An-Najah University Journal for Research – A

Natural Sciences

Estimation of Synthetic Unit Hydrographs' Parameter Values: The Case of Wadi Al-Badan Sub-Catchment, West Bank, Palestine

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Received 2nd Sep. 2023, Accepted: 14th Feb. 2024, Published 1st Aug. 2024. https://doi.org/10.35552/anujr.a.38.2.2211

Abstract: Developing unit hydrographs is critical in gauged catchments. Due to the lack of local data, engineers should strive to estimate discharges based on empirical (synthetic) methods in ungauged catchments. Synthetic unit hydrograph methods, such as the Snyder and Soil Conservation Service are popular and play an essential role in hydrology. These methods are simple, requiring only catchment characteristics. Therefore, these methods are valuable tools for simulating runoff in ungauged catchments. This research paper focuses on the Al-Badan sub-catchment, which is located in the northeastern part of the West Bank in Palestine with an area of 83 km^2. The study used a de-convolution matrix approach to develop an average one-hour unit hydrograph by selecting four significant rainfall events in the period (2005-2007), and the direct runoff hydrographs which are measured by Al-Badan flume located in the outlet of the sub-catchment. By computing the characteristics of the average one-hour UH with a peak discharge of 4.52 m^3/sec and time to peak of 5 hours, Snyder and SCS UHs were developed to suit Al-Badan sub-catchment physical characteristics. The parameters were determined for the Snyder; peaking coefficient depends on the storage capacity of the catchment C_p = 0.88 and the non-dimensional regional coefficient representing catchment storage effects and slope C_t = 1.26 and for the SCS; C_p = 1.90 and the coefficient depending on the total runoff volume occur before peak discharge C = 2.92. These synthetic one-hour UHs were examined for two selected rainfall events that occurred in the period (2017–2019) by comparing observed and simulated direct runoff hydrographs. The performance was tested statistically. Results showed that the synthetic UHs are suitable for application and that the SCS method is more applicable.

Al-Badan Flood in 09 Feb,2006

Keywords: Unit hydrograph; Synthetic unit hydrograph; direct runoff hydrograph; Ungauged catchment; Al-Badan sub-catchment; Palestine.

Introduction

Water is connected to everything of life as "God made from water every living thing". Water is connected to everything in life. We need to understand the importance of water and how to save its source (1). Loren Eiseley abbreviates the water system in one sentence: "If there is magic on this planet, it is contained in water" (2).

For decades, one of the most widely held notions in the water literature has been that the hydrological cycle is a fundamental concept in hydrology. The hydrologic cycle is "the continuous circulation of water in its liquid, solid, and vapor phases between the atmosphere, the lithosphere, and the hydrosphere". Precipitation and runoff are essential elements of the hydrologic cycle (3). There are several forms of precipitation, including rainfall, snowfall, hail, frost, and dew (4). In Palestine, rainfall is the most dominant form of precipitation (5).

Hydrologists seek to investigate surface water, including systems, flows, distributions, properties, and management, on Earth, according to recent theoretical developments. Starting with the catchment's water balance and determining the volume and depth of rainfall and runoff (6), in like manner, studies investigate the procedure to transform the rainfall hyetograph into a runoff hydrograph. Peak flow (Q_P) and time to the peak (T_P) are the main hydrograph characteristics that must be estimated for any catchment. According to hydrologists, the estimation of these characteristics is highly complex in ungauged catchments compared to gauged ones (7).

This research constitutes a relatively new area that has emerged from the urgent need to conduct studies on water in Palestine, especially in the West Bank. A growing need for measuring and understanding runoff data (8) will enhance the proper design of hydraulic structures and prevent natural disasters such as floods.

A unit hydrograph (UH) of different durations can be derived in gauged catchments where rainfall and runoff records are available. The UH is the direct runoff hydrograph (DRH), created by the Sherman method in 1932, resulting from a unit depth of excess rainfall (ER) of constant intensity that is spread out evenly over the catchment (9).

Given the rainfall data, the availability of UH for any catchment is critical to predicting runoff hydrographs. Worldwide,

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most catchments are ungauged, meaning rainfall data are available, but runoff (streamflow) data are not. In such catchments, transforming rainfall photographs into runoff hydrographs is challenging (10). Several hydrologists and researchers have developed synthetic (empirical) unit hydrographs (SUHs) to be used for ungauged catchments (11).

