. The first recorded and estimated peaks are 4.67 m^3/s and 4.45 m^3/s respectively, resulting an error of peak discharge (EQ_p) of –4.71%. The second peak was not recorded. The excess rainfall depth was calculated at 1.1 mm and the rainfall depth is 5.5 mm. As a result f_t equal 5.5–1.1= 4.4. Substituting in Equation (12) gives $k = 0.66$ for the selected storm. This was used to develop the infiltration capacity curve which was applied to calculate the excess rainfall. The infiltration capacity curve is as shown in Figure 7. The resulting excess rainfall from the above storm is about 6 mm distributed as shown in Figure 8. For the storm of 14/2/2004, the base flow was separated from the recorded discharge.

Discharges at Al-Badan Flume for this rainstorm were recorded using the stage flow curve for the flume. The stage readings were taken manually. The automatic recorder was installed in August 2004 and all events afterwards were recorded automatically. The manual readings produce discrete points and do not cover the whole period of the storm, as fewer records are taken during nights. Recorded discharges for this rainstorm were compared with the KW–GIUH generated hydrograph.

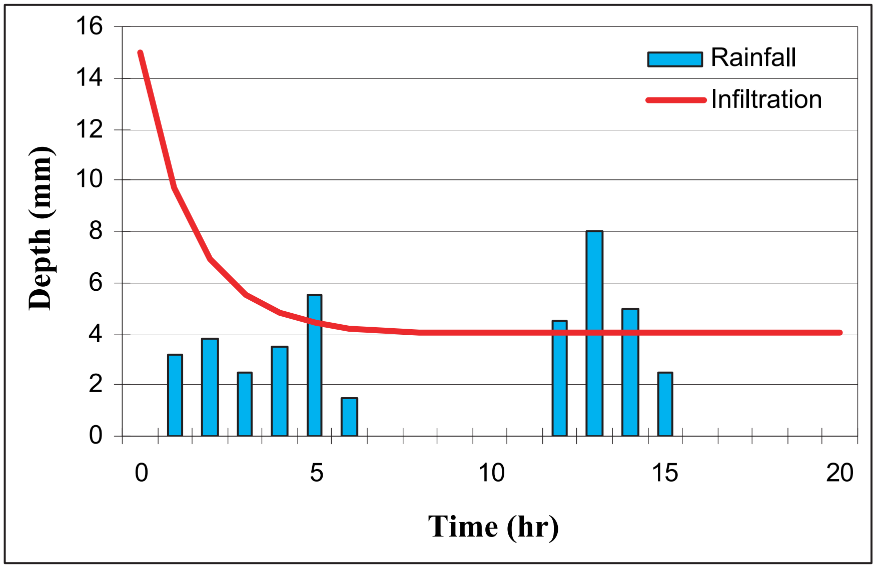

Figure 7. Rainfall depth and infiltration capacity curve of 14/2/2004 event

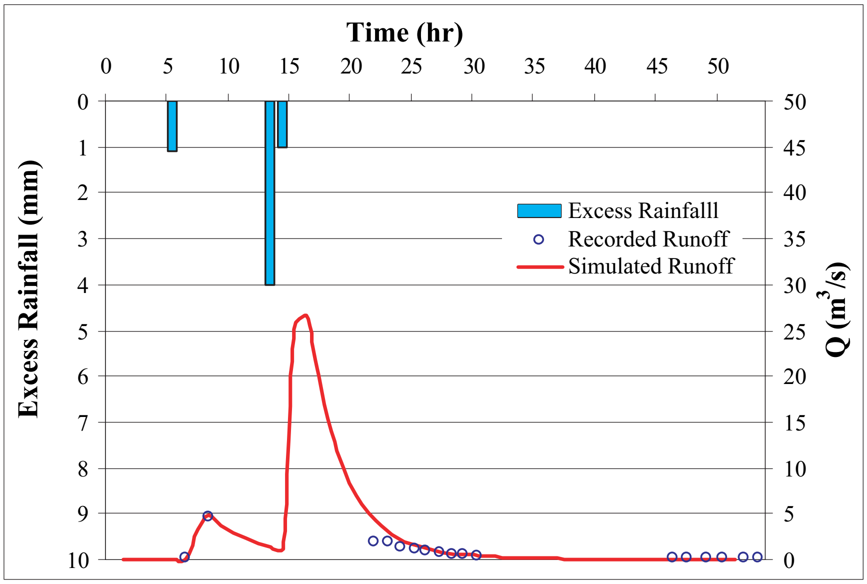

Figure 8. Recorded and estimated direct runoff hydrograph for Al-Badan Sub-catchment, event of 14/2/2004

Recorded and estimated hydrographs were as shown in Figure 8. The relative matching between the simulated runoff hydrograph and the recorded flows seems reasonable and within the acceptable limits, which indicates the applicability of the GIUH model to the catchment.

