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Applicability of the GIUH model to estimate flood peaks from ungauged catchments in arid areas – a case study for the West Bank

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Abstract Water scarcity and low per capita water allocation are the major characteristics of arid and semi-arid regions. This paper provides a methodology to determine runoff from ungauged catchments. The basic approach involves the utilization of a simple event-based Geomorphological Instantaneous Unit Hydrograph model (GIUH) that is capable of determining the hydrograph based on rainfall data and on catchment geomorphological characteristics obtained from GIS tools. A GIUH model has been developed for the Badan and Faria subcatchments within the Faria catchment in Palestine, and successfully applied and validated against observed flow data. The model estimated that peak discharge increased as the overland flow roughness coefficient decreased, which reflects the surface roughness conditions in the catchment. However, when compared with the overland flow roughness coefficient, the channel flow roughness coefficient had a smaller effect on simulated peak flow. Results of the sensitivity test indicated that changing the value of each of the geomorphological parameters resulted in a change in the peak discharge, with changes to subcatchment area having the largest impact. However, with the GIS maps, the geomorphic properties of catchments could be measured accurately minimizing the error in estimating runoff.

Key words Geomorphological Instantaneous Unit Hydrograph (GIUH) rainfall–runoff model; ungauged catchments; arid areas; Palestine

INTRODUCTION

Estimation of streamflow from ungauged catchments is a major concern to water resources engineers and planners and especially in arid and semi-arid areas due to water scarcity and low per capita water allocation. This situation is further exacerbated when such catchments are agriculturally dominated and encounter a high population growth rate. In arid areas, only a few events produce the runoff which occurs mainly through ephemeral stream flows. The Faria catchment in Palestine is one of these arid catchments where the lack of proper management of natural resources, and the lack of hydrological information, have resulted in the inefficient use of the existing surface water and groundwater resources. The rapidly growing rural population, about 3.5% annually, has resulted in increased demand for natural resources, mainly land and water. There is an urgent need to assess and model the sustainable-yield to determine the threshold limits of water resources available within the catchment. This study should include surface water and groundwater and be carried out considering climatic conditions, land-use patterns and possible future demand. Most surface runoff in the catchment is not utilized as there are no dams in the Faria catchment to store the excess water, when available.

The nature of streamflow in a catchment is strongly related to the rainfall and catchment geomorphic characteristics. The runoff characteristics depend on the temporal and spatial distribution of excess rainfall quantity. The geomorphic characteristics are the channel network, topography, the surrounding landscape and land use, which transform the rainfall input into an output hydrograph at the outlet of the catchment. For ungauged catchments, the practice among researchers has often been to consider a number of physical variables and then empirically relate them to indices of frequency curves, flow duration curves, mean annual and monthly discharges, or to rainfall–runoff model parameters. The majority of these studies reveal two important problems: one associated with the use of physically definable variables and the other related to statistical methods. In general, continuous simulation models developed worldwide need parametric calibration in order to work for local catchment conditions other than the areas where the models have been developed or calibrated. Furthermore, scale problems may arise when using *in situ* parameters within hydrological models (Grayson *et al*., 1992). However, the lack of observed data required for the calibration of such models makes it difficult to successfully apply such models in ungauged situations.

The primary objective of this paper is to provide a methodology to determine runoff from ungauged arid catchments. The study will test the suitability of the Kinematic-Wave Geomorphological Instantaneous Unit Hydrograph (KW-GIUH) model (Lee & Yen, 1997) and incorporate GIS tools to obtain the catchment geomorphological characteristics to determine the hydrograph from the ungauged agriculture-dominated Faria catchment.