As a result, it has become essential to develop methods to generate parameters that may be utilized in catchments with acceptable accuracy. Several SUHs for ungauged catchments were developed in the past by Snyder (1938), Clark (1945), Nash (1958), Espy-Winslow (1968), and Soil Conservation Service (SCS) (1972) (12).

Globally, and specifically in Palestine, rapid urban development led to a large quantity of rainfall becoming runoff. Deep infiltration is only a tiny fraction of the hydrological cycle, resulting in water problems such as increased flooding risk due to increased Q_P and decreased T_P. The rainfall-runoff process is related to complex factors in catchments, leading to the use of available rainfall-runoff data to predict the discharge runoff of ungauged catchments by using empirical equations (e.g., Snyder, SCS). Knowing the value of the discharge runoff helps solve hydrologic problems and design hydrologic structures (13,14).

The main goal of this research is to parameterize the SUHs (Snyder and SCS) based on the available rainfall and runoff data for the period (2005-2007) at the Wadi Al-Bathan sub-catchment. The main goal of this study was achieved by analyzing available rainfall and runoff data to select major rainstorm events, developing a one-hour average UH to determine Snyder and SCS parameters, and then simulating the DRH for some rainstorms in the (2017-2019) rainy seasons and comparing them with the observed DRHs.

Study Area

Al-Badan sub-catchment is one of the Faria catchments and is located in the north-eastern part of the West Bank in Palestine. It has an area of about 83 km^2 (see Figure 1). The topography starts at 900 m above the mean sea level (MSL) in the Nablus Mountains and decreases drastically to about 50 m above the MSL at the sub-catchment outlet. The climate in the study area is predominately Mediterranean characterized by a semi-arid, dry, and hot summer with almost no precipitation. 90% of the annual rainfall occurs in winter and autumn. The maximum, mean, and minimum annual temperatures of Al-Badan in Nablus are 26 °C, 20 °C, and 15 °C, respectively. The mean annual relative humidity was 77%. As for evaporation, winter months, where moisture is available from rain, have low evaporation rates, but summer months, with high evaporation rates, have no rain, so evaporation greatly exceeds the rainfall in the period from April to October (5,15).

Methods and Data Analysis

Data Collection and Methods

Data was collected from multiple sources. At first, it was compiled from scientific papers and reports related to the study and a few M.Sc. theses that deal with hydrological analysis and hydrological models in the study area. In addition, the hydrological data were obtained from Dr. Sameer Shadeed, who collected data for his Ph.D. study in the period (2005–2007) from four rainfall gauges and thereafter in the period (2017–2019) from seven rainfall gauges. In addition, the runoff data was also collected from a flume located in the outlet of the Al-Badan sub-catchment. Furthermore, physical sub-catchment characteristics were derived from the different shapefiles by using ArcGIS.

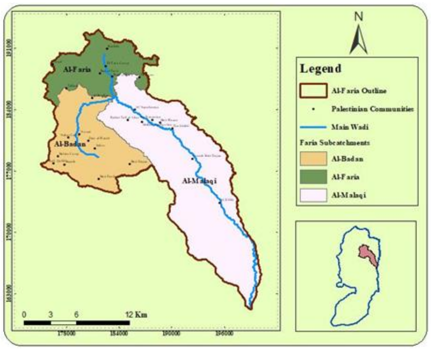

Figure (1): Outline of Faria Sub-Catchments.

The hydrological collected data were analyzed using Microsoft Excel. Firstly, selected the significant rainstorm events from the period (2005–2007) and estimated ER for each storm, and then analyzed runoff data to define observed DRH for each storm. After that, a de-convolution matrix was used to derive UH for each storm and then built an average UH.

Based on the one-hour average UH and some empirical equations of SUHs (Snyder and SCS), the SUHs for the study area were developed. Then, the SUH parameters associated with (Q_P) and (T_P) were determined. After that, the SUHs for two selected storms from the period (2017–2019) were examined by comparing the observed DRH with the simulated DRH from the use of SUHs.

