HYDROGRAPH ESTIMATION IN SEMIARID REGIONS USING GIS SUPPORTED GIUH MODEL

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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 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 watersheds using historical rainfall-runoff data and unit hydrographs derived from them. Such procedures are questioned for their reliability due to the climatic and physical changes in the watershed 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. In this study, the lately developed GIUH model is applied to Al-Badan watershed of Faria catchment located in the northeastern part of the West Bank, Palestine. The Faria catchment characterizes a semiarid region, with annual rainfall depths ranging on average from about 150 to 600 mm. The Geographical Information System (GIS) techniques are used to shape the geomorphological features of the catchment. The application of the GIS supported GIUH model has proved reasonable agreement between the simulated runoff hydrograph and the recorded flows. The paper has elaborated on the applicability of the unit hydrograph theory and the GIUH to semiarid regions.

Keywords: GIUH; GIS; Flow hydrographs; Semiarid regions.

INTRODUCTION

The computation of flow hydrograph characteristics is a major concern of water resources engineers and scientists. The nature of stream flow in a catchment is related to the rainfall characteristics and watershed geomorphology. The rainfall characteristics are the temporal and spatial distribution of the rainfall quantity. The geomorphic characteristics are the channel network, topography, and surrounding landscape, which translate the rainfall input into an output hydrograph at the outlet of the watershed. Traditionally the unit hydrograph approach is being applied for rainfall-runoff modeling for all kinds of catchments including arid and semiarid regions. Shaheen [1] has investigated the rainfall-runoff process in semiarid regions. He has concluded that such watersheds acting as partial contributing and variable resources do not obey the assumptions of the traditional unit hydrograph approach. Runoff in such watersheds is subsurface flow dominated instead of surface flow dominated and the interaction between surface and subsurface flows can not be neglected as the case in the traditional unit hydrograph theory.

A significant advance in the unit hydrograph approach for ungauged watersheds is the development of the Geomorphologic Instantaneous Unit Hydrograph (GIUH) (Yen and Lee [2] and Lee and Yen [3]). In the GIUH approach, rainfall excess 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 produce runoff from rainfall for ungauged watersheds. They have been proposed to estimate floods for ungauged streams by using only the information obtainable from topographic maps or remote sensing possibly linked with the Geographic Information Systems (GIS) and Digital Elevation Model (DEM) (Snell and Sivapalan [4], Jain et al. [5], and Hall et al. [6]). The objective of this study is to apply the GIS supported GIUH approach for the estimation of flow hydrographs in semiarid regions. With the given geomorphic properties of the watershed, the unit hydrograph can be determined hydraulically without using any recorded data of past rainfall or runoff events. This approach reduces the excessive topographic data and computational efforts required in full hydrodynamic deterministic routing of watershed runoff. The interaction between the surface and subsurface flows can be considered in such an approach through the variation of the infiltration parameters and thus attaining the rainfall-runoff process in arid and semiarid regions.

GIS provide a digital representation of the watershed 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. The integration of GIS into hydrologic models follows one of the two approaches: (i) develop hydrologic models that operate within a GIS framework, (ii) develop GIS techniques that partially parameterize existing hydrologic models. Jain et al. [5] has applied the second approach to Gambhiri river catchment in India and concluded that the peak characteristics of the flows are more sensitive to the various storm pattern as well as method of critical sequencing followed for the computation of the design storm.

The available GIUH program (version 1.2) can be applied to watersheds with stream network of up to the seventh order. It 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. GIUH can be applied to any excess rainfall through convolution to produce the direct runoff hydrograph. The approach is applied here to Al-Badan watershed of the upper Faria catchment of the West Bank, Palestine. The results are compared to the traditional SCS approach to further verify the applicability of the GIUH model to semiarid regions. The relative matching between the simulated runoff hydrograph and the recorded flows seems reasonable and within the acceptable limits.

STUDY AREA

The area under consideration is the Faria catchment located in the northeastern part of the West Bank. It lies within the Eastern Aquifer Basin (EAB) and has a catchment area of about 330 km^2. EAB is one of the three major groundwater basins underlying the West Bank area and forming the West Bank water resources. The Faria catchment extends from the ridges of Nablus Mountains down the eastern slopes to the Jordan River. The upper portion of the Faria catchment extends 25 km east of Nablus city to Al-Malaqi Bridge, where the two main streams contributing to the Faria catchment meet. These are Al-Faria and Al-Badan streams.