CATCHMENT DESCRIPTION

The Faria catchment is located in the northeastern part of the West Bank (Fig. 1) with a total area of about 330 km^2. Ground surface elevations in the catchment exceed 900 m above mean sea level (m.s.l.) in the western areas of the catchment and drop gradually down to 250 m below m.s.l. near the Jordan River. The climate is dominantly a Mediterranean, semi-arid climate, characterized by mild rainy winters that last about five months and moderately dry, hot summers. There are six rainfall stations in the study area. Average annual rainfall intensity in the study area reaches 600 mm in the northern and western parts of the catchment. Rainfall intensity decreases towards the east and south. Rainfall isohyets were interpolated from the readings obtained from the six stations using GIS-based technology. The Faria catchment under study is divided into three subcatchments (Fig. 1) which are the Faria subcatchment, Badan subcatchment and Malaqi subcatchment; their areas are 64 km^2, 85 km^2 and 185 km^2, respectively. Runoff data were measured through two Parshall flumes with data loggers at Malaqi Bridge (Fig. 1) that measure the flow of the two main streams of upper Faria catchments, Al-Faria and Al-Badan. The rainfall data were also obtained from tipping-bucket raingauges installed at selected locations within the catchment. Arc View GIS was used to prepare the Thiessen polygons for the study area to estimate

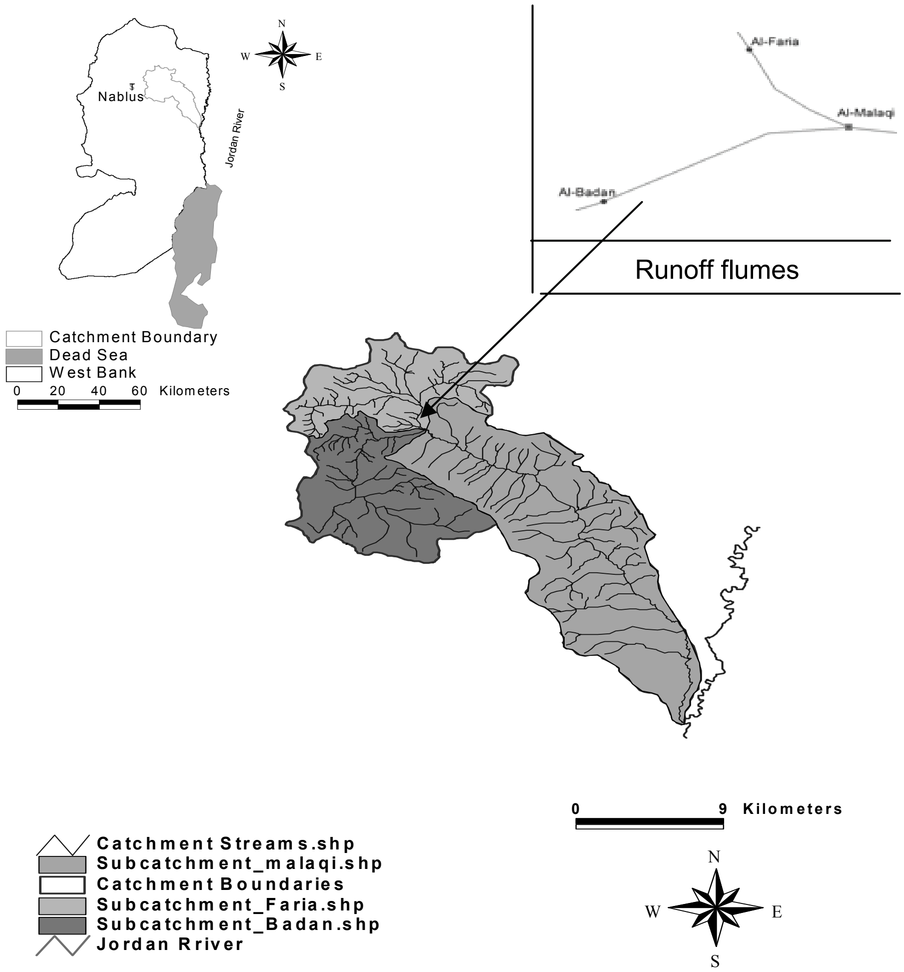

Fig. 1 The three subcatchments of the Faria catchment

the areal average rainfall for the subcatchments. Results showed that the long-term average yearly subcatchment rainfall was 551.6 mm, 492.7 mm and 270.7 mm, for the Badan, Faria, and Malaqi, respectively. For the rainy season of 2004/2005 the subcatchment rainfall was 619 mm, 604 mm and 303 mm for Badan, Faria, and Malaqi catchments, respectively.