Rainfall-Runoff Data Analysis for Rainy Seasons 2005-2007

1) Rainfall and Runoff Analysis

The four major rainstorm events were "Event 1" in 2005–2006 and "Events 2, 3, and 4" in 2006–2007. The Thiessen polygon method was applied to determine the average rainfall depth over a study catchment for these events. In addition, the infiltration index (φ-Index), which is the average rainfall intensity above which the rainfall volume is equal to the runoff volume or the depth of the rainfall equals the depth of the runoff, was calculated by trial and error using equation 1 for each storm (16):

$$\varphi - \text{index} = \frac{1}{t}(P - R) \qquad (1)$$

Where;

φ - index: Infiltration index in mm/hr.

P: The total rainfall depth in mm.

R: The total runoff depth in mm.

t: The total time the rainfall intensity exceeds the infiltration index in hours.

For the same events, the obtained DRH that contributed to the runoff at the catchment outlet through analysis of runoff data, and in the hydrological system definition, after the abstraction of φ-index from total rainfall, got ER in the catchment, which is equal to direct runoff (17). The rainfall hyetograph, DRH, and - φ Index for the four events are presented in (Figure 2).

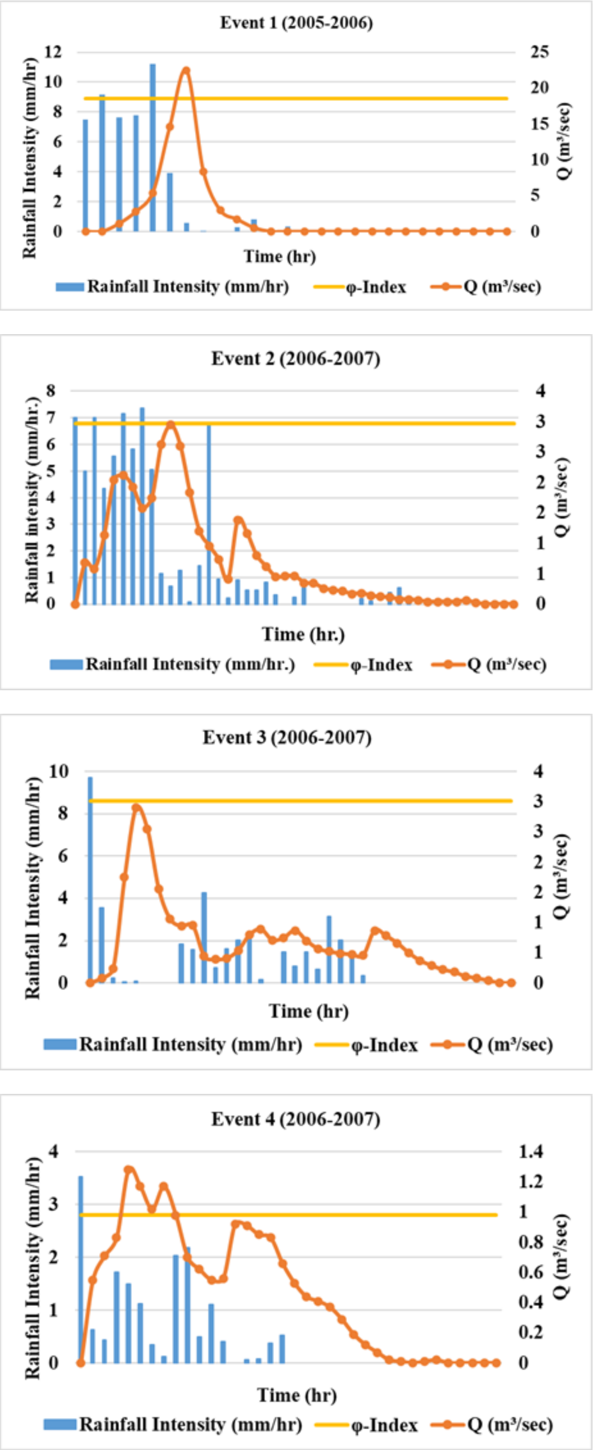

Figure (2): Rainfall Hyetograph, DRH, and φ-Index for Events [1-4] in the Rainy Seasons (2005-2007).