Event 2, 5/2/2005

During the rainy season of 2005, only one double peak considerable event was recorded and is simulated here. The event brought about 100 mm amount of rainfall and lasted 27 hours. Recorded discharges at Al-Badan Flume for this rainstorm were compared with the KW–GIUH generated hydrograph. Complete hourly data were recorded by the automatic divers installed on the flume. The 5/2/2005 storm was chosen from the records, where clear peak of the recorded discharges was produced. The recorded rainfall of the three stations (Nablus, Taluza, and Beit Dajan) located within Al-Badan sub-catchment was averaged over the sub-catchment by applying the Thiessen method. The areal averaging of the rainfall over the catchment is necessary because the unit hydrograph theory assumes uniform rainfall.

The excess rainfall hyetograph was determined by deducting the abstractions from the rainfall using the phi-Index method. For the storm of 5/2/2005, the base flow was separated from the recorded discharge. Baseflow for this event was estimated at about 1.8 m^3/s. The model calculated phi-Index is 5.32 mm (Figure 9) and the resulted KW–GIUH excess rainfall from this storm is about 4.5 mm. From the results of both events, it can be concluded that the runoff in the Faria catchment is in the range of 4.5% to 15% of the annual rainfall.

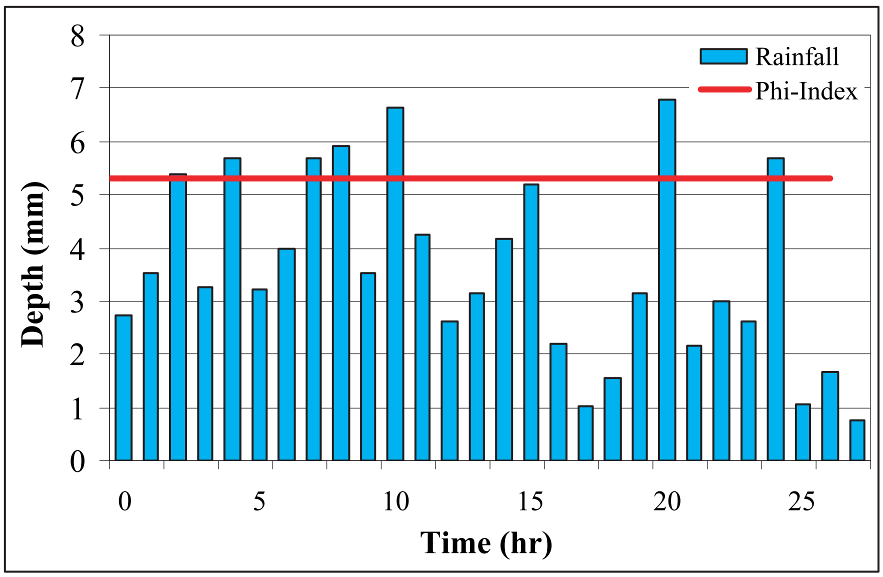

Figure 9. Rainfall depth and the Phi-Index of event of 5/2/2005

Recorded discharges for this rainstorm were compared with the simulated GIUH hydrograph to verify the model. Recorded and simulated hydrographs are shown in Figure 10. The coefficient of efficiency (CE) is estimated at about 0.73.

Two peaks have been observed for this event also. The first recorded and estimated peaks are 10.13 m^3/s and 8.81 m^3/s respectively resulting an error of peak discharge (EQ_p) of –13.03%. The second peak resulted about the same recorded and simulated discharge values. From the above it can be concluded that the simulated and observed results are in good agreement to assume the applicability of the KW–GIUH model to Al-Faria semiarid catchment.