MODEL DEVELOPMENT

A significant advance in modelling runoff from ungauged catchments was the development of the Instantaneous Unit Hydrograph (IUH) using geomorphic stream-order information of the catchment. In this stream-order-based IUH approach, each of the channels is assigned an order following the Strahler stream-ordering system (Strahler, 1957). A difficulty in applying the geomorphology-based unit hydrographs lies in the determination of the travel time, a hydraulic problem. As an alternative approach, Lee & Yen (1997) used the kinematic-wave theory to analytically determine the travel times for overland and channel flows in a stream-ordering sub basin system, and then substituting it in the GIUH model to develop a kinematic-wave based GIUH model (KW-GIUH) for catchment runoff simulation. The resultant instantaneous unit hydrograph is a function of the rate of water input (intensity of rainfall excess in application). In applying the instantaneous unit hydrographs for hydrograph simulation, the model deals with temporally non-uniform rainfall through convolution integration of the instantaneous unit hydrographs applied to the rainfall excess of varying intensities with time.

As detailed in Lee & Yen (1997) the travel times Tx_{oi} and Tx_i and the water depth h_{COi} are computed from equations (1) and (2) and aided by equations (3), (4) and (5). An explanation of the notation is given in Table 1.

$$T_{Xoi} = \left(\frac{n_O \overline{L}_{Oi}}{\overline{S}_{Oi}^{1/2} q_L^{m-l}} \right)^{1/m} P_{x_i x_j} \tag{1}$$

$$T_{Xi} = \frac{B_i}{2 q_L \overline{L}_{Oi}} \left[\left(h_{coi}^m + \frac{2 q_L n_c \overline{L}_{Oi} \overline{L}_{Ci}}{B_i \overline{S}_{ci}^{1/2}} \right)^{1/m} - h_{coi} \right] \tag{2}$$

$$\overline{L}_{oi} = \frac{AP_{OAi}}{2 N_i \overline{L}_{ci}} \tag{3}$$

$$h_{coi} = \left[\frac{q_L n_c (N_i \overline{A}_i - AP_{OA_i})}{N_i B_i \overline{S}_{Ci}^{1/2}} \right]^{1/m} \tag{4}$$

$$B_i = \frac{B_\Omega \sum_{l=1}^{i} \overline{L}_{c_l}}{\sum_{l=1}^{\Omega} \overline{L}_{c_l}} \tag{5}$$

The mean of the drainage area of order i ($\overline{A}_i$) and the ratio of ith-order overland area to the catchment area (P_{OAi}) are estimated using the equations (6) and (7) respectively:

$$\overline{A}_i = \frac{1}{N_i} \sum_{j=1}^{N_i} A_{ij} \tag{6}$$

$$P_{OA_i} = \frac{1}{A} \left(N_i \overline{A}_i - \sum_{l=1}^{i-1} N_l \overline{A}_l P_{x_l x_i} \right) \tag{7}$$

The stream network transitional probability of the raindrop moving from an *i*th-order channel to a *j*th-order channel is computed as recommended by Lee & Yen (1997):

$$P_{x_i xj} = \frac{N_{i,j}}{N_i} \tag{8}$$

The geomorphic characteristics, stream order as well as the overflow contributing areas for the three subcatchments were estimated using the Digital Elevation Model (DEM) and Arc-View GIS tools. The selection of the other model input parameters,

Table 1 List of abbreviations.

