An-Najah National University

Faculty of Graduate Studies

ESTIMATION SYNTHETIC UNIT HYDROGRAPHS PARAMETERS FOR WADI AL-BATHAN SUB-CATCHMENT

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Dedication

I dedicate this thesis to the people of credit as continuous alms to my father's soul and my mother's beating heart.

Acknowledgements

I want to express my heartfelt gratitude and praise to Almighty Allah for all the graces and mercies he has given me throughout my life and work.

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Finally, it was the happiest moment of my life, and I had achieved the first of my dreams.

Declaration

I, the undersigned, declare that I submitted the thesis entitled:

ESTIMATION SYNTHETIC UNIT HYDROGRAPHS PARAMETERS FOR WADI AL-BATHAN SUB-CATCHMENT

I declare that the work provided in this thesis, unless otherwise referenced, is the researcher’s own work, and has not been submitted elsewhere for any other degree or qualification.

Student's Name: **Ghossoun Zeyad Tawfiq Hamedallah**

Signature:

Date: **29/03/2023**

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ESTIMATION SYNTHETIC UNIT HYDROGRAPHS PARAMETERS FOR WADI AL-BATHAN SUB-CATCHMENT

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Abstract

Developing unit hydrographs is critical for hydraulic structure design and water resource management in gauged catchments. Due to the lack of local data, engineers should strive to estimate discharges based on empirical (synthetic) methods that can predict runoff based on rainfall in the ungauged catchments.

Synthetic unit hydrographs, such as the Snyder and Soil Conservation Service (SCS), are popular and play an essential role in hydrology. These methods are simple, requiring only catchment characteristics such as area, length of mainstream, and slope. Therefore, these methods serve as valuable tools to simulate runoff from the ungauged catchment to estimate peak discharge, time to peak, and runoff volume.

This research study is Al-Bathan 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-Bathan flume located in the outlet of the sub-catchment.

By computing the characteristics of the average one-hour unit hydrograph with peak discharge is 4.52 m^3/sec and time to peak is 5 hours, Snyder and SCS hydrographs were developed to suit Al-Bathan sub-catchment physical characteristics. The parameters were determined for the Snyder, where $C_p = 0.88$ and $C_t = 1.26$, and the SCS, where $C_p = 1.90$ and $C = 2.92$. Therefore, these parameters fit the study area.

These synthetic one-hour unit hydrographs were examined during two events (2017–2019) by comparing observed and simulated direct runoff hydrographs for these events. The performance was tested statistically using the Nash-Sutcliff coefficient, coefficient of determination, volume error, and percentage bias. Results showed that the synthetic unit hydrographs are suitable for application and that the SCS method is more accurate.

Keywords: Al-Bathan Sub-catchment; Direct Runoff Hydrograph; Palestine; Synthetic Unit Hydrograph; Unit Hydrograph; Ungauged Catchment.

Chapter One

Introduction and Theoretical Background

1.1 General Background

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 (Kılıç, 2020). Loren Eiseley abbreviates the water system in one sentence: "If there is magic on this planet, it is contained in water" (Dzuriz et al., 2018).

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 (Klate & Kuchment, 2004). There are several forms of precipitation, including rainfall, snowfall, hail, frost, and dew (Ronald, 1992). In Palestine, rainfall is the most dominant form of precipitation (PMD, 2022).

Hydrologists seek to investigate surface water, including systems, flows, distributions, properties, and management, on the Earth according to recent theoretical developments. Starting with the catchment's water balance and determining the volume and depth of rainfall and runoff (Huntington, 2006). In like manner, studies investigate the procedure to transform the rainfall hyetograph into a runoff hydrograph. Peak flow and time to the peak are the main hydrograph characteristics that need to be estimated for any catchment. According to hydrologists, the estimation of these characteristics are highly complex in ungauged catchments compared to gauged ones (Sule & Alabi, 2013).

This research constitutes a relatively new area that has emerged from the urgent need to conduct studies on the water in Palestine, especially in the West Bank. In Palestine, the techniques of runoff are not adequate. There is a growing need for measuring and understanding runoff data (Shadeed, 2008).

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 (Adeyi et al., 2020).

Given the rainfall data, the availability of UH for any catchment is critical to predicting runoff hydrographs. Worldwide, most catchments are ungauged, meaning rainfall data are available, but runoff (streamflow) data are not. In such catchments, transforming rainfall hyetographs into runoff hydrographs is challenging (Singh et al., 2014). Several hydrologists and researchers have developed synthetic (empirical) unit hydrographs (SUHs) to be used for ungauged catchments (El-Sayed, 2018).

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 SCS (1972) (Safarina et al., 2011).

Worldwide, 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 peak discharge and decreased time to peak. 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 (Sivapalan et al., 2003; Zehe et al., 2005).

1.2 Objectives

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 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.

1.3 Research Questions

In light of the identified objectives, this research aimed to answer the following questions:

- How to analyze available rainfall and runoff data to transform the rainfall hyetograph into a runoff hydrograph?
- How to derive a one-hour average UH from several UHs of a certain duration?
- What are the significant parameters in the SUHs to deal with?
- How to use parameters to develop UHs for certain durations?

1.4 Research Needs and Motivations

The water resources in Palestine are limited, so studying and managing, and seeking procedures to save them are priorities to face significant and growing shortfalls in the water supply.

The development of the water sector in Palestine is impeded by institutional deficiencies arising from several factors, including a paucity of reliable data, governance challenges, constraints imposed by occupation, inadequate financial resources, and technical limitations that hinder the effective exploitation of water resources (PWA, 2012).

Moreover, global problems such as climate change and increased human activities escalate the risk of hydrological problems by increasing volume. As a result, the peak discharge and frequency of floods increase in the catchment (Courty et al., 2018).

Therefore, to control runoff, especially in ungauged catchments, we look forward to using SUHs (e.g., Snyder and SCS) to obtain runoff hydrographs from some selected rainstorm events. This situation has compelled the dire need to parameterize such SHUs based on the available rainfall and runoff data, as in the case of wadi Al-Bathan sub-catchment.

The derivation of parameters for the SUHs will provide clear information for future studies that predict hydrological problems and manage surface water at wadi Al-Bathan sub-catchment. Furthermore, derived SUHs parameters can aid in the proper design of various hydraulic structures (e.g., dams, culverts, bridges, and waterways). These save people from suffix hydrological problems, prevent environmental destruction, and decrease economic losses.

1.5 Literature Review

1.5.1 Hydrologic Cycle

The hydrologic cycle, commonly known as the water cycle, is a fundamental concept in hydrology. Evaporation, precipitation, interception, transpiration, infiltration, percolation, runoff, etc., are all part of the hydrologic cycle (Klate & Kuchment, 2004). The two most critical influences on the hydrologic cycle are precipitation (including rainfall, snowfall, hail, sleet, dew, drizzle, etc.) and runoff (surface runoff, interflow, and baseflow (BF)) (Hou et al., 2020).

The most common forms of precipitation are rainfall and snow. Precipitation varies spatially and temporally. The return period, the intensity of rainfall, and the duration of storms are factors that influence the runoff generation mechanism (Shaw, 1994).

The water from precipitation that flows over the ground's surface towards stream channels, oceans, lakes, or low points of the earth's surface is called "runoff." Runoff occurs when precipitation exceeds hydrologic losses. The factors that affect the rate of runoff include rainfall amount, intensity, duration, soil type, soil moisture, vegetation, ground cover, and topography (Fang et al., 2005). Rainfall and runoff values for a given catchment can be analyzed, known as "Rainfall-Runoff Analysis"(Kebila, 2008).

1.5.2 Rainfall-Runoff Analysis

The concern for rainfall-runoff analysis is the physical mechanisms within the catchment that result in the conversion of a rainfall hyetograph into a runoff hydrograph. Floods and other hydrological problems can be predicted using rainfall-runoff transformation processes (Bonner, 2019).

For scientists and hydrologists, deriving correlations between the rainfall over the catchment area and runoff is a crucial challenge. In most countries, vast amounts of money are being spent to analyze the rainfall and runoff to reduce and mitigate the risk of severe rainfall events. From this point, engineers worked for many years on many pieces of research to find physical, empirical, or combined relations to describe the rainfall-runoff processes (Tarboton, 2003).

The total stream flow hydrograph (TRH) has two components: BF and DRH. The DRH results from ER passing through a catchment at a constant rate for a specific duration. The ER is a part of rainfall that becomes direct runoff at the catchment’s outlet. The excess rainfall hyetograph (ERH) is simulated after subtracting all hydrologic losses (infiltration, evaporation, interception, depression storage, etc.) from the rainfall hyetograph (Nurkholis et al., 2019). The BF is the portion of the stream flow that exists before rainfall and is contributed by groundwater. BF may vary considerably along the stream due to geological influences and groundwater levels (Gonzales et al., 2009).

The shape of the hydrograph is affected by both physiographic and climate factors. Physiographic factors include the characteristics of the catchment, the infiltration, and the channel (Ramírez, 2000). Climate factors include temperature, initial losses, evaporation, and storm characteristics (Beine & Parsons, 2013).

When DRH results from one unit of ER depth that occurs uniformly over the catchment and at a specific duration, the so-called "UH"(Jena & Tiwari, 2006).

1.5.3 Unit Hydrograph

In 1932, Sherman introduced the UH method and improved catchment rainfall-runoff analysis. It is still one of the methods used to predict floods for any gauged catchment (Fedorova et al., 2018; Singh et al., 2014).

Sherman's UH method should be used with less than 2,000 square miles of the catchment. If the catchments are more extensive, they can be subdivided into smaller sub-catchments, and each of those is subjected to a hydrograph analysis depending on storm patterns (Salami et al., 2017).

Prior research as well as recent studies have indicated that the use of UHs is highly effective in determining the values of stream flow records and forecasting floods based on rainfall data This proficiency in understanding the “flood hydrograph” produced by single storms facilities the alleviation of hydrological problems. In addition, the Natural Resources Conservation Service (NRCS) uses hydrographs in water evaluation to determine the impact of different scenarios, such as land use change and climate change, on the change of the runoff volume and peak flow (Holnbeck & Parrett, 1996).

In summary, the primary assumption of the UH theory is that rainfall has a uniform distribution both in space and time. As an illustration, the rainfall rate did not vary during storm events (Kilgore, 1997).

In reality, rainfall events are seldom and rarely uniform in space and time. Hence, rainfall events are highly subject to a nonlinear response (Courty et al., 2018).

The UH is not accurate enough to predict DRH. Therefore, there are some limitations to using UHs, such as that precipitation must be from only rainfall. This means the UH method does not apply to areas where a significant portion of storm precipitation is in the form of snow. In addition, the catchment should not have plenty of storage, like ponds, tanks, etc., which affects the discharge flow and storage (Ramírez, 2000).

In most cases, rainfall and runoff data are unavailable or insufficient to derive the UH of the catchment. As a result, there is a need to use SUHs for ungauged catchments (Fang et al., 2005), which are common in Palestine (Shadeed, 2008).

SUH methods are based on empirical or theoretical formulas that relate hydrograph peak discharge and timing to catchment characteristics (Sule & Alabi, 2013).

1.5.4 Synthetic Unit Hydrograph

1.5.4.1 General Background

The theory of UH for gauged catchments can be extended to predict hydrology systems in ungauged catchments based on an understanding of soil, land use, climate, and topographical controls on catchment responses and, on the other hand, based on analyzing inherent variability in observed runoff response data (Sivapalan et al., 2003).