2) Derive One-Hour UH

The derivation of the one-hour UH is needed for the DRH and the ER. A de-convolution approach matrix was used to determine the ordinates of the one-hour UH by equation 2. The resulting one-hour UH should represent the one-unit depth of runoff (18). The one-hour average UH had a unit depth of 1 mm, Q_P of 4.52 m^3/sec, T_P of 5 hours, and time base (T_b) of 40 hours, as depicted in (Figure 3).

$$[U] = [P^TP]^{-1} [P^T] [Q] \qquad (2)$$

Where;

[U]: Matrix of the unit hydrograph.

[Q]: Matrix of the direct runoff.

[P^T]: Transpose of the matrix of the excess rainfall.

[P^TP]$^{-1}$: Inverse matrix of the transpose matrix of the excess rainfall multiplied by a matrix of the excess rainfall.

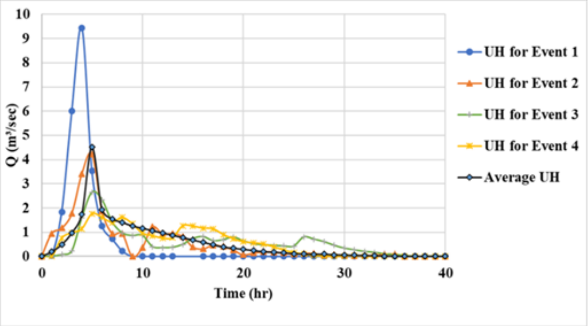

Figure (3): One-hour Unit Hydrographs and Average Unit Hydrographs for Al-Badan Sub-Catchment.

Rainfall-Runoff Data Analysis for Rainy Seasons 2017-2019

1) Rainfall and Runoff Analysis

The two major rainstorm events were "Event 5" in 2017–2018 and "Event 6" in 2018–2019. The average rainfall depth over a study catchment and the φ-Index were also determined. The observed runoff generation in these events was measured, and this observed runoff was graphed as DRH. (Figure 4) depicts the rainfall hyetograph, DRH, and φ-Index for these events.

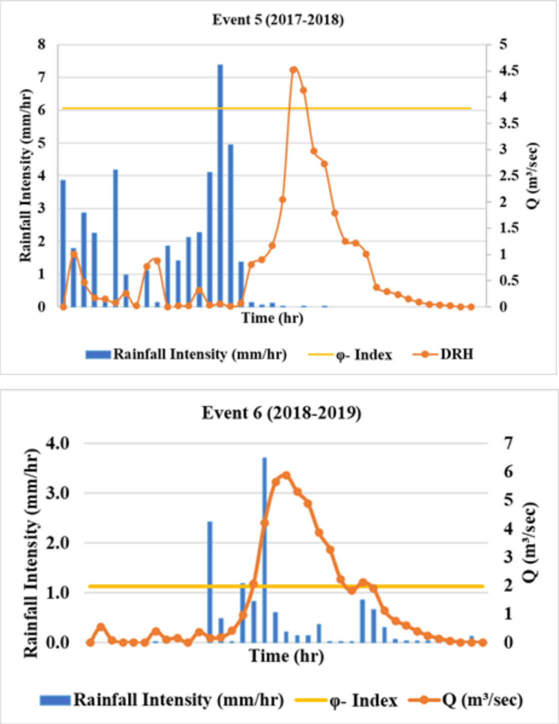

Figure (4): Rainfall Hyetograph, DRH, and φ-Index for Events [5-6] in the Rainy Seasons (2017-2019).

2) Snyder and SCS Methods

The Snyder method allows the computation of five characteristics of the required UH for a given ER duration. It includes (T_P), (Q_P), (T_b), and width (W) in time units at 50% and 75% of (Q_P). This is mainly done to estimate the rainfall-runoff relationship by using the physical parameters of a drainage catchment, such as the length of the mainstream of the catchment (L) being 19 km, the distance from the outlet to the point on the mainstream that is nearest to the centroid of the catchment (L_{ca}) being 9.12 km, and the slope (s) being 4%. The main thing that affects the accuracy of Snyder's SUH is figuring out catchment characteristics parameters like (C_t), which is the non-dimensional regional coefficient representing catchment storage effects and slope, and (C_p), which is the peaking coefficient depending on the storage capacity of the catchment and is also called a regional coefficient. By setting empirical equations that relate catchment characteristics, Snyder's SUH is close to the observation UH (19).