Abbreviation	Description
Tx_i	Rainwater travel time for the *i*th-order channel
Tx_{oi}	Travel time through the *i*th-order overland plane
h_{co}	Water depth at the entrance of the *i*th-order channel
$\overline{L}_{oi}$	Mean length of the *i*th-order overland flow planes
N_i	Number of *i*th-order channels
$\overline{L}_{ci}$	Mean *i*th-order stream length
$\overline{A}_i$	*i*th-order sub watershed contributing area
P_{OA_i}	Ratio of *i*th-order overland area to the watershed area
$\overline{S}_{ci}$	Mean *i*th-order channel slope
$\overline{S}_{oi}$	Mean *i*th-order overland slope
n_o	Overland flow roughness
n_c	Channel flow roughness
B_{i}	*i*th-order channel width
q_L	Intensity of rainfall excess
B_Ω	Channel width at watershed outlet
m	An exponent recognized as 5/3 from Manning equation (Lee & Yen, 1997)
$\overline{A}_i$	*i*th-order sub catchment contributing area
P_{OA_i}	Ratio of *i*th-order overland area to the catchment area
$P_{x_i x_j}$	Stream network transitional probability
N_i	Number of *i*th-order channels
A_{ji}	Area of the overland flow regions that drains directly into the jth channel of order *i*, and also includes overland areas draining into the lower order channels tributary to this *j*th channel of order *i*
A	Catchment area
Ω	Catchment highest stream order

Table 2 GIUH Input parameters for Faria, Badan, and Malaqi subcatchments.

Parameter	Faria subcatchment				Badan subcatchment				Malaqi subcatchment		
	Order				Order				Order		
	1	2	3	4	1	2	3	4	1	2	3
N_i	49	8	3	1	41	6	2	1	62	16	1
$\overline{L}_{ci}$ (m)	1031	2120	3496	2621	1379	3202	5027	3172	1920	2611	32084
$\overline{A}_i$ (km^2)	0.937	5.099	18.365	64.0	1.370	10.12	40.73	85.28	1.81	8.38	184.96
P_{OAi}	0.717	0.11	0.142	0.031	0.66	0.31	0.018	0.012	0.606	0.285	0.109
$\overline{S}_{ci}$ (m/m)	0.117	0.058	0.033	0.031	0.14	0.062	0.051	0.029	0.14	0.063	0.01
$\overline{S}_{oi}$ (m/m)	0.107	0.085	0.161	0.093	0.17	0.092	0.14	0.135	0.146	0.122	0.081
Area (km^2)	64.0				85.28				184.96		
n_o	1.0				2.0				1.5		
n_c	0.03				0.03				0.03		
B_Ω (m)	3.70				4.60				5		

namely overland flow roughness coefficient n_o and channel flow roughness coefficient n_c was based on literature and field data (Emmett, 1978; Lee & Yen, 1997). The n_o value varies with vegetation cover, surface roughness and catchment characteristics whereas the n_c value varies with channel characteristics.

Table 2 provides the geomorphological characteristics of the Faria subcatchments needed for the GIUH model. The result of the calculations of the stream network transitional probability for the three sub- catchments are shown in Table 3. The above geomorphological characteristics were used in the GIUH model developed by Lee & Yen (1997) to obtain the output hydrographs (Fig. 2).

Table 3 Stream network transitional probability.

Description	Badan	Faria	Malaqi
$P_{1,2}$	0.61	0.74	0.73
$P_{1,3}$	0.34	0.22	0.27
$P_{1,4}$	0.05	0.04	0
$P_{2,3}$	1	0.87	1
$P_{2,4}$	0	0.13	0
$P_{3,4}$	1	1	0

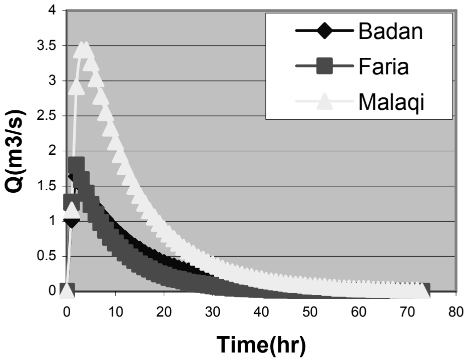

Fig. 2 Theoretical 1 mm-GIUH for Faria, Badan and Malaqi subcatchments.

COMPARISON OF GIUH MODEL WITH THE OBSERVED HYDROGRAPH

During the rainy season of 2004/2005, a major storm recorded during February was used to verify the model. Hourly rainfall and surface runoff data were used to verify the developed GIUH model by comparing the simulated and measured runoff.