The upper Faria catchment is about 117 km^2 representing 35% of the total Faria basin. The two main sub-catchments forming upper Faria basin are Al-Faria of about 63.8 km^2 and Al-Badan of about 53.4 km^2. The annual average rainfall ranges from 600 mm at the headwater to 150 mm at the outlet to the Jordan River. The GIUH approach is applied here to Al-Badan watershed. Figure 1 shows Al-Badan watershed and the rainfall distribution within the Faria catchment.

In Faria catchment, daily rainfalls are available for 6 stations but for different number of years and not as continuous time series except for Nablus station. Rainfall intensity readings are also available for two stations in the Faria basin, Nablus and Beit Dajan, and for about three to nine years only. Nablus and Talluza stations have the largest average annual rainfall and Faria station has the lowest. It is noted also that Tubas station has average annual rainfall of about 415 mm, which nearly equals the average of the annual average rainfalls of the six stations within the Faria catchment at about 430 mm. In general, rainfall averages decrease moving from north to south and west to east.

No enough runoff data are recorded for the Wadi Faria drainage basin. Most of the data available are monthly data estimated using direct measurements of the runoff at selected locations and periods of the year. Therefore and to collect rainfall-runoff data necessary for the detailed modeling of storm events, the Water and Environmental Studies Institute (WESI) constructed, August 2002, two Parshall flumes at Al-Malaqi Bridge. The flumes are to measure the flows at the two main streams of upper Faria catchments, Al-Faria and Al-Badan. The flumes were constructed in context of GLOWA project (Impacts of global changes on surface water resources in wadis contributing to the lower Jordan River basin). Maximum and minimum flows that can be measured by the flumes at Al-Faria and Al-Badan are 15 m^3/s, 0.19 m^3/s and 25 m^3/s, 0.23 m^3/s respectively.

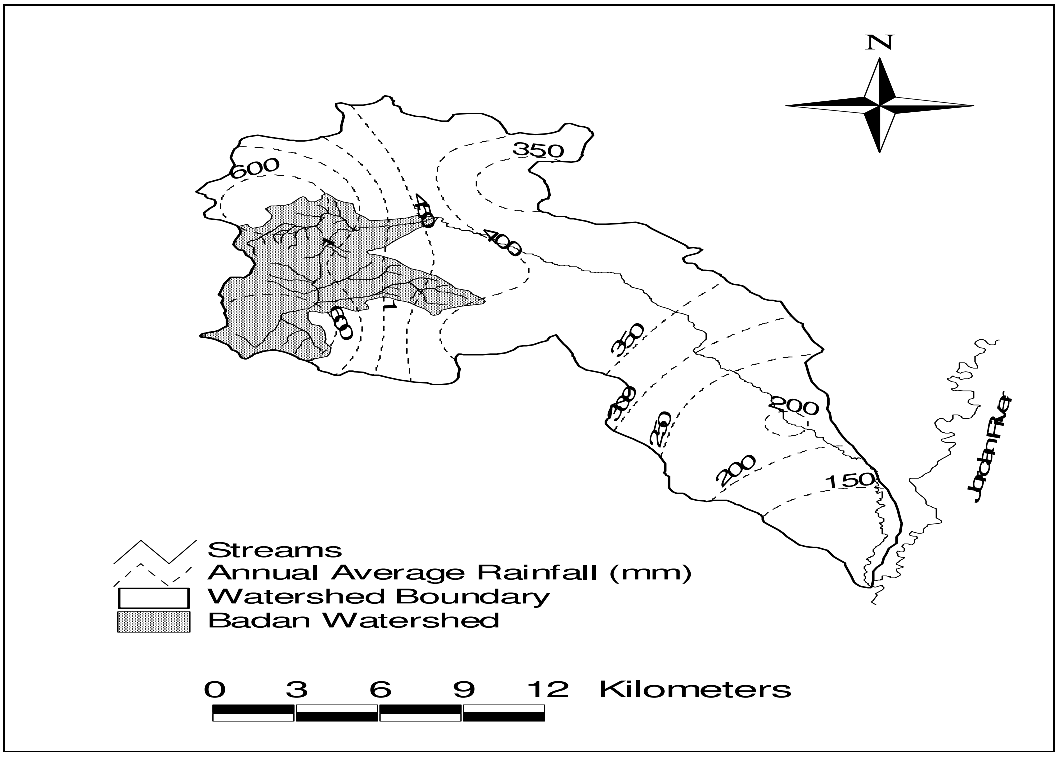

Figure 1: Al-Badan watershed and rainfall distribution within the Faria catchment

The eastern slopes of the West Bank area, where Faria catchment is located, are characterized as semiarid. Arid regions are those in which rainfall on a given piece of land is not sufficient for regular crop production whereas semiarid areas are those in which the rainfall is sufficient for short season crops and where grass is an important element of the natural vegetation. The hydrological characteristics of surface runoff vary with land use and seasons. In arid and semiarid regions, the degree of slope exercises a strong control on the amount of runoff than in humid areas. On the hillside, the initial losses being compensated by steeper gradients, bare rocky surfaces and low wastage through vegetation, but rain falling on gently sloping plains will be less effective in producing runoff than in humid areas (Chow [7]). These geomorphic characteristics are reflected in the parameters estimation required for the application of the GIUH model. GIS tools are to facilitate these estimations.