The word "synthetic" in SUH means that UH is based on the physical characteristics of the catchment rather than an analysis of rainfall and runoff data (Rinanti et al., 2017).

Research on the hydrology of ungauged catchments has been in this domain since the early 1990s. From 2003 to 2012, the International Association of Hydrological Sciences was in charge of this topic. They did this so that scientists could quickly look up information about new ways to predict discharge in an ungauged catchment (Singh et al., 2014).

SUH is a common and important method for estimating water resources, mainly by predicting the runoff of ungauged catchments. When SUHs are constructed, the area, length of the stream, land use, and soil type of the catchment must be considered (Fedorova et al., 2018; Musa et al., 2014; Rinanti et al., 2017; Sharma, 2018).

The SUHs can be grouped into four categories: (a) conceptual, (b) geomorphological, (c) probabilistic, (d) and traditional. Traditional SUHs are simple and easy to develop, requiring less data to derive UH based on theoretical and empirical equations related to the physical catchment characteristics; however, adjustments are needed for SUHs to correspond to the physical characteristics of the catchment and ER. This will be accomplished by estimating specific coefficients in empirical equations (Bhunya et al., 2011a). Many studies, like those by Bernard, Clark, Nash, Gray, Chow, SCS, and Snyder have linked the UH constant-coefficient to the characteristics of the catchment to figure out the UH for an ungauged catchment (Sharma, 2018; Singh et al., 2014).

However, the SUHs commonly used in the generation of UH for ungauged catchments include Snyder's related hydrograph characteristics of time to peak (T_P) and peak discharge (Q_P) to catchment characteristics and SCS based on a dimensionless UH (Jena & Tiwari, 2006).

1.5.4.2 Snyder's Synthetic Unit Hydrographs

Equations of Snyder’s (1938), which resulted from a study of 20 catchments with a size of 25 - 25,000 km^2 located in Appalachian Highlands of the United States (Sule & Alabi, 2013), and after analysis of numerous hydrographs for these catchments (Adeyi et al., 2020), developed an empirical set of equations for SUHs in a specific area in the United States of America (USA). These equations are used in the USA and many other countries but with some modifications (Ilic et al., 2018).

The Snyder method allows the computation of five characteristics of the required UH for a given ER duration. It includes (T_p), (Q_p), time base (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 (Kilgore, 1997).

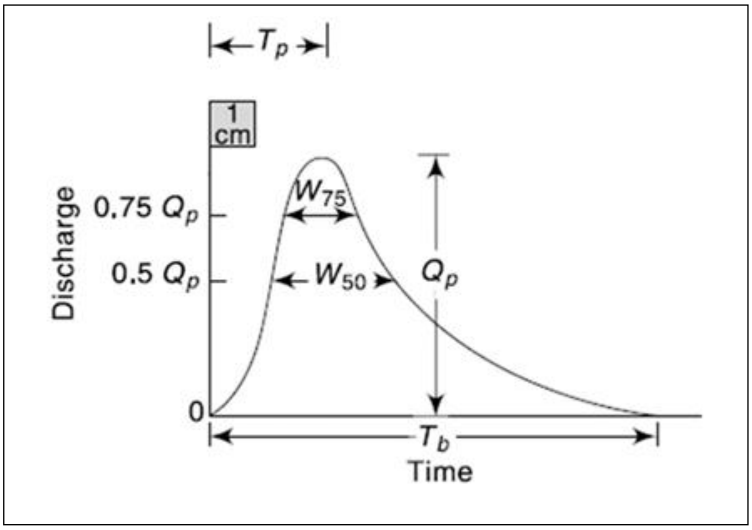
The development sketch of SUH is based on the determination of five elements, as shown in (Figure 1.A).

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 (Kalgonda Patil & Bhagwat, 2019; Kilgore, 1997).

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 (Mcenroe & Zhao, 1999).

Figure 1.A

Elements of Snyder's SUH



(Subramanya, 2003)

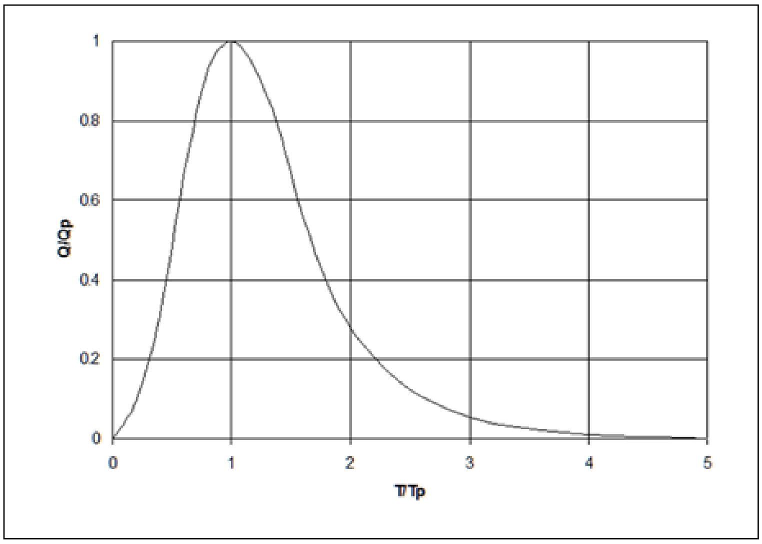
1.5.4.3 SCS Synthetic Unit Hydrograph

The SCS method was developed in 1964, and it was further developed in 1972 and 1986. The SCS is a dimensionless triangle hydrograph (derived from many catchments in different geographical regions) approach used to create UH for ungauged catchments smaller than 30 km^2 in the USA (Gulbahar, 2016), and this development was 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 (Budi et al., 2011; Sharma, 2018). The X-Axis is made up of dimensionless time units, and Y-Axis is made up of dimensionless discharge units, as shown in (Figure 1.B), the ordinate ($Q \backslash Q_P$) equals one when ($t \backslash T_p$) equals one (Salami et al., 2009).

The parameters that use SCS dimensionless UH are differ and change from region to region depending on geographies, such as urban catchments, rural catchments (with rolling hills or slightly sloped or very flat), and mixed urban and rural catchments. That means the standard SCS-UH may need to be modified by changing parameters

Figure 1.B

SCS Dimensionless Unit Hydrograph



(Subramanya, 2003)

1.6 Previous Hydrological Studies in the Faria Catchment

Many researchers who have studied hydrological analysis have shown an interest in the Faria catchment. The research began in the past and continues to this day.

An early study carried out by Shadeed and Wahsh (2002) utilized some synthetic models to simulate runoff generation in the upper Faria catchments. In another study, Takruri (2003) studied rainfall data in the Faria catchment and derived approximations of the intensity duration frequency (IDF) curves for the station at Bait Dajan (Sulaiman, 2017).

The literature review also shows that a study by Shadeed (2005) tried to use the kinematic wave-based geomorphological instantaneous UH (KW-GIUH) hydrological model to simulate the rainfall-runoff process. Later in 2008, Shadeed used the coupled TRAIN-ZIN model to make a runoff generation map based on known spatial model parameters for terrain types and up-to-date hydrological modeling (Shadeed, 2008).

Also, in the same year, in the study of Salahat (2008), an integrative analysis of the methods for rainfall-runoff simulation was performed. A regression relationship between rainfall intensity and runoff coefficient has been developed. In addition, the development of an integrated prediction-optimization model for water harvesting, storage, and utilization in Faria catchment was proposed.

In the study of Sulaiman (2017), a preliminary visualization of rainfall-runoff modeling was performed using hydrologic engineering center-hydrologic modeling system (HEC-HMS) software, which is used to simulate the rainfall response in the Faria catchment. In addition, a more recent hydrological model, WRF-Hydro, in the same area was tested and found to be equally good at simulating rainfall events. Therefore, both models could be used as prediction tools for other areas with similar hydrological conditions. However, these models must be calibrated and improved to increase their effectiveness.

Chapter Two
Materials and Methods

2.1 The Study Area

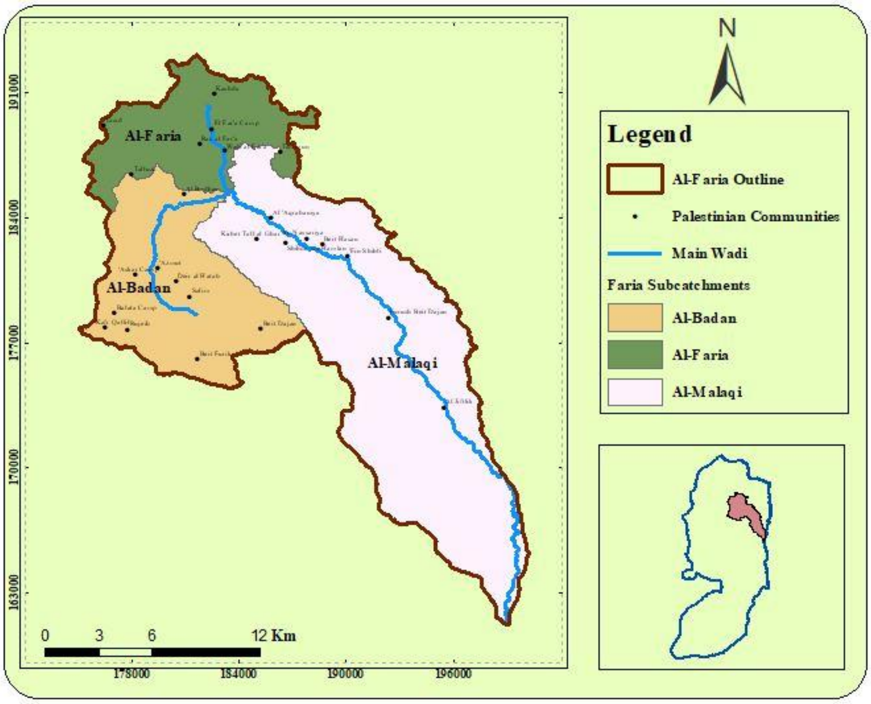
2.1.1 Geography and Topography

In general, the Faria catchment is located in the northeastern part of the West Bank, in Palestine, with a total area of about 320 km^2. The catchment extends from the ridges of Nablus Mountains down the eastern slopes to the Jordan River. Al-Faria natural stream extends from Ras Al-Faria and Al-Bathan in the upper areas of the catchment to the Jordan River (Shadeed et al., 2022). This natural stream is the primary water supply system in the catchment. Al-Faria catchment is divided into three sub-catchments: Al-Faria, Al-Bathan, and Al-Malaqi (Shadeed & Lange, 2010), as shown in the outline of Faria catchment in (Figure 2.A).

The topography of Faria catchment starts at an elevation of about 920 meters above sea level and descends drastically to about 350 meters below sea level (Shadeed et al., 2022).