Baseflow separation

In arid areas the surface runoff is very precious. For validation of the hydrology, the direct runoff and baseflow components of the streamflow hydrograph need to be separated. The surface runoff was estimated using the daily-based Web-based Hydrograph Analysis Tool (WHAT) available at http://pasture.ecn.purdue.edu/~what (Lim *et al.*, 2005) after baseflow separation. Figure 3 shows the baseflow separation

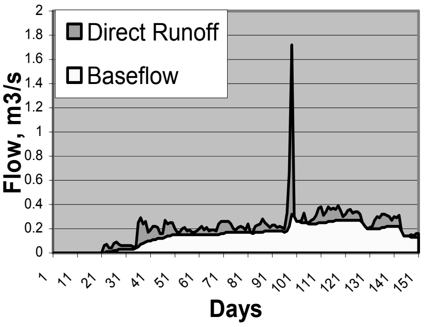

Fig. 3 Baseflow separation for Faria subcatchment using the WHAT model.

for the Faria subcatchment using the WHAT model. The baseflow values obtained from the WHAT model were 3 270 000 and 1 890 000 m^3 year^{-1} for Badan and Faria streams, respectively. Models used for baseflow separation have been used by hydrologists for many years. The baseflow separated for storms in the Faria catchment using the WHAT model were compared with values obtained from the AWBM model (Boughton, 2004), an industry standard in Australia. Hence, the results from the WHAT model were considered satisfactory.

Model verification

Five criteria were chosen to analyse the degree of goodness of fit: runoff volume error (Error Qv); the coefficient of determination (R^2); the coefficient of efficiency (CE) (Nash & Sutcliffe, 1970); the error of peak discharge (Error Qp) and the error of the time to peak discharge (Error Tp). As shown in Fig. 4(a) and (b), the simulated and recorded hydrographs for Badan and Faria subcatchment are in good agreement. As shown in Table 4, Error Qv is less than 5% for both subcatchments. R^2 between simulated and observed hydrographs for the Faria and Badan subcatchments is 0.81 and CE is 0.80. The study area was ungauged before 2004. It was only possible to record one storm event during the monitoring period in 2005. More data from a longer period of observation are needed to draw consistent conclusions. The error of peak discharge is less than 10%, and the error of time to peak discharge is one hour.

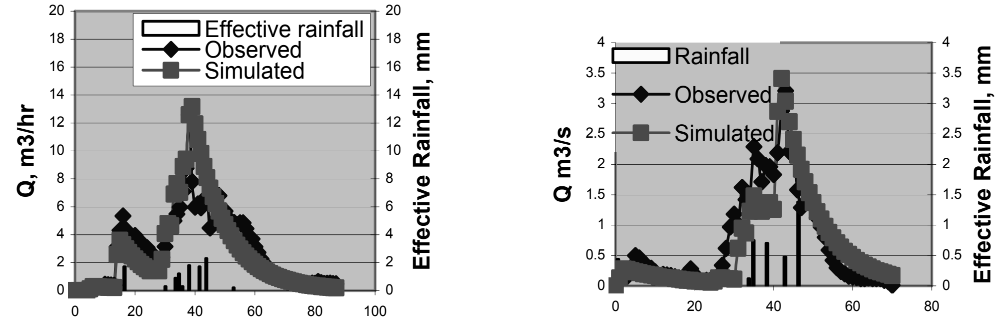

Fig. 4 Recorded and estimated direct runoff hydrograph for (a) Badan subcatchment, and (b) Faria subcatchment.

Table 4 Simulation results of major storm event for Badan and Faria subcatchments.

Sub-catchment	Recorded			Simulated			Evaluation criteria				
	Qv 1000 m^3	Qp (m^3/s)	Tp (h)	Qv (1000 m^3)	Qp (m^3/s)	Tp (h)	Error Qv (%)	R^2	CE	Error Qp (%)	Error Tp (h)
Badan	917	12.59	38	901	13.17	39	1.74	0.81	0.80	4.6	1
Faria	186	3.21	43	179	3.41	42	3.76	0.81	0.80	6.23	–1