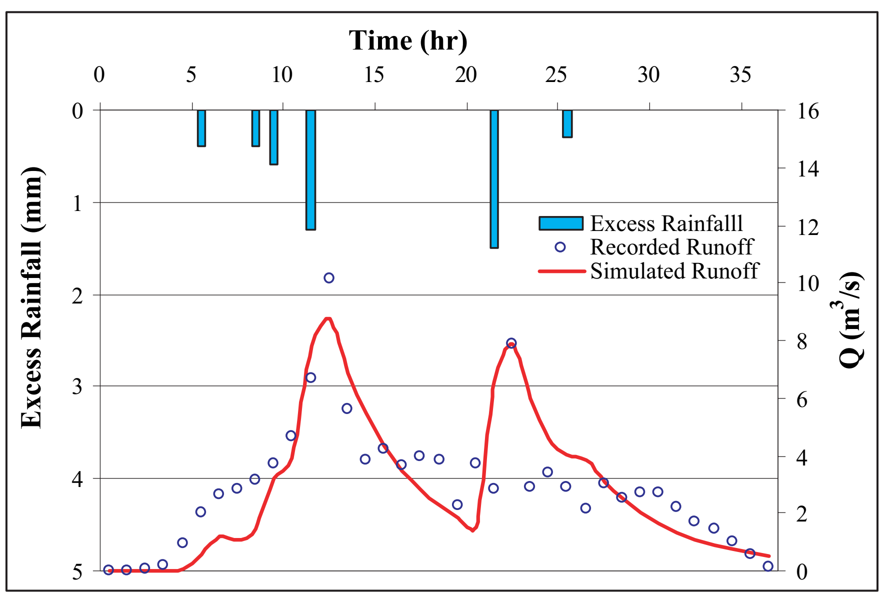

Figure 10. Recorded and estimated direct runoff hydrograph for Al-Badan Sub-catchment, event of 5/2/2005

DISCUSSION AND CONCLUSION

The KW–GIUH model that is based on the catchment stream ordering and on network structuring and incorporating with kinematic wave approximation for the rainwater travel time estimation, demonstrates the high capability to generate instantaneous unit hydrograph without the need for runoff and rainfall data. In the model, the travel time for overland and channel flows in a stream ordering sub basin system are solved analytically from lower to higher order subbasins for known roughness coefficients for both overland areas and channels. The hydraulic responses of a catchment are represented by the combination of a series of probability density functions of travel time. The travel time is a function of the amount of water in the flow that is represented by the spatially uniform intensity of excess rainfall.

In contrast to the traditional unit hydrograph theory which assumes the linearity as one of its basic assumptions, the KW–GIUH model released this restriction since the produced GIUH is a function of excess rainfall considering the intensity and the interaction between surface flow and subsurface flow intensity.

GIUH unit hydrographs were derive for the three sub-catchments of the whole Faria catchment. These sub-catchments are Al-Badan, Al-Faria, and Al-Malaqi having areas of about 85 km^2, 64 km^2, and 185 km^2 respectively. Estimated peak discharges of 1-mm excess rainfall for three sub-catchments are 4.26 m^3/s, 3.21 m^3/s, and 7.4 m^3/s respectively.

The non-availability of sufficient rainfall–runoff records has limited the testing of the validity of the KW–GIUH methodology implemented here to semiarid nature catchments. Nevertheless, two rainfall events were simulated on Al-Badan sub-catchment using the generated KW–GIUH hydrograph. Estimated hydrographs were compared with the recorded discharges to verify the results of the model and reasonable matching was obtained.

In this context, it is to be noted here that the assumption of uniform distribution of excess rainfall over the catchment is not consistent with the semiarid nature of the Palestinian catchments. But, the new version of the geomorphologic-based IUH model that was developed by Lee and Chang [10] considers the PCA concept and incorporates surface- and subsurface-flow processes, making it more suitable to the studied conditions in future works.

ABBREVIATIONS

$T_{x_{oi}}$ = time for the flow to reach equilibrium
q_{o_i} = ith-order overland flow discharge per unit width
q_L = lateral flow rate
h_{os_i} = ith-order water depth at equilibrium
Q_{cs_i} = ith-order channel discharge at equilibrium
$T_{x_{rk}}$ = travel time for the channel storage component
$T_{x_{ck}}$ = travel time for the channel translation component
P_{OA_i} = ratio of the ith-order overland area to the catchment area
A = total area of the catchment
N_i = ith-order stream number
$\overline{L}_{c_i}$ = ith-order stream length
n_o = overland flow roughness
n_c = channel flow roughness
$\overline{A}_i$ = ith-order sub catchment contributing area
$\overline{S}_{o_i}$ = ith-order overland slope
$\overline{S}_{c_i}$ = ith-order channel slope
$P_{x_i x_j}$ = stream network transitional probability
B_Ω = channel width at catchment outlet
Ω = stream network order.

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