Figure 2.A

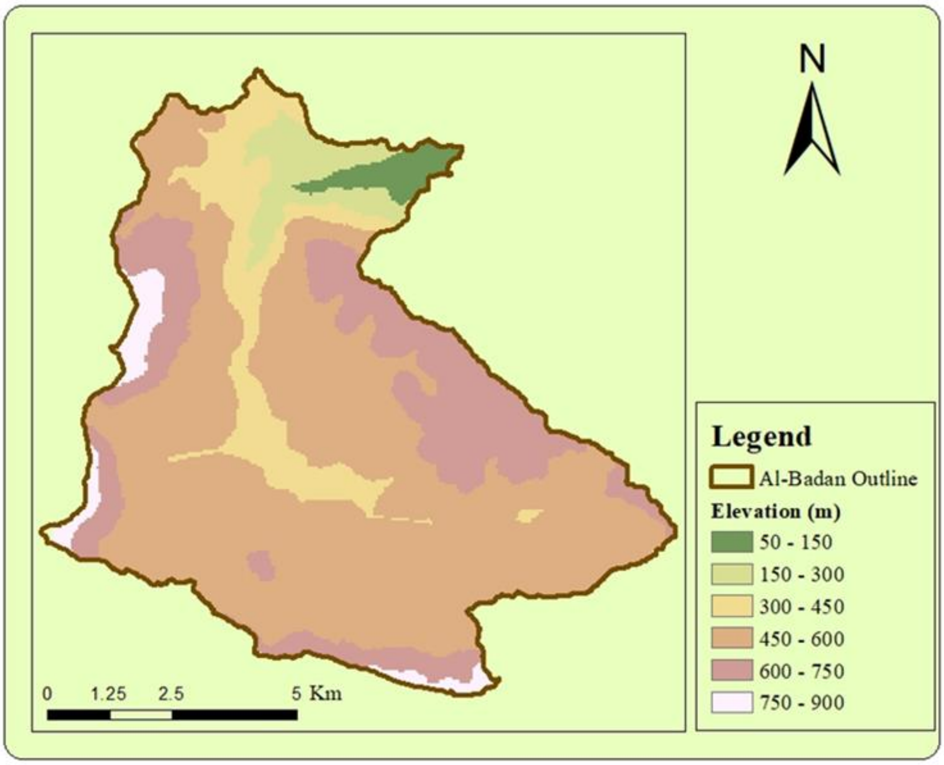
Outline of Faria Sub-Catchments



The topography in Al-Bathan sub-catchment as presented in (Figure 2.B) starts at 900 meters above the mean sea level in the Nablus Mountains and decreases drastically to about 50 meters above the mean sea level at the sub-catchment outlet. The topographic relief changes significantly through this sub-catchment in a short distance of less than 20 km affecting the catchment’s prevailing metrological conditions.

Figure 2.B

Topographic Map of Al-Bathan Sub-Catchment



2.1.3 Soil and Land use

According to (Figure 2.C), Al-Bathan sub-catchment has different soil types. These are Grumusols (Vertisol as American name) and Terra Rossas, Brown Rendzinas, and Pale Rendzinas (Inceptisol as American name), with 75% of the total area, Inceptisol covers almost the entire Al-Bathan sub-catchment. Furthermore, because all soil textures are the clay, the infiltration rate is low, resulting in increased surface runoff potential.

The land use map (Figure 2.D) is divided into six categories. The classes are agricultural areas (21%), built-up areas (11%), natural forests (2%), natural grassy hill slopes (33%), olive plantations (16%), and scattered olive plantations (17%).

Figure 2.C

Soil Types of Al-Bathan Sub-Catchment

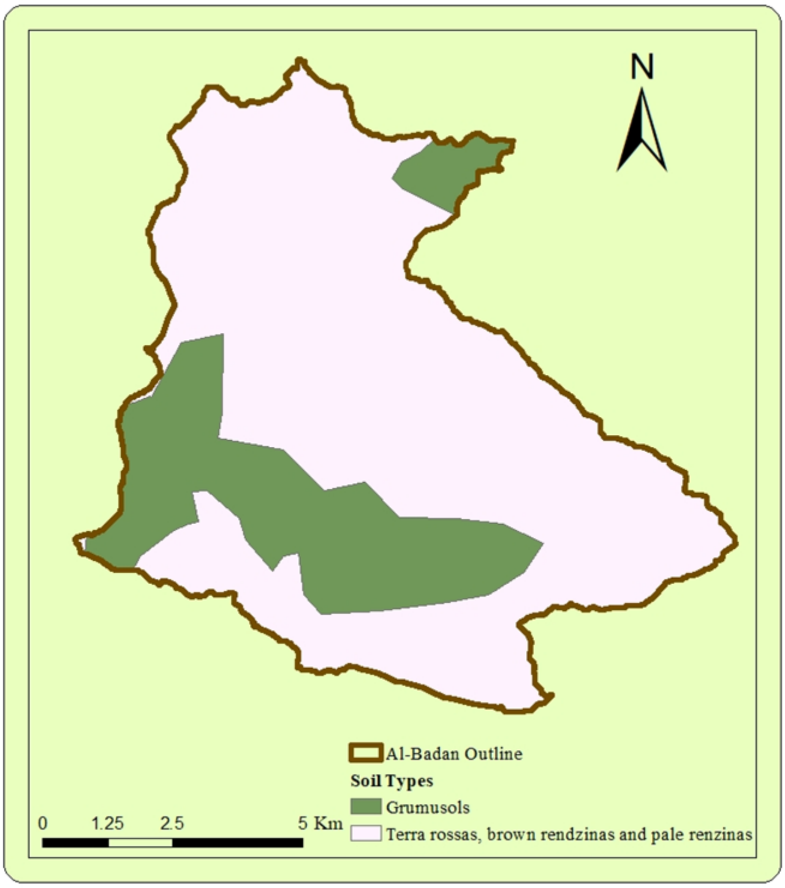
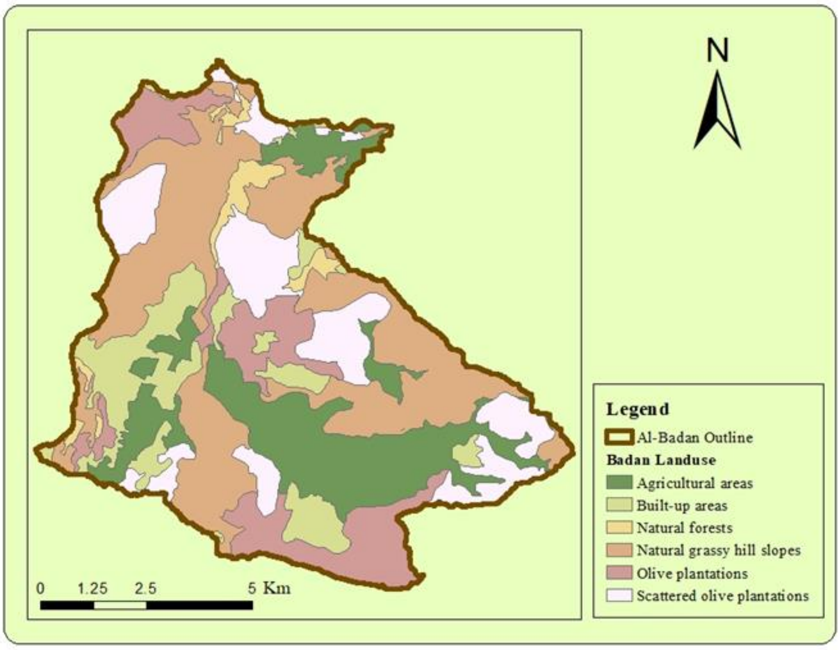


Figure 2.D

Land use Map of Al-Bathan Sub-Catchment



2.1.4 Climatology

The climate in Al-Bathan sub-catchment is predominately Mediterranean characterized by a semi-arid, dry, and hot summer with almost no precipitation, especially in the months of June, July, and August. The winter season is cool and sometimes very cold, with rainfall between October and April. 90% of the annual rainfall occurs in the winter and autumn, which account for the majority of rainfall events (PMD, 2022; Shadeed & Lange, 2009).

The maximum, mean, and minimum annual temperatures of Al-Bathan in Nablus are 26 °C,20 °C, and 15 °C, respectively. The mean annual relative humidity was 77%. The minimum relative humidity value occurs in May during Khamaseen weather, while the maximum relative humidity is usually registered in December, January, and February. 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 (PCBC, 2021; Shadeed & Lange, 2009).

2.2 Methodology

Objectives, needs, and motivations were defined to achieve the ultimate goal of this research study. The characteristics of the study area included topography, soil, land use, climate, and hydrological data such as rainfall and runoff were collected.

Data collection came from many different 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 simulated from Dr. Sameer Shadeed, who collected data for his PhD 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 Al-Bathan sub-catchment. Furthermore, physical sub-catchment characteristics were derived from the different shapefiles by using ArcGIS.

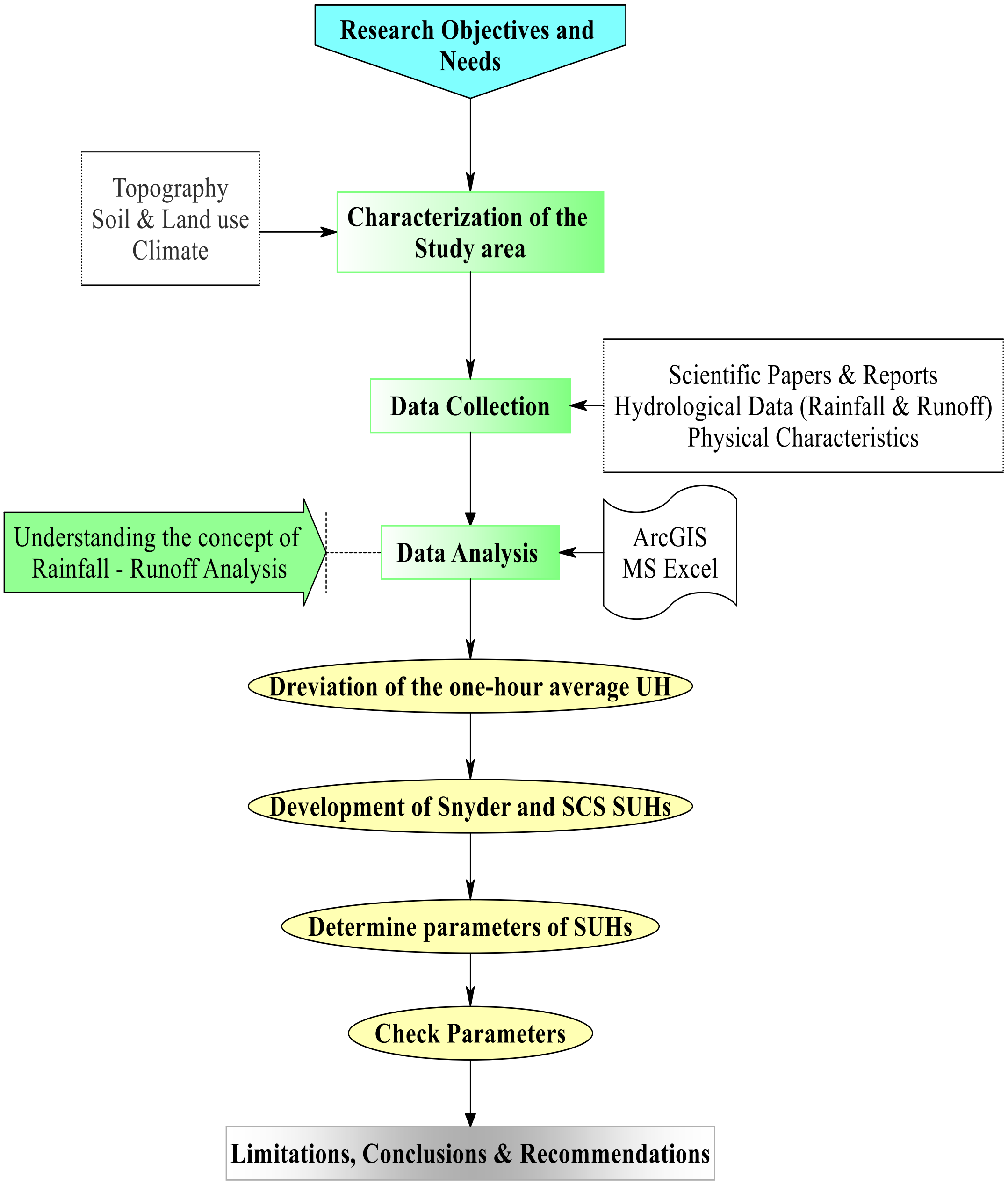
The hydrological collected data were analyzed using Microsoft Excel. Firstly, selected the significant rain storm events from the period (2005–2007) and estimated ER for each storm, and then analyzed runoff data to define observed DRH for each storm. After that, used a de-convolution matrix to derive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

Finally, conclusions, limitations, and recommendations were presented. The overall research methodology is illustrated in (Figure 3).