Sensitivity analysis

Sensitivity analysis was conducted for different model input parameters to test the effect of each parameter on the peak discharge. The n_o and n_c values were changed to investigate the effect on the simulated hydrograph. Table 5 presents the peak discharge values and the % errors when n_o values were changed by ±25% from the original value for all three subcatchments. The channel flow roughness (n_c) is kept constant at the original value 0.03. Table 6 depicts the peak discharge values when n_c is 0.01, 0.03 and 0.05. The possible % error compared to the original n_c value is also presented in Table 6. It is possible for an error of such a magnitude to occur as n_o and n_c values are obtained from published research. A change in n_o value from 1.0 to 0.75 for Faria subcatchment, 2.0 to 1.5 for Badan subcatchment and 1.5 to 1.125 for Malaqi subcatchment can cause errors of 16% to 17% in the estimation of the peak flow. These results are consistent with those of Lee & Chang (2005) who reported that the estimation of peak discharge is sensitive to the accurate selection of the overland flow roughness coefficient. Further, the coefficients of efficiency and of determination were used to compare the model efficiency under different values of n_o as given in Table 7. As depicted in Table 7, the change in n_o value has reduced the CE and R^2 values in the Faria catchment from 0.8 to 0.73, and 0.81 to 0.77, respectively.

Table 5 Peak discharge for different values of n_o at $n_c = 0.03$ (shaded column represent actual used values).

Subcatchment	Value	$n_o = 1.5$	$n_o = 2.0$	$n_o = 2.5$
Badan	Qpeak (m^3/s) %Error	1.91 17%	1.64	1.45 12%
Subcatchment	Value	$n_o = 0.75$	$n_o = 1.0$	$n_o = 1.25$
Faria	Qpeak (m^3/s) %Error	2.16 16%	1.86	1.66 11%
Subcatchment	Value	$n_o = 1.125$	$n_o = 1.5$	$n_o = 1.875$
Malaqi	Qpeak (m^3/s) %Error	4.1 16%	3.54	3.17 11%

Table 6 Peak discharge for different values of n_c at n_o = 2, 1, 1.5 for Badan, Faria, and Malaqi subcatchments respectively (shaded column cells represent actual used values).

Subcatchment	Value	$n_c = 0.01$	$n_c = 0.03$	$n_c = 0.05$
Badan	Qpeak (m^3/s) % Error	1.64 0%	1.64	1.61 1.8%
Faria	Qpeak (m^3/s) % Error	1.87 0.5%	1.86	1.83 1.6%
Malaqi	Qpeak (m^3/s) % Error	3.83 8%	3.54	3.38 4.5%

Table 7 The coefficient of efficiency (CE) and the coefficient of determination (R^2) for different values of n_o at $n_c = 0.03$ (shaded column cells represent actual used values).

Subcatchment	Value	$n_o = 1.5$	$n_o = 2.0$	$n_o = 2.5$
Badan	CE	0.78	0.80	0.80
	% Variation	2.5 %		0 %
	R^2	0.80	0.81	0.81
	% Variation	1.2 %		0 %
Subcatchment	Value	$n_o = 0.75$	$n_o = 1.0$	$n_o = 1.25$
Faria	CE	0.77	0.80	0.73
	% Variation	3.8 %		8.8 %
	R^2	0.81	0.81	0.77
	% Variation	0 %		4.9 %

A sensitivity test was also conducted on the selection of the number of stream order for subcatchments. The stream order was decreased by one order to investigate the effect of the stream order level on the model results. As shown in Fig. 5, decreasing the Faria subcatchment stream order from fourth level to third level resulted in decreasing the peak discharge from 1.86 to 1.09 $m^3 s^{-1}$, or 41%. A similar effect was noticed for Badan and Malaqi subcatchments where decreasing the stream order level resulted in decreasing the peak value from 1.64 to 0.87 $m^3 s^{-1}$ (47%) and from 3.54 to 2.04 $m^3 s^{-1}$ (42%) for the Badan and Malaqi subcatchments, respectively. As a result it is important to select the correct stream order when developing the GIUH model. The catchment stream network map includes all intermittent and permanent lines. Therefore it is recommended to select the stream order based on the stream network map when developing the GIUH.