METHODOLOGY AND RESULTS

The boundary of Al-Badan watershed and all its flow paths and streams have been mapped using the available GIS program. The maps in their digital forms have been used to estimate the input parameters of the GIUH. Strahler's stream ordering system has been followed. According to this system, it was found that Al-Badan watershed is of the fourth order. For Al-Badan watershed, the elevation varies from 680 to 90 m above sea level. Figure 2 shows the drainage network map and the stream orders of Al-Badan watershed.

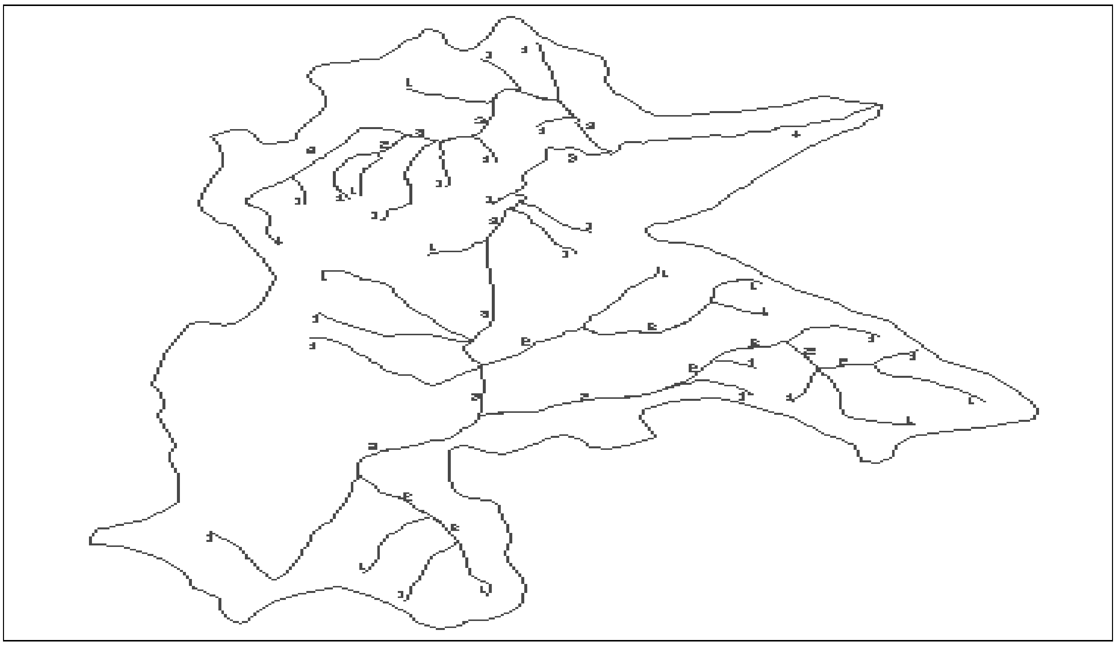

Figure 2: Drainage network and the stream orders of Al-Badan watershed

The procedure for the application of the GIUH model suggested by Lee and Yen [3] is applied here to produce the IUH for Al-Badan watershed. The values of the overland and channel roughness coefficients, n_o and n_c, are respectively kept constant for the watershed. The input rainfall is taken as 1 cm and the rainfall duration as one hour. The mean of the drainage area of order i and the ratio of *i*th-order overland area to the watershed area are estimated using the two equations respectively:

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

$$P_{OAi} = \frac{1}{A}\left(N_i \overline{A}_i - \sum_{i=1}^{i-1} N_i \overline{A}_i P_{xixj} \right) \tag{2}$$

It should be noted that A_{ij} denotes not only the areas of the overland flow regions that drains directly into the *j*th channel of order i, but it also includes overland areas draining into the lower order channels tributary to this *j*th channel of order i. The stream network transitional probability of the raindrop moving from an *i*th-order channel to a *j*th-order channel is computed as:

$$P_{xixj} = \frac{N_{i,j}}{N_i} \tag{3}$$

The other parameters needed for the application of the GIUH program have been estimated and are listed in Table 1. The resulting IUH hydrograph for Al-Badan watershed due the application of the GIS supported GIUH model following the above procedure is shown in Figure 3.