Figure 3

A Flow Chart Describing the General Methodology



2.3 Data Collection

The results of a rainfall-runoff analysis study depend a lot on the quality of the data and the way the calculations are done. The rainfall and runoff data with low quality will produce poor results. (Bonner, 2019).

Identifying parameters for empirical equations is always difficult, especially when there is not much data available for the study area. However, this problem can be solved by estimating parameter values linked to the catchment's physical features (Kebila, 2008).

In general, rainfall storms are classified according to intensities and durations; this study couldn't do that because of limited and inadequate rainfall measurements.

This study includes the following data collection:

- Scientific papers and reports related to UH and SUH and a few M.Sc. theses dealing with hydrological analysis and hydrological modeling in the Faria catchment were discussed in chapter one.
- Physical sub-catchment characteristics are analyzed by GIS.
- Hydrological (rainfall and runoff) data. There is very little hydrological data for Al-Bathan sub-catchment. The majority of the data were simulated from Shadeed (2008). MS Excel was used to list the hydrological data for each one-hour time step for rainfall depth recorded at each rainfall station (See Appendix A Tabs. 1, 2, 3, 4, 5 & 6).

2.3.1 Rainfall Data

Rainfall data is one of the most critical inputs for rainfall-runoff analysis and forecasting. In a rainfall-runoff study, accurate knowledge of rainfall is necessary for accurately calculating the runoff generation. Stations (rain gauges) are essential devices that record the amount of rainfall at a specific location (Zehe et al., 2005). Tipping Bucket Rain gauges (TBRs) are widely used in hydrology to measure rainfall intensity due to their good time resolution at high rainfall intensities (Shadeed, 2005).

Rainfall data for Al-Bathan sub-catchment were collected from four TBRs (Taluza, Nablus, Salim, and Beit Dajan) between (2005- 2007).

Ten years later, another three TBRs (Lubadi, Beit Furik, and Badan) were installed within the boundary of Al-Bathan sub-catchment as show in (Figure 4.A), and rainfall data were simulated from (2017-2019). The basic data for these stations are summarized in (Table 1).

Figure 4.A

Rainfall Stations and Runoff Parshall Flume Device within Al-Bathan Sub-Catchment

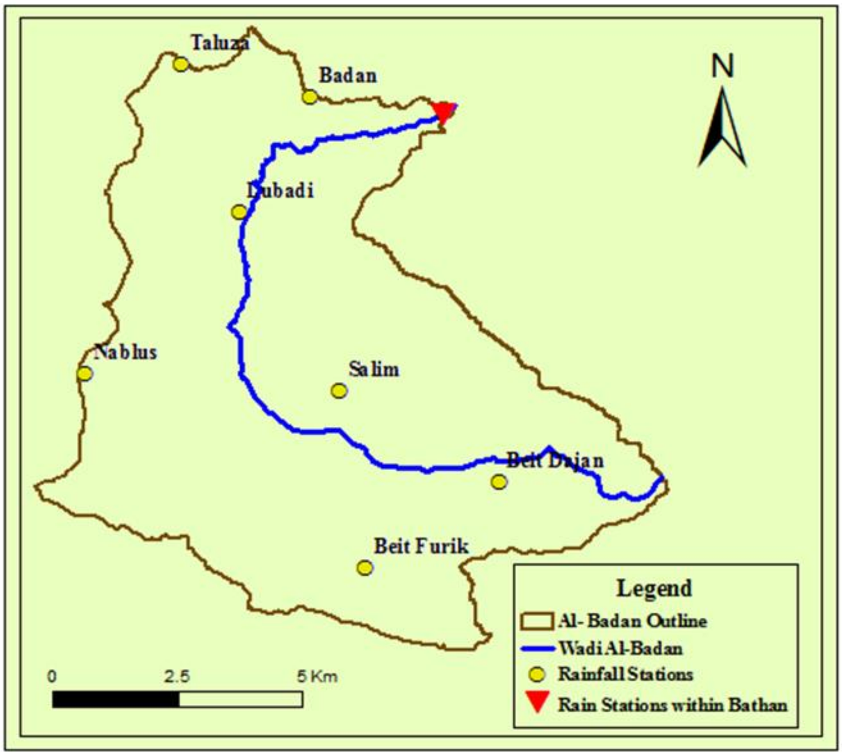


Table 1

Summary of the Available Rainfall Stations within Al-Bathan Sub-Catchment

Rainfall Stations	Coordinates		Elevations (m)	Average Rainfall (mm)
	Y (km)	X (km)		
Taluza	178	186	500	580
Nablus	176	180	570	600
Salim	181	180	514	450
Beit Dajan	184	178	520	390
Lubadi	179	183	335	580
Beit Furik	182	176	540	410
Badan	181	186	270	480

2.3.2 Runoff Data

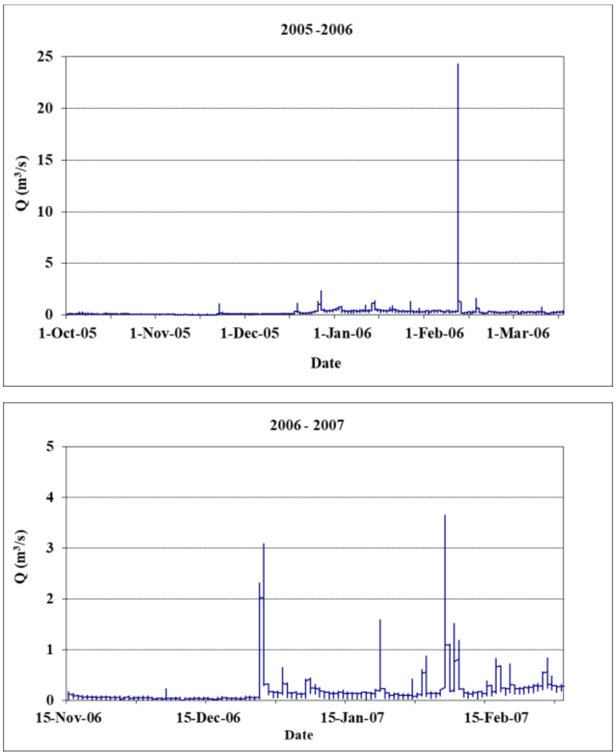
Most hydrologic analyses involve runoff from catchments, so measurement is vital. Runoff measurements can be used to develop empirical relationships between variables and peak discharge or runoff volume(Chatterjee & Singh, 2014). Many calculations to predict the runoff characteristics of ungauged catchments are based on these relations. The runoff collection data in (2005-2007) are illustrated in (Figure 4.B).

There are numerous approaches to measuring runoff (direct and indirect determination). Hydraulic structures such as weirs and flumes are one type of direct runoff measurements. The flumes, also known as Parshall flumes, are installed in an open channel to measure the water depth as it passes over an obstruction (a flume) to measure runoff rates (Subramanya, 2003).

Al-Bathan sub-catchment has one Parshall flume built at the catchment's outlet; data loggers installed alongside critical flume sections record water level information inside the flumes (Shadeed et al., 2007), as shown in (Figure 4.A).

Figure 4.B

Runoff of Al-Bathan Sub-Catchment for the Two Rainy Seasons (2005-2007)



2.3.3 Physical Characteristics

Physical characteristics were analyzed in Al-Bathan sub-catchment using GIS. Each of these characteristics is important in hydrologic analysis and is required for development of a SUH for the catchment by creating relationships between them and hydrological data to achieve the study's objectives. (Figure 5) depicts the length of the mainstream of the catchment (L), the distance from the outlet to the point on the mainstream which is nearest to the centroid of the catchment (L_{ca}), both measured in km, and slope (s) and (Table 2) tabulates the summary of physical derived characteristics.

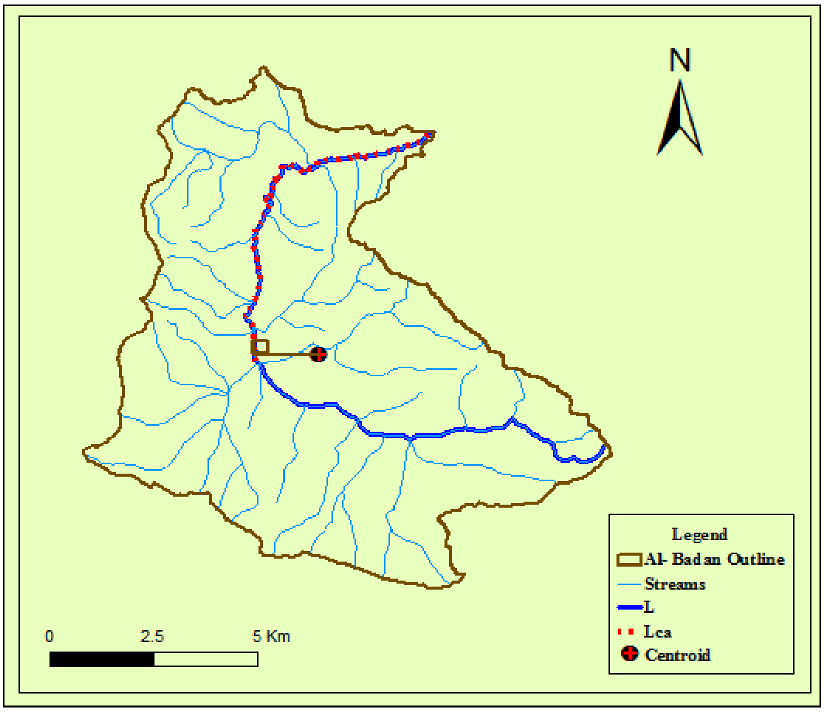
Table 2

Summary of Physical Characteristics for Al-Bathan Sub-Catchment

Catchment Characteristics	Values
A	83 km^2
s	4%
L	19 km
L_{ca}	9.12 km

Figure 5

Streams for Al-Bathan Sub-Catchment and some of its Physical Characteristics



2.4 Data Analysis

2.4.1 Rainfall-Runoff Data Analysis for the Rainy Seasons 2005-2007

A. Rainfall Data Analysis

As stated in Section 2.3, the collected rainfall data from (2005-2007) was analyzed to determine major rainstorm events that contribute to the most significant runoff volume. Hourly rainfall was created by summing up the data. The data has been analyzed according to the following points:

- The first year (2005-2006), consisted of one event called "Event 1", and the second year (2006-2007) consisted of three events called "Event 2, Event 3, and Event 4". Characteristics of these events were studied and tabulated to find the relationship between rainfall and runoff in the Al-Bathan sub-catchment, as shown in (Table 3).
- The average rainfall depth over a study catchment should be determined. To calculate the spatially distributed rainfall for an area, the point rainfall needs to be converted to areal rainfall. In this study, the method that has been used is the Thiessen polygon, as illustrated in (Figure 5.A).
- This method assigns weight to each rainfall gauge based on the catchment area that is closest to that gauge. The representative area for each rainfall gauge was computed through GIS and tabulated in Appendix A (Tab. 7).
- Then multiply the area of the polygon by the rainfall amount for each rainfall gauge and divide by the total area of Al-Bathan sub-catchment as an equation to compute the average rainfall over the sub-catchment (Brassel & Reif, 1979).

$$P_{avg} = \frac{1}{A}\sum_{i=1}^{N} A_i P_i \tag{1}$$

Where;

P_{avg}: Average rainfall in mm.