Since the coefficients (C_t) and (C_p) differ from region to region, it is desirable to estimate their values from the UHs of a catchment and use them in the study catchment. Snyder's equations can be applied to scale the hydrograph data from one catchment to a similar one (20) The coefficients can be estimated by empirical equations 3 and 4 (21):

$$t_P = 0.75\ C_t\ (L\ L_{ca})^{0.3} \tag{3}$$

Where;

t_p: Lag time in hr.

$$= \frac{2.78\ Cp\ A}{tp'} \tag{4}$$

Where;

t_p': Modified lag time in hr.

The SCS is a dimensionless triangle hydrograph (derived from many catchments in different geographical regions) approach used to create UH for ungauged catchments through a relationship that expressed the expression between time (T) to (T_P) and discharge (Q) to (Q_P) as a function of catchment characteristics to develop SUH (22), also the parameters that use SCS dimensionless UH differ and change from region to region depending on geographies. The coefficients can be estimated by empirical equations 5 and 6 depending on the total runoff; volume is expected to occur before Q_P (12,23):

$$T_b = C\ T_p \tag{5}$$

$$Q_P = C_P\ \frac{A}{TP} \tag{6}$$

Where;

C: The coefficient depending on the total runoff volume occurs before Q_P.

C_p: The peaking coefficient.

The Snyder and SCS one-hour derived in the Al-Badan sub-catchment are illustrated in (Figures 5 and 6).

3) Synthetic Unit Hydrographs Parameters Estimations

Based on the characteristics of the one-hour average UH and by using the empirical equations that relate to the derivation of one-hour Snyder and one-hour SCS SUHs for Al-Badan sub-catchment, the derived parameters, that relate to Q_P and T_P in both SHUs, are determined to suit Al-Badan sub-catchment and any catchment that has the same metrological and hydrological characteristics. The parameters that were derived from equations are C_p = 0.88, C_t = 1.26 in Snyder equations, and C_p = 1.90, C = 2.92 in SCS equations.

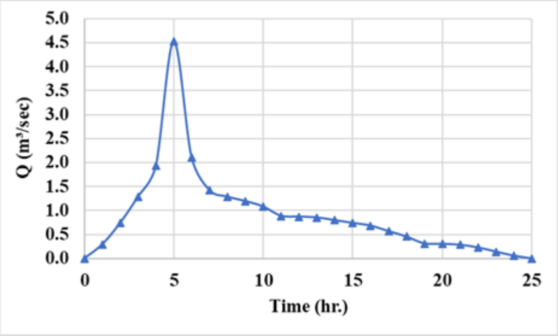

Figure (5): One-Hour Snyder Unit Hydrograph for Al-Badan Sub-Catchment.

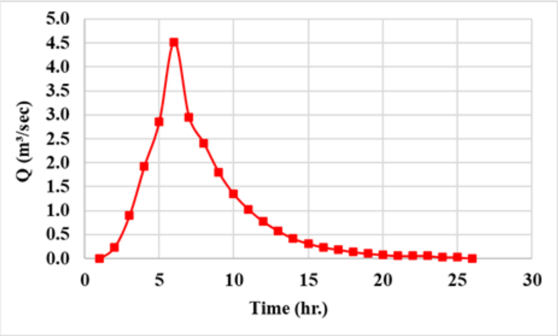

Figure (6): One-Hour SCS Unit Hydrograph for Al-Badan Sub-Catchment.

Verification of the Simulated Results

1) Statistical Analysis

Several standard statistical tests of error functions, such as volume error (VE) and percentage bias (PBIAS), Nash-Sutcliffe Coefficient (EFC), and coefficient of determination (R^2), were used to look at performance measurements between observed and simulated DRH (1).