Table 1: GIUH input parameters for Al-Badan watershed

Parameter	**Stream Order**			
	1	**2**	**3**	**4**
N_i	32	5	2	1
$\overline{L}_{ci}$ (km)	1.132	2.692	4.798	3.165
$\overline{A}_i$ (km^2)	0.939	5.816	24.775	53.3568
P_{OA_i}	0.563	0.228	0.137	0.0713
$\overline{S}_{ci}$ (m/m)	0.028	0.0388	0.0424	0.0284
$\overline{S}_{oi}$ (*m/m*)	0.107	0.09	0.0356	0.0284
Area (km^2)	53.355			
Base flow (m^3/s)	0.174			
n_o	0.1			
n_c	0.04			
B_Ω (m)	4.57			

$P_{x_i x_j}$					
$\boldsymbol{P_{1,2}}$	$\boldsymbol{P_{1,3}}$	$\boldsymbol{P_{1,4}}$	$\boldsymbol{P_{2,3}}$	$\boldsymbol{P_{2,4}}$	$\boldsymbol{P_{3,4}}$
18/32	14/32	0/32	5/5	0/5	2/2

The primary goal of developing IUH of a watershed is to apply it for hydrograph generation for design or project storms. During the rainy season of 2003, only one considerable storm was recorded and can be simulated here.

The point rainfall recorded at Nablus meteorological station located near the headwater was averaged over the watershed to consider the variation in the rainfall distribution within the watershed. The rainfall isohyets method was applied for this purpose. As to 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 [1]. Excess rainfall of the rainfall event was determined. The total rainfall of 14/2/2003 simulated event is about 40 mm measured as point rainfall at Nablus station. To estimate the excess rainfall (ER), Horton method was applied. The resulting excess rainfall from the above storm is about 6mm distributed as shown in Figure 4.

Based on the above methodology and using the GIS and the digital maps, the storm is applied to the generated GIUH and the direct runoff hydrograph is estimated. The GIUH estimated hydrograph and the recorded data for the simulated rainfall-runoff event of Al-Badan watershed are shown in Figure 4. The estimated and recorded flow values match reasonably. The difference between the estimated and recorded peak flow at time t = 7 hrs is less than 10%. Also the figure reflects good match in both the time to peak and the lag time.

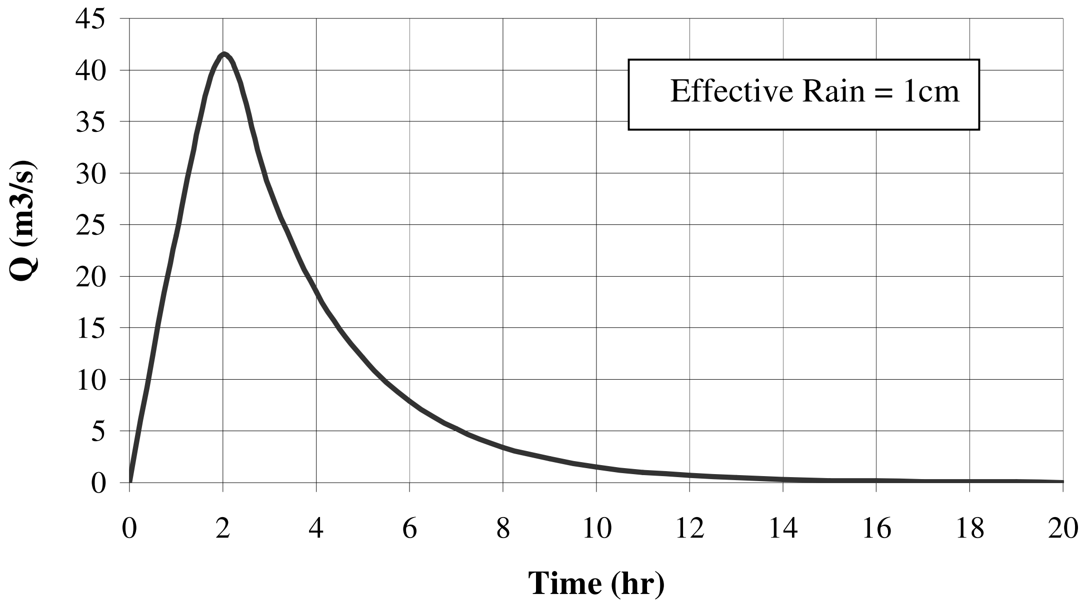

Figure 3: Generated GIUH flow hydrograph for Al-Badan watershed

In this context, it is to note here that the assumption of uniformly distribution of the excess rainfall over the watershed is not consistent with the semi-aridity nature of the Palestinian watersheds that behave as variable sources and partially contributing. Nevertheless, the results of the simulation of the event using the GIS supported GIUH are promising and indicate the applicability of the model to semiarid regions.