P_i: Rainfall recorded at various rainfall gauges in mm.

A_i: Area of Thiessen polygon of rainfall gauges in km^2.

N: Number of rainfall gauges.

A: Area of the catchment in km^2.

- In hydrological calculations involving floods, using a constant value of infiltration (infiltration index) for the storm's duration is recommended. One type of infiltration index commonly used is the Phi-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. The φ- index value is the sum of interception, depression storage, and infiltration; it is also calculated by trial and error using the below equation. The trial ends when the φ-index value becomes less than or equal to the lowest value in the remaining rainfall intensities (Al-Smadi, 1998).

$$\varphi\text{ - index} = \frac{1}{t}\ (P\text{-}R) \qquad (2)$$

Where;

φ - index: Infiltration index in mm/hr.

P: The total rainfall depth in mm.

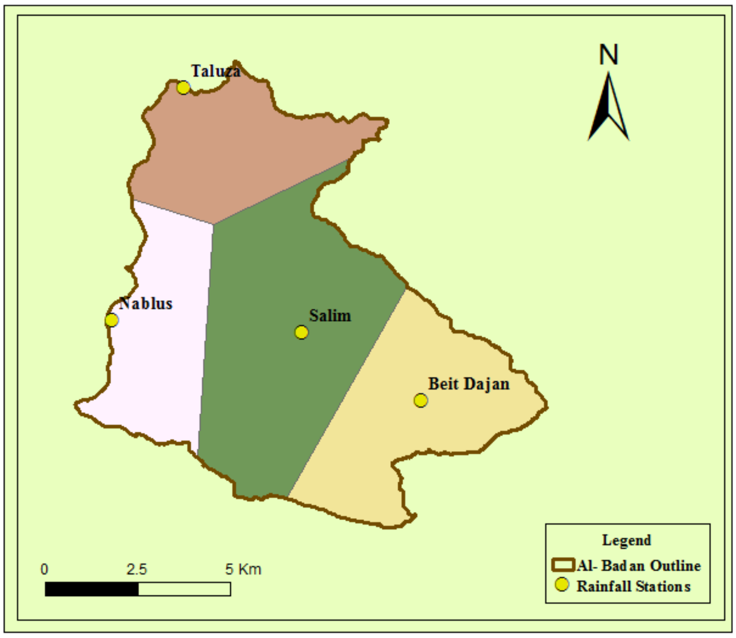
R: The total runoff depth in mm.

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

- In hydrological analysis, not all rainfall turns into direct runoff (DR) or contributes to the runoff at the catchment outlet. There is a loss of rainfall, and the amount of loss is calculated as in the previous point; therefore, to figure how much rainfall contributes to the DR, there should be an abstraction of total rainfall from the φ-index to get ER (Ramírez, 2000).

Figure 5.A

Thiessen Polygons for four Rainfall Stations in Al-Bathan Sub-Catchment in the Rainy Seasons (2005-2007)



B. Runoff Data Analysis

The rainy season (October to March) has the most rainfall in the Al-Bathan sub-catchment. As a result, surface runoff occurs during these months. From (Figure 4.B) it is clear that the (Q) in the flume varies with time, especially in response to rainstorm events.

The most significant runoff occurred in February for "Event 1" and in December, February, and February for "Events 2, 3, and 4", respectively. Runoff for Al-Bathan sub-catchment for the two seasons (2005-2007) was shown in (Figure 4.B), and some runoff characteristics for the events were mentioned in (Table 3). The natural flood image on the 9th of February 2006 was shown in (Figure 5.B).

Since one of the objectives of this research study is to determine the observed runoff in Al-Bathan sub-catchment from the measured total runoff (TR), if BF discharge could be separated from the total runoff hydrograph (TRH), a DRH would result (Shaw, 1994).

In this step of the analysis, the BF was separated from the TRH to determine the observed DRH, which allowed reading the discharge value of a specific time and calculation of the runoff depth for each event, which was then compared to the ER for the same event. (Figure 5.C to 5.F) show how the BF was separated from the TRH for each event. If the DR and ER for each event were known, the UH from complex storms could be calculated using the de-convolution matrix approach. The rainfall hyetograph, DRH, and φ-Index for the four events are presented in (Figure 5.G)

Figure 5.B

Al-Bathan Flood in 09Feb,2006

(Shadeed, 2008)