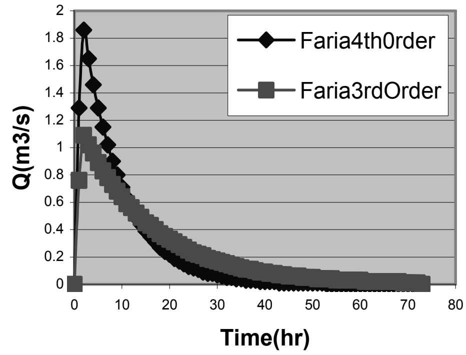

Fig. 5 Sensitivity analysis of stream order level on Faria 1 mm-GIUH.

The channel width at the catchment outlet (B_Ω) is the only geomorphic parameter that cannot be obtained from a topographic map or GIS maps. Therefore it is important to carry out a sensitivity analysis for B_Ω. As shown in Table 8, the channel width was changed by 25% from the original channel width of the Faria subcatchments. A change of 25% in B_Ω resulted in a change of peak discharge by 2.5% for Malaqi subcatchment. The peak discharge values in Badan and Faria subcatchments were less than 1% indicating B_Ω is not sensitive in estimating the peak flow.

Table 8 Peak discharge values and time to peak for different values of channel width at catchment outlet B_Ω (m) for Faria subcatchments 1mm-IUHs (Dark column cells represent actual used values).

Subcatchment	Value	3.45	4.14	4.6	5.06	5.75
Badan	Qpeak (m^3/s) % Error	1.63 0.6	1.64 0	1.64	1.64 0	1.63 0.6
Subcatchment	Value	2.78	3.33	3.7	4.07	4.62
Faria	Qpeak (m^3/s) % Error	1.86 0	1.86 0	1.86 0	1.86 0	1.86 0
Subcatchment	Value	3.75	4.5	5	5.5	6.25
Malaqi	Qpeak (m^3/s) % Error	3.63 2.5	3.57 0.8	3.54	3.52 0.6	3.50 1.1

Changing the value of each of the geomorphic parameters by 10% (number of *i*th-order channels N_i, mean *i*th-order stream length $\overline{L}_{ci}$, *i*th-order sub catchment contributing area $\overline{A}_i$, mean *i*th-order overland slope $\overline{S}_{oi}$, mean *i*th-order channel slope $\overline{S}_{ci}$ and subcatchment area) resulted in a change in the peak discharge value up to 8%. However, with the GIS maps the geomorphic properties of catchments could be measured accurately, minimizing the error in estimating the runoff.

CONCLUSIONS

The GIS based Geomorphological Instantaneous Unit Hydrograph can be determined without using any recorded data of past rainfall or runoff events. The Kinematic-Wave Geomorphological Instantaneous Unit Hydrograph (KW-GIUH) was developed and successfully applied to simulate runoff from the ungauged semi-arid subcatchments of the Faria catchment in the West Bank. Hence it is applicable to obtain runoff hydrographs in ungauged catchments. However, data from more storm events for a longer period of observation is needed to draw consistent conclusions for the study area. Sensitivity analyses were conducted for all input parameters. It is important to select the correct value of overland flow roughness coefficient n_o as the peak flow increased by 17% with a decrease of 25% in the value of n_o. An error of 25% for n_o is possible as it is obtained from nomograms. Hence extra care should be taken when determining this parameter. However, the change in channel flow roughness coefficient n_c had a smaller effect on simulated peak flow. Results also showed that B_Ω the channel width at catchment outlet, is not sensitive in estimating the peak flow. Changing the value of each of the other geomorphological parameters by 10% (number of *i*th-order channels N_i, mean *i*th-order stream length $\overline{L}_{ci}$, *i*th-order sub catchment contributing area $\overline{A}_i$, mean *i*th-order overland slope $\overline{S}_{oi}$, mean *i*th-order channel slope $\overline{S}_{ci}$ and subcatchment area) resulted in a change in the peak discharge value of up to 8%. The stream order is the other important parameter used to develop the GIUH model. As a result it is important to follow the stream order based on the stream network map. However, with the wide availability of GIS maps, the geomorphic properties of catchments could be measured accurately.

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