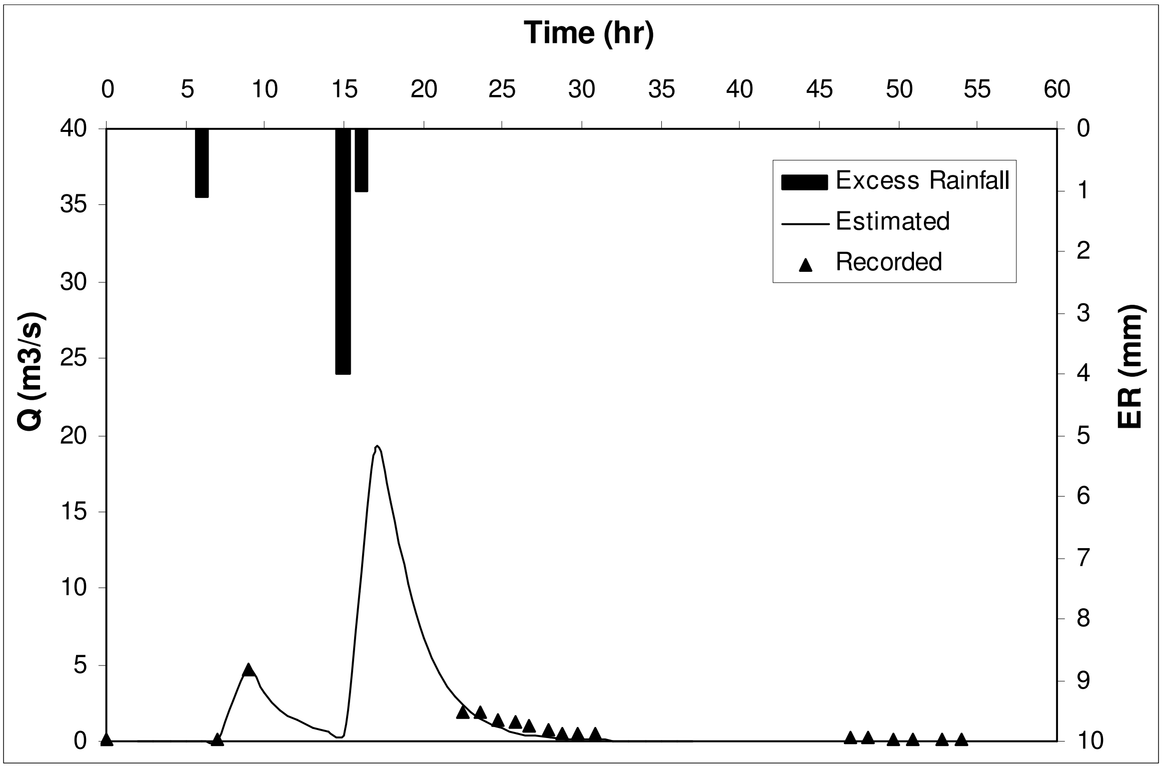

Figure 4: Recorded and estimated direct runoff hydrograph for Al-Badan watershed

CONCLUSIONS

The hydrologic response of a watershed to excess rainfall input is linked to the geomorphic structure of the watershed. Therefore the recently developed GIUH model has been applied by several authors to derive unit hydrographs for several ungauged watersheds. The GIS supported GIUH model is applied here to Al-Badan watershed of the Faria catchment located in the northeastern part of the West Bank, Palestine.

The non-availability of sufficient rainfall-runoff records has limited the testing of the validity of the methodology implemented here to semiarid nature watersheds. Nevertheless, the simulation of the one event recorded during the winter of the year 2003 and applying the GIUH, which uses the Kinematics Wave Equation and considers the details of the geomorphic characteristics of the watershed, has resulted reasonable match between the estimated runoff hydrograph and the measured stream flows.

Among the important limitations of the above methodology for applying the GIS supported GIUH model is the velocity and roughness estimation of the different order channels. The simulation of the interaction between the subsurface and surface flows is needed for the simulation of the semiarid regions and Karstic nature watersheds. The partial contribution of the semiarid watersheds to outflow hydrographs is overcome using different infiltration parameters for each of the different order channels.

Abbreviations:

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_Ω channel width at watershed outlet
$P_{x_i x_j}$ stream network transitional probability
$N_{i,j}$ number of the *i*th-order channels contributing to *j*th-order channels

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