Figure 5.C

TRH and BF for Event 1

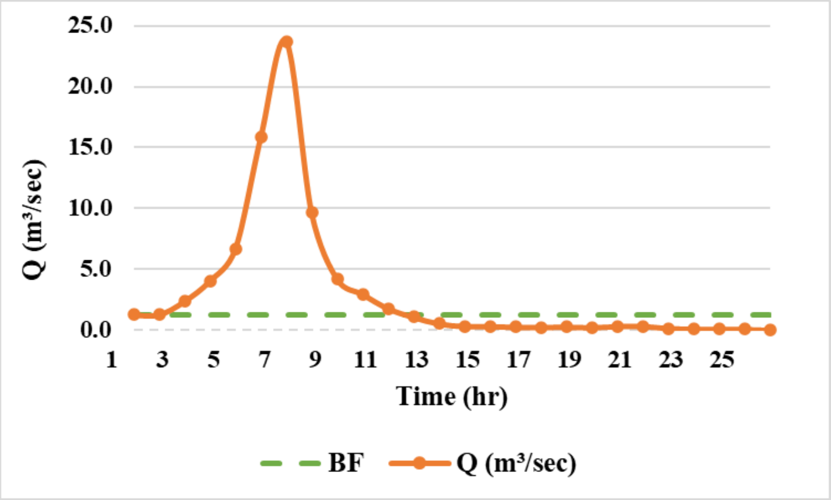


Figure 5.D

TRH and BF for Event 2

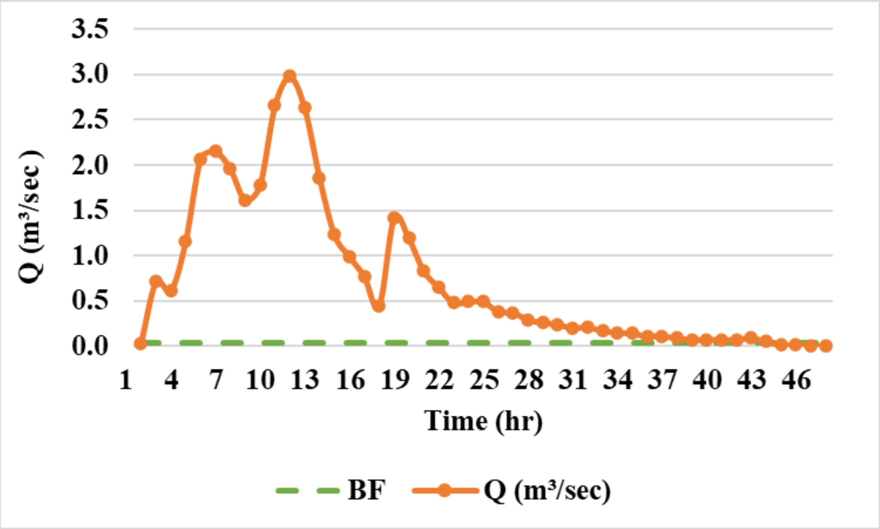


Figure 5.E

TRH and BF for Event 3

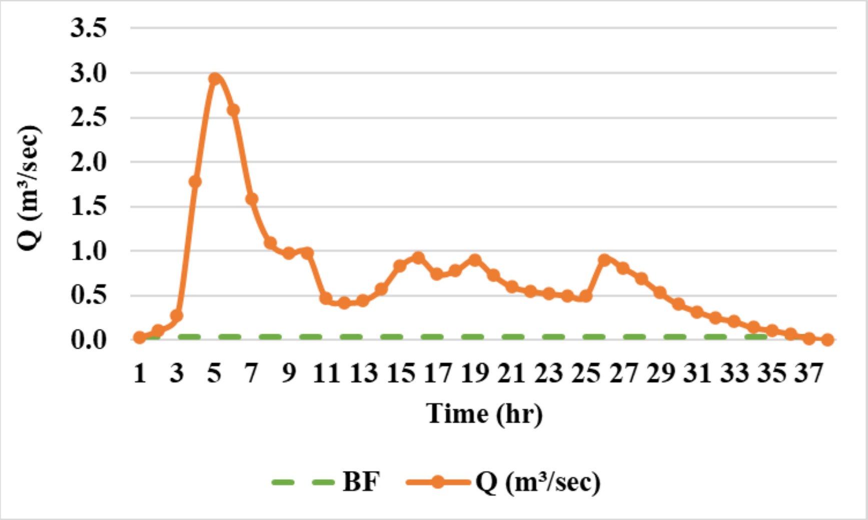


Figure 5.F

TRH and BF for Event 4

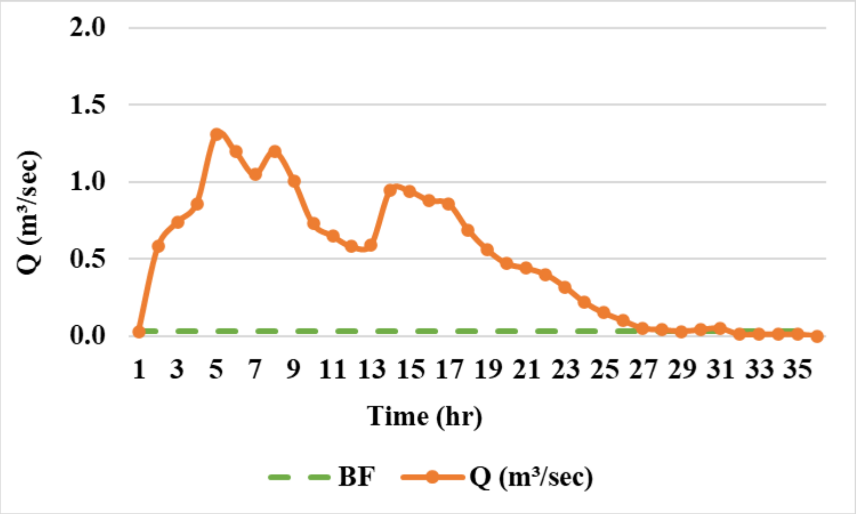
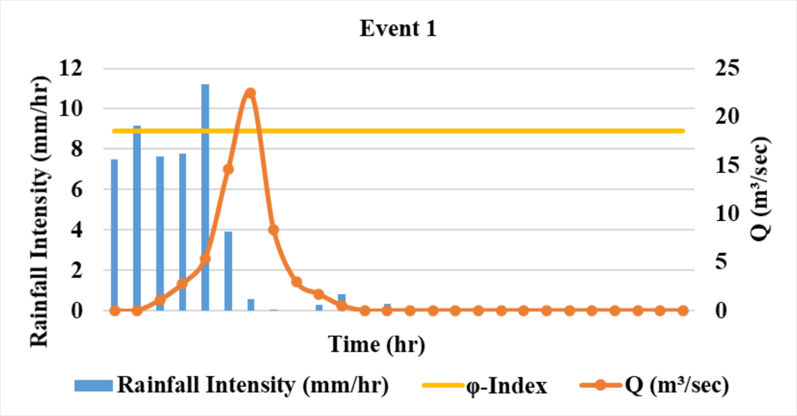
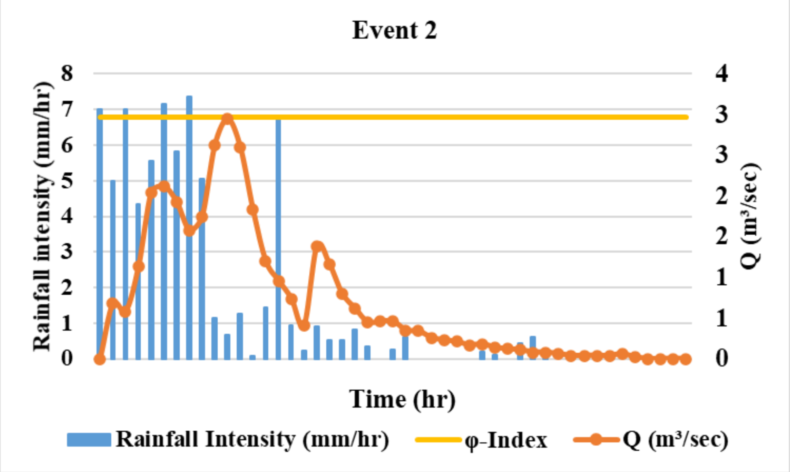
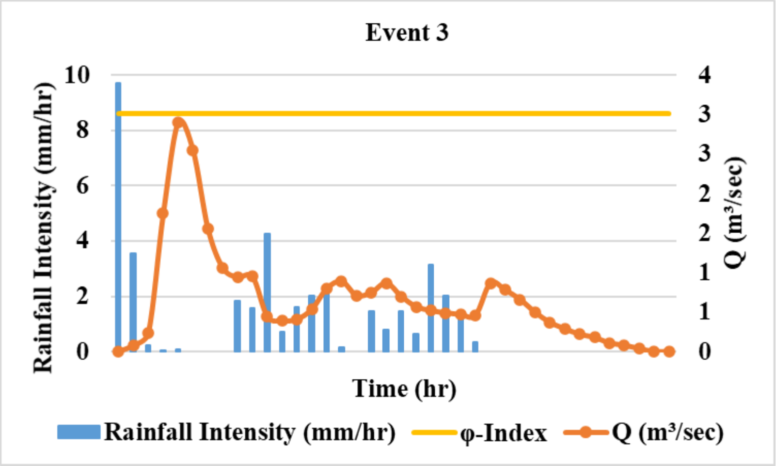


Figure 5.G

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







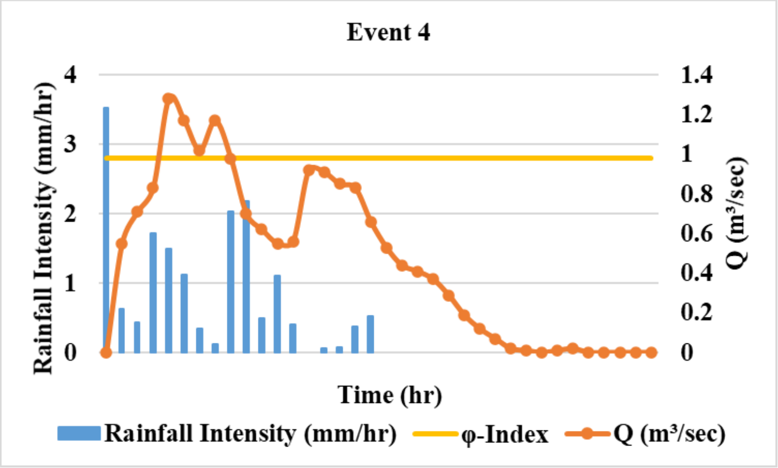


Table 3

Characteristics of the Rainfall Events [1-4] in the Rainy Seasons (2005-2007)

Parameter	Event 1	Event 2	Event 3	Event 4
Year of event	2005/2006	2006/2007	2006/2007	20067/2007
Date of occurrence	09 Feb.2006	26-28 Dec.2006	03-05 Feb.2007	06-07 Feb.2007
Amount of rainfall (mm)	50	73	40	17
φ-index (mm/hr)	8.90	6.78	8.61	2.81
Excess rainfall (mm)	2.61	1.45	1.09	0.72
Runoff depth (mm)	2.60	1.43	1.09	0.72
Runoff volume (m^3)	215,748	118,908	90,504	60,444

2.4.2 De-Convolution Approach to Derive One-Hour UH

The derivation of the one-hour UH involves many steps; the first one is specifying the DRH to determine the runoff volume, and the second was estimating the ER, which was analyzed before. Furthermore, de-convolution was used to determine the ordinates of the one-hour UH. The resulting one-hour UH should represent the one-unit depth of runoff (Chow et al., 1988; Fedorova et al., 2018).

The convolution of discrete values of UH with ER to produce the DRH is provided by the below equation. The reverse process (de-convolution) can derive a UH based on P and Q (Chow et al., 1988; Fedorova et al., 2018).

$$Q_n = \sum_{m=1}^{n \leq M} P_m U_{n-m+1} \qquad (3)$$

Where;

Q: Direct runoff in (m^3/sec).

P: Excess rainfall in (mm/hr).

U: Unit hydrograph.

m: Pulses of the unit hydrograph.

n: Pulses of the direct runoff.

M: Pulses of the excess rainfall.

This equation can be arranged in a mathematical matrix as below.

$$[P]\,[U] = [Q] \qquad (4)$$

$$\begin{bmatrix} \mathbf{P_1} & \mathbf{0} & \mathbf{0} & \cdot & \cdot & \cdot & \mathbf{0} & \mathbf{0} & \cdot & \cdot & \cdot & \mathbf{0} & \mathbf{0} \\ \mathbf{P_2} & \mathbf{P_1} & \mathbf{0} & \cdot & \cdot & \cdot & \mathbf{0} & \mathbf{0} & \cdot & \cdot & \cdot & \mathbf{0} & \mathbf{0} \\ \mathbf{P_3} & \mathbf{P_2} & \mathbf{P_1} & \cdot & \cdot & \cdot & \mathbf{0} & \mathbf{0} & \cdot & \cdot & \cdot & \mathbf{0} & \mathbf{0} \\ \cdot & & & & & & & & & & & & \cdot \\ \cdot & & & & & & & & & & & & \cdot \\ \cdot & & & & & & & & & & & & \cdot \\ \mathbf{P_M} & \mathbf{P_{M-1}} & \mathbf{P_{M-2}} & \cdot & \cdot & \cdot & \mathbf{P_1} & \mathbf{0} & \cdot & \cdot & \cdot & \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \mathbf{P_M} & \mathbf{P_{M-1}} & \cdot & \cdot & \cdot & \mathbf{P_2} & \mathbf{P_1} & \cdot & \cdot & \cdot & \mathbf{0} & \mathbf{0} \\ \cdot & & & & & & \cdot & & & & & & \\ \cdot & & & & & & \cdot & & & & & & \\ \cdot & & & & & & \cdot & & & & & & \\ \mathbf{0} & \mathbf{0} & \mathbf{0} & \cdot & \cdot & \cdot & \mathbf{0} & \mathbf{0} & \cdot & \cdot & \cdot & \mathbf{P_M} & \mathbf{P_{M-1}} \\ \mathbf{0} & \mathbf{0} & \mathbf{0} & \cdot & \cdot & \cdot & \mathbf{0} & \mathbf{0} & \cdot & \cdot & \cdot & \mathbf{0} & \mathbf{P_M} \end{bmatrix} \begin{bmatrix} \mathbf{U_1} \\ \mathbf{U_2} \\ \mathbf{U_3} \\ \cdot \\ \cdot \\ \cdot \\ \mathbf{U_{N-M+1}} \end{bmatrix} = \begin{bmatrix} \mathbf{Q_1} \\ \mathbf{Q_2} \\ \mathbf{Q_3} \\ \cdot \\ \cdot \\ \cdot \\ \mathbf{Q_M} \\ \mathbf{Q_{M+1}} \\ \cdot \\ \cdot \\ \cdot \\ \mathbf{Q_{N-1}} \\ \mathbf{Q_N} \end{bmatrix}$$

Where;

[P]: Matrix of the excess rainfall.

[U]: Matrix of the unit hydrograph.

[Q]: Matrix of the direct runoff.

In this study, the values of [P] and [Q] were known, and the [U] was determined by the following equation.

$$[U] = [P^T P]^{-1} [P^T] [Q] \qquad (5)$$

Where;

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

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

Equation (5) was used to calculate the UH ordinates for the four events. The MS-Excel UHs for four events gave a few negative ordinates, which were then adjusted until the runoff depth was 1 mm. The following steps were used to compute the average one-hour UH from the four storm events:

- Determined the peak discharge and time to the peak for each one-hour UH.
- Computed the ordinate of the average peak discharge and the average time to peak and plotted them on a graph.
- Sketched a new one-hour UH that represented a one-hour average UH and passed through the ordinate defined in the previous step.
- Determined the volume of a one-hour average UH and the depth of the runoff.
- The one-hour average UH ordinates were sketched and adjusted until it had an area of one-unit depth (mm).

2.4.3 Rainfall-Runoff Data Analysis for the Rainy Seasons 2017-2019

The data has been analyzed according to the following points:

- The (2017-2018) season consisted of an event called "Event 5", and the next one, (2018-2019), consisting of an event called "Event 6". As shown in (Table 4), the characteristics of these events were tabulated to find the relation between rainfall and runoff.
- The average rainfall depth over a study area was calculated using equation (1), which is based on the Thiessen polygon. The representative area for each rainfall gauge was computed by GIS, as tabulated in Appendix A (Tab. 8), and illustrated in (Figure 5.H).
- ER was calculated by subtracting the φ-index for each event computed using equation (2) from the total rainfall.
- For events 5 and 6, the most significant runoff occurred in February and March, respectively. Runoff for Al-Bathan sub-catchment for these seasons was shown in (Figure 5.I), and some of the runoff characteristics for these events were tabulated in (Table 6).
- The observed runoff generation in these events was measured, and this observed runoff was graphed as DRH. (Figure 5.J) depicts the rainfall hyetograph, DRH, and φ-Index for these events. The convolution method in equations 3 and 4 was used to figure out the simulated DRH, which will be discussed in chapter 3.