The VE is defined as:

$$E = \left(\frac{\sum_i^n (Qsi\text{-}Qoi)}{\sum_i^n Qoi}\right) \tag{7}$$

The PBIAS is defined as:

$$PBIAS = \frac{\sum_i^n Qoi\text{-}\sum_i^n Qsi}{\sum_i^n Qoi} \times 100 \tag{8}$$

The EFC equation:

$$EFC = 1 - \left(\frac{\sum_i^n (Qoi\text{-}Qsi)^2}{\sum_i^n (Qoi\text{-}\ \bar{Q}o)^2}\right) \tag{9}$$

The R^2 equation:

$$R^2 = 1\text{-} \left(\frac{\sum_i^n (Qoi\text{-}Q\hat{}\,)^2}{\sum_i^n (Qoi\text{-}\ \bar{Q}o)^2}\right) \tag{10}$$

Where;

Q_{si}: The simulated or simulated runoff.

Q_{oi}: The observed runoff.

$\bar{Q}_o$: The mean observed runoff.

Q^: Predicted discharge from the statistical value inferred from the observed value.

i: The time step.

n: The number of time steps.

If the value of VE is close to zero (∓), good performance is attained; moreover, the value of (%) PBIAS indicates very good performance at (≤∓15), satisfactory performance at (∓15<X<∓25). and unsatisfactory performance at (≥∓25). Possible values of EFC range from [-∞ to 1]. A value equal to 1 indicates the performance is perfect (all the simulated values equal their corresponding observation values), and a value equal to 0 indicates the simulated values are as accurate as the mean of the observed data. On the other hand, the negative EFC values indicate bad simulated values. Therefore, EFC values that are preferred to be larger than 0 and close to 1. Possible values of R^2 are between 0 and 1. There is no correlation between the observed and simulated values when the value is 0. On the other hand, a value of one indicates that the predicted values' dispersion matches that of the observed values.

2) Verification of Simulated Results for Rainy Seasons 2017-2019

As for the results of the simulated DRHs by the Snyder and SCS methods, by multiplying the one-hour Snyder UH and one-hour SCS-UH for Al-Badan sub-catchment with ER for each event, the parameters of Q_P and T_P and runoff volume for both events were determined, as shown in (Tables 1 and 2). Furthermore, the performance measurements for both events were tabulated in (Tables 3 and 4), in addition to the illustration of the DRHs for both compared with the observed DRH for each event in (Figure 7).

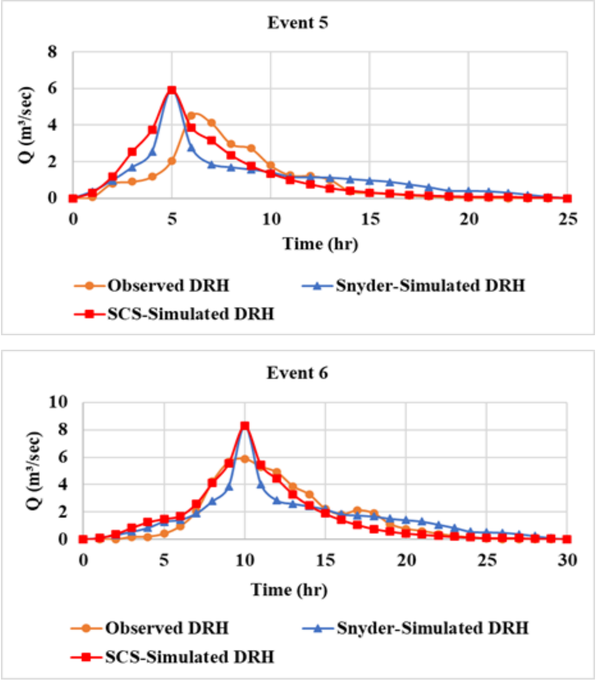

Figure (7): Observed, Snyder and SCS Simulated DRHs for Events [5 and 6].

Table (1): Peak Discharges and Time to Peaks of Observed, Snyder and SCS-Simulated Direct Runoff Hydrograph for Event 5.

Parameter	**Observed DRH**	**Snyder-Simulated DRH**	**SCS-Simulated DRH**
	Event 5		
T_p (hr)	6	5	5
Q_p (m^3/sec)	4.52	5.92	5.92
Runoff volume (m^3)	93,168	108,756	108,720

Table (2): Peak Discharges and Time to Peaks of Observed, Snyder and SCS-Simulated Direct Runoff Hydrograph for Event 6.