Table 4

Characteristics of the Rainfall Events [5 and 6] in the Rainy Seasons (2017-2019)

Parameter	Event 5	Event 6
Year of event	2017/2018	2018/2019
Date of occurrence	17-18 Feb.2018	15-17 Mar.2019
Amount of rainfall (mm)	43	13
φ-index (mm/hr)	6.06	1.97
Excess rainfall (mm)	1.31	2.18
Runoff depth (mm)	1.31	2.18
Runoff volume (m^3)	109,058	180,693

Figure 5.H

Thiessen Polygons for Rainfall Stations in Al-Bathan Sub-Catchment for the rainy seasons (2017-2019)

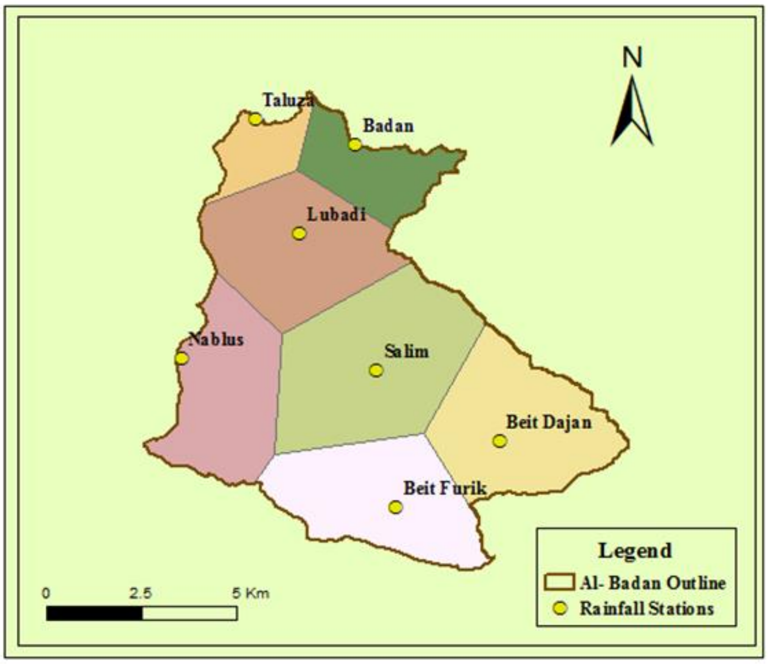


Figure 5.I

Runoff of Al-Bathan Sub-Catchment for the Two Rainy Seasons (2017-2019)

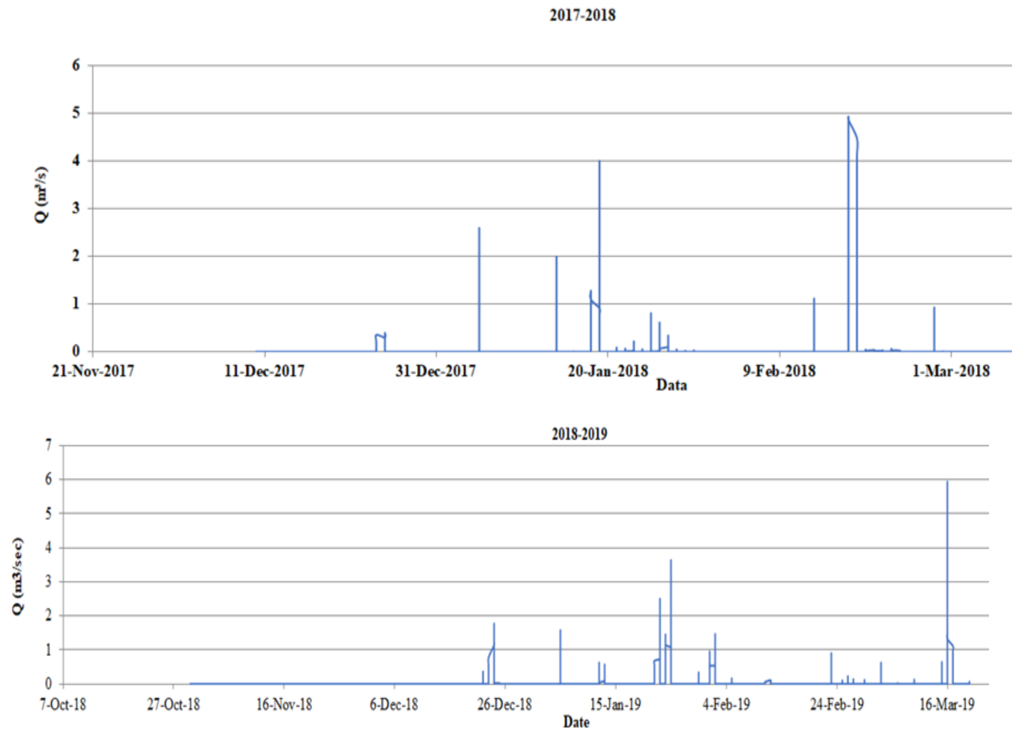
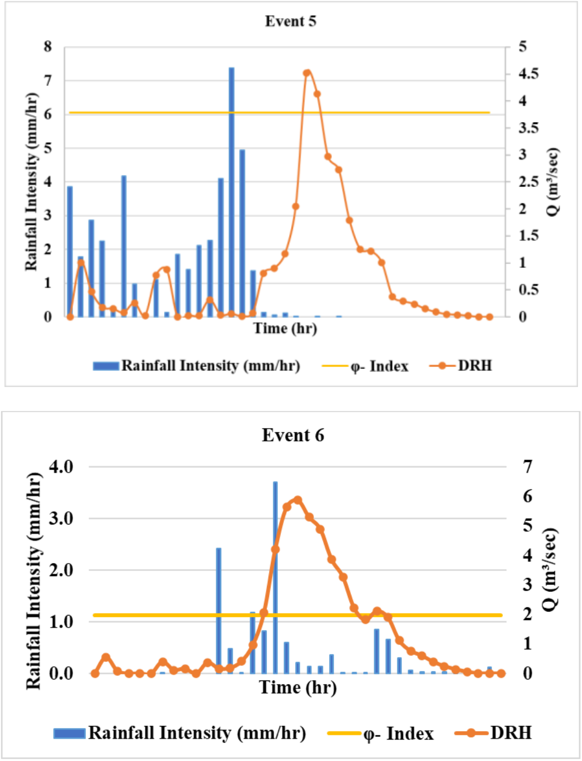


Figure 5.J

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



2.4.4 Snyder and SCS Methods

C. A. Snyder Method

The first empirical relationships between catchment characteristics such as A, L, and L_{ca}, as reported in Section 2.3.3, was developed by Snyder (1938) to compute the characteristics and parameters required for establishing SUH.

Snyder came up with an empirical equation for the basin lag time (t_P) in hours (hr), where (t_p) was defined as the time between the mass center of ER and the DRH discharge peak. Physically, it indicated the average time it took for the water to move from all parts of the catchment to the outlet during a storm (Adeyi et al., 2020; Anupam, 2015; Fang et al., 2005; Hettiarachchi, 2022; Salami et al., 2009; Wałęga, 2016):

$$t_p = 0.75\ C_t\ (L\ L_{ca})^{0.3} \tag{6}$$

Where;

t_p: Lag time in hr.

L: Length of the mainstream of the catchment in km.

L_{ca}: The distance from the outlet to the point on the mainstream which is nearest to the centroid of catchment in km.

C_t: Non-dimensional regional constant representing catchment storage effects and slope.

The coefficient (C_t) values differ according to the nature of the catchment. For example, some references discussed the coefficient between the values of 1.8 to 2.2 (Ilic et al., 2018), while others addressed the coefficient between the values of 1.35 to 1.65 or ranging from 0.3 to 6.0 (Chow et al., 1988), and several references discussed the coefficient between the range 1.0 to 4.33 (Bhunya et al., 2011). Furthermore, few references considered coefficient values from 1.2 to 2.2 (Kilgore, 1997).

The standard peak discharge (Q_{ps}) is the highest measured volume of runoff over the catchment; it is a function of hydrograph time relation parameters (Adeyi et al., 2020; Anupam, 2015; Fang et al., 2005; Hettiarachchi, 2022; Salami et al., 2009; Wałęga, 2016). It is expressed as:

$$Q_{Ps} = \frac{2.78\ Cp\ A}{tp} \qquad (7)$$

Where;

Q_{ps}: Standard peak discharge in m^3/sec for 1 cm of ER depth.

A: Area of the catchment in km^2.

C_p: Peaking coefficient, which depends on the storage capacity of the catchment.

The coefficient C_p differs from one reference to another; one reference relies on a range of 0.56 to 0.69 (Singh et al., 2014)), another accepts a range of 0.3 to 0.93 (Adeyi et al., 2020), and another discusses a range between 0.31 to 1.22 (Bhunya et al., 2011).

The standard SUH has a 5.5 ratio between the t_p and standard duration of ER, t_r in hours Assume t_r differs significantly from the duration of desired UH (nonstandard rainfall duration), t_R in hr in this case, the t_p is affected and can be modified by doing the following (Adeyi et al., 2020; Anupam, 2015; Fang et al., 2005; Hettiarachchi, 2022; Salami et al., 2009; Wałęga, 2016):

$$t_p' = t_P + 0.25\ (t_R - t_r) \qquad (8)$$

$$t_p' = \frac{21}{22}\ tp + \frac{t_R}{4} \qquad (9)$$

Where;

t_p': Modified of lag time in hr.

Therefore, the following provides Q_p for durations other than the standard duration (Adeyi et al., 2020; Anupam, 2015; Fang et al., 2005; Hettiarachchi, 2022; Salami et al., 2009; Wałęga, 2016):

$$Q_p = \frac{2.78\ Cp\ A}{tp'} \qquad (10)$$

Where;

Q_p: Peak discharge in m^3/sec for 1 cm of ER depth.

The time to peak in hours (T_P) of SUH can be calculated as:

$T_P = \frac{tR}{2} + t_p'$ (11)

The below relation estimates (T_b) in hours:

$T_b = 72 + 3\ t_p'$ (12)

The values of $\frac{Tb}{Tp}$ <= 5, if larger then it is recommended $T_b = 5\ T_P$.

Through the three well-known characteristic points of the UH (e.g., T_p, Q_p, and T_b), with their own criteria, one can draw various UHs, but to help define the shape of the UHs and make them clear, two additional characteristics relate to the width of the UH at 50% *(W_{50})* and 75% (W_{75}) of Q_p, the widths measured in hours (Adeyi et al., 2020; Anupam, 2015; Fang et al., 2005; Hettiarachchi, 2022; Salami et al., 2009; Wałęga, 2016):

$W_{\%} = C_w\ (\frac{QP}{A})^{-1.08}$ (13)

Where;

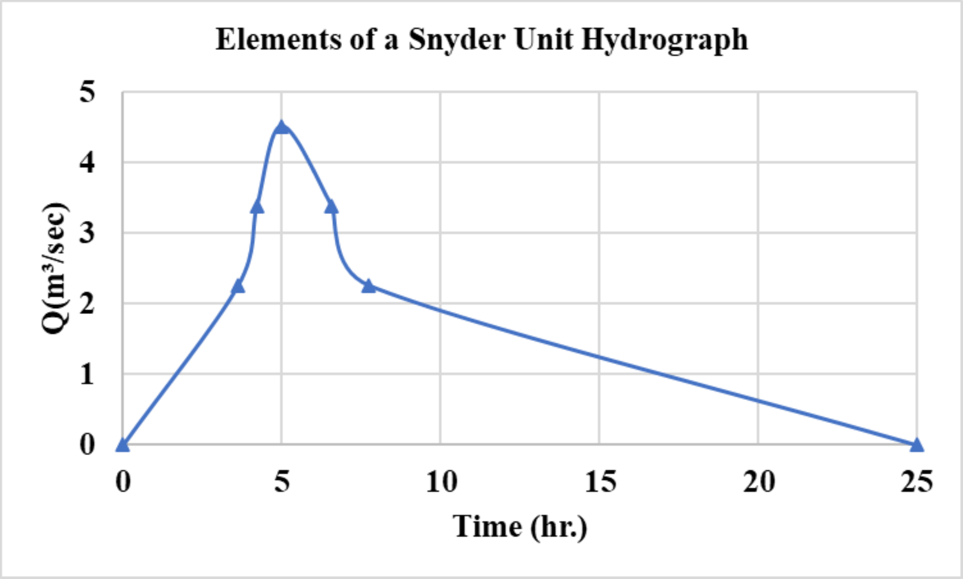
$W_{\%}$: Widths of UH at a certain percent of Q_P in hours.