Parameter	**Observed DRH**	**Snyder-Simulated DRH**	**SCS-Simulated DRH**
	Event 6		
T_p (hr)	10	10	10
Q_p (m^3/sec)	5.89	8.30	8.28
Runoff volume (m^3)	173,916	177,696	178,344

Table 3: Performance Coefficients of Events [5 and 6] for Observed, Snyder, and SCS-Simulated DRHs.

Events	**Snyder**			
	EFC	**VE**	**PBIAS (%)**	**R^2**
Event 5	0.26	0.16	-16.7	0.67
Event 6	0.79	0.02	-2.17	0.69
Events	SCS			
	EFC	VE	PBIAS (%)	R^2
Event 5	0.35	0.16	-16.6	0.84
Event 6	0.87	0.02	-2.15	0.88

Conclusions

The two essential characteristics of the average UH of the Al-Badan sub-catchment were Q_p = 4.52 m^3/sec and T_p = 5 hours. A UH is a hydrograph produced by one unit of ER flowing uniformly over the catchment at a given time. The theory of UH for gauged catchments can be extended to predict hydrological systems in ungauged catchments based on physical characteristics by using Snyder and SCS methods.

The Snyder UH derived for Al-Badan sub-catchment based on five characteristics (Q_p, T_p, T_b, W_{50}, and W_{75}) and also determined the parameters of both C_p = 0.88 and C_t = 1.26 based on these characteristics, which fall in the ranges reported in the body of literature review [0.3-1.22] and [3-6.0], respectively for 1 cm depth of ER.

As for the SCS method, depending on the triangle hydrograph with three characteristics (Q_p, T_p, and T_b), 34% of the total runoff volume is under the rising limbs in UH. Based on these results and the coordinates of SCS dimensionless UH, SCS-UH was established. After that, the related C_p = 1.90 and C = 2.92 were determined for 1 cm depth of ER.

Using S-curve or superposition methods, these SUHs can be used to calculate the volume of runoff and determine Q_p and T_p for any rainfall events of different durations.

Implication of Study Results

Applying the simulated results of this study in similar hydrological and meteorological catchments, in turn, will enhance the proper design of hydraulic structures and manage water resources.

Abbreviations and Specific Symbols

Abbreviation and Symbol	Meaning
C_p	The peaking coefficient depends on the storage capacity of the catchment
C_t	Non-dimensional regional coefficient representing catchment storage effects and slope
C	The coefficient depending on the total runoff volume occurs before Q_P
DRH	Direct Runoff Hydrograph

ER	Excess rainfall or Effective rainfall
EFC	Nash-Sutcliffe Coefficient
L	Length of mainstream of the catchment
L_{ca}	The distance from the outlet to the point on the mainstream which is nearest to the centroid of the catchment
PBIAS	Percentage of Bias
Q_P	Peak discharge or Peak flow
R^2	Coefficient of determination (square ratio)
s	The slope of the catchment
SCS	Soil conservation services
SUH	Synthetic unit hydrograph
T_b	Time Base
T_P	Time to Peak
t_p	Lag Time
$t_{p'}$	Modify lag time
UH	Unit hydrograph
VE	Volume Error
$W_{\%}$	Widths of UH at a certain percent of Q_p in hours
φ-Index	Phi-index, which is the average rainfall intensity above any storm in which the depth of the rainfall equals the depth of the runoff

Ethics approval and consent to participate

The authors confirm that they respect the publication ethics and consent to their work's publication.

Consent for publication

The authors consent to the publication of this work.

Availability of data

The availability of data is available upon request.

Author's contribution

The authors confirm their contribution to the paper as follows: Ghossoun Hamedallah was involved in the study conception, theoretical calculations and modeling, data analysis and validation, and manuscript drafting. Sameer Shadeed was involved in the formulation of the general idea of the research, providing rainfall and runoff data, manuscript editing, and proofreading. All authors reviewed the results and approved the final version of the manuscript.

Funding

This research is funded by the Middle East Desalination Research Center (MEDRC), with contributions organized by the Palestinian Water Authority (PWA).

Conflicts of interest

The authors declare that there is no conflict of interest regarding the publication of this article

Acknowledgments

The authors would like to express their gratitude to everyone who helped bring this article to completion. Also, the authors are interested in conveying thanks to reviewers of the An-Najah University Journal for Research, A: Natural Sciences, for their helpful comments, which enhanced the paper's value.

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