C_w: Constant of widths at 50% and 75% equals 2.14 and 1.22, respectively.

The elements of a Snyder for Al-Bathan sub-catchment were illustrated in (Figure 6.A).

Figure 6.A

Elements of a Snyder Unit Hydrograph for Al-Bathan Sub-Catchment



D. B. SCS Method

The SCS method's fundamental steps for developing the UH can be summarized as follows:

- Determined the physical characteristics of Al-Bathan sub-catchment, as mentioned in Section 2.3.3.
- Kirpich equation was used to calculate the time of concentration (t_c) in minutes, as (Fang et al., 2005):

$$t_c = 0.01947\ L^{0.77}\ s^{-0.385} \tag{14}$$

Where;
L: Length of channel or ditch from headwater to outlet in m.
s: Average catchment slope in m\m was calculated from the elevation difference along the flow path to a maximum flow length.

- T_p and t_p in hours can be calculated using the following equations (Safarina Ariani Budi et al., 2011; Wahab Salami et al., 2009):

$$T_p = \frac{tr}{2} + t_p \tag{15}$$

$$t_p = 0.6\ t_c \tag{16}$$

- In a typical SCS dimensionless UH (SCS triangular UH), 37.5% of the total runoff volume is expected to occur before Q_p; in this case:

$$T_b = 2.67\ T_p \tag{17}$$

And since the volume under the UH is equal to the catchment area times a unit depth, the (Q_p) in m^3/sec for a 1 cm of ER depth (Bhunya et al., 2011; Safarina Ariani Budi et al., 2011; Wahab Salami et al., 2009):

$$Q_p = 2.08\ \frac{A}{Tp} \tag{18}$$

As mentioned in equation 18, the expression using factor 2.08 only applies if the SCS triangular UH has a particular geometry, that is, with 37.5% of its volume in the rising limb. These typical or standard parameters (C_p = 2.08 and C = 2.67) are not one-sizefits-all catchments. As a result, depending on the location and geography of the catchment, the parameters may need to be adjusted while still maintaining the one-unit depth under the UH.

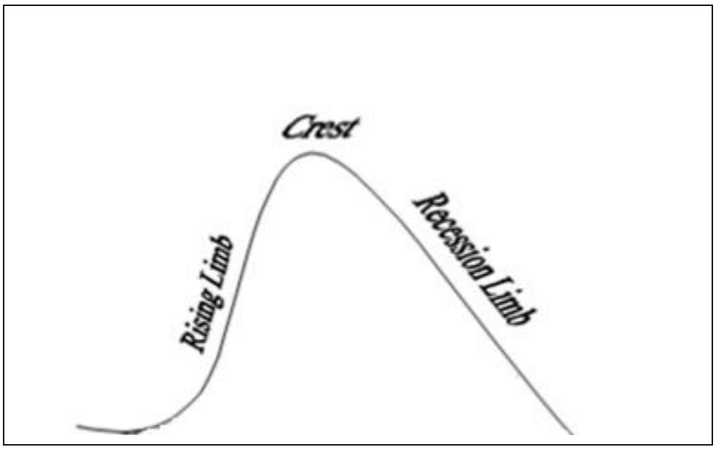
In this study, one-hour SCS-UH accounts for 34% of total runoff volume under the rising limbs, with the remaining volume accounting for 66%. The rising limb is depicted in (Figure 6.B). Assuming the same 34% of the volume on the left of T_p for triangular SCS-UH, could estimate the T_b and then estimate the C coefficient concurrently with it. The curvilinear and equivalent triangular dimensionless runoff hydrograph is shown (Figure 6.C).

By using the equations of (T_b) and (Q_p), and depending on the area under the SCS triangular UH that is equivalent to a one-unit depth and also equal to one-half the base of triangular (CT_P) multiplied by the height of it (Q_p), the C_p coefficient could be estimated.

(Tab. 9) in Appendix A shows the coordinates of the SCS dimensionless UH that can be used to build Al-Bathan one-hour.

Figure 6.B

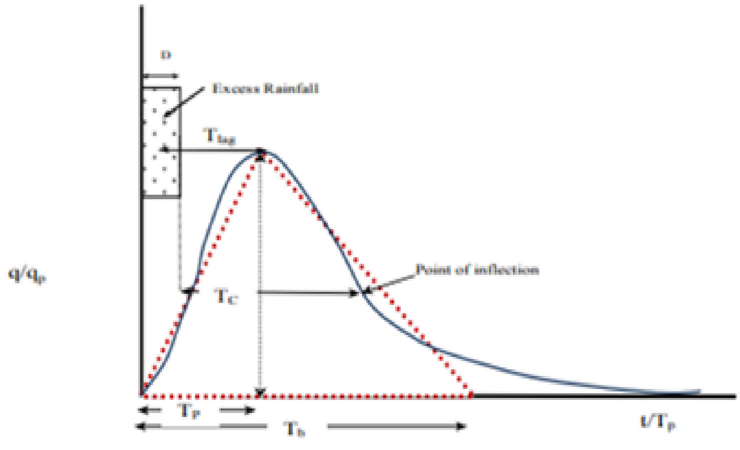
Schematic the Essential Components of a Hydrograph



(Adeyi et al., 2020)

Figure 6.C

Curvilinear and the Equivalent Triangular SCS-UH Dimensionless Runoff Hydrograph



Chapter Three

Results

3.1 Derivation of One-Hour Average Unit Hydrograph

After analyzing rainfall and runoff data as described in Section 2.4.2, the one-hour UH for "Events 1–4" in the rainy seasons (2005–2007) is depicted in (Figure 7.A). In addition, the UH ordinates from Q_p and T_p were estimated for each storm, as shown in (Table 5).

Table 5

Peak Discharges and Time to the Peaks for Events [1-4]in the rainy Seasons (2005-2007)

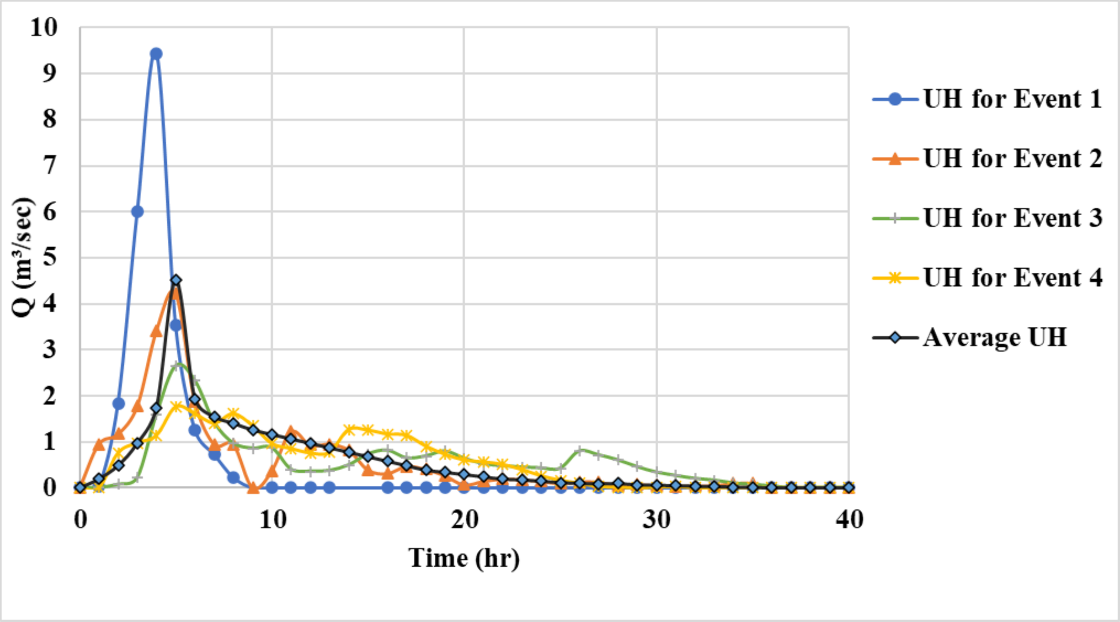
Parameter	UH Event 1	UH Event 2	UH Event 3	UH Event 4
T_p (hr)	4	5	5	5
Q_p (m^3/sec)	9.44	4.23	2.66	1.76

Furthermore, through the characteristics of the four one-hour UHs, the one-hour average UH was derived as described in the points in Section 2.4.2, and the one-hour average UH was plotted with the four one-hour UHs on a single graph (Figure 7.A). Analyzing the sketched ordinates shows that all one-hour UHs are different in Qp, Tp, and Tb.

As a result of these one-hour UHs, the one-hour average UH had a one-unit depth of mm, a Q_p of 4.52 m^3/sec, a T_p at 5 hours, and a T_b of 40 hours.

Figure 7.A

One-hour Unit Hydrographs and Average Unit Hydrographs for Al-Bathan Sub-Catchment



The one-hour average UH was used to determine the simulated (obtained) DRH and compare it with the observed DRH for "Events 1-4". 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 this average UH (Chea & Oeurng, 2017; Ilic et al., 2018).

The VE is defined as:

$$VE = \left(\frac{\sum_i^n (Qsi\text{-}Qoi)}{\sum_i^n Qoi}\right) \tag{19}$$

The PBIAS is defined as:

$$PBIAS = \frac{\sum_i^n Qoi\text{-}\sum_i^n Qsi}{\sum_i^n Qoi} \text{ x } 100 \tag{20}$$

The EFC equation:

$$EFC = 1 - \left(\frac{\sum_i^n (Qoi\text{-}Qsi)^2}{\sum_i^n (Qoi\text{-}\bar{Q}o)^2}\right) \tag{21}$$

The R^2 equation:

$$R^2 = 1- \left(\frac{\sum_i^n (Qoi\text{-}Q\hat{})^2}{\sum_i^n (Qoi\text{-}\bar{Q}o)^2}\right) \qquad (22)$$

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 step.

If the value of VE is close to zero $(\mp)$, good performance is attained; moreover, the value of (%) PBIAS indicates very good performance at $(\leq \mp 15)$, satisfactory performance at $(\mp 15 < X < \mp 25)$. and unsatisfactory performance at $(\geq \mp 25)$(Chea & Oeurng, 2017; Ilic et al., 2018).

The EFC is a dimensionless transformation of the sum of squared errors. And R^2 is the covariance, and the multiplied standard derivation of the observed and predicted values are expressed as a square ratio. As a result, it compares the single dispersion of the observed and predicted series to the combined dispersion (Chicco et al., 2021). Both have become one of the most commonly used goodness-of-fit measures for assessing rainfall-runoff performance (Shadeed, 2008).

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 (Xiaohui Zhong & Utpal Dutta, 2015).

Possible values of R^2 are between from 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 (Dufour, 2011).

Table 6

Performance Coefficients of Events [1-4] for Observed and Average-Simulated DRHs

Events	EFC	VE	PBIAS (%)	R^2
Event 1	0.50	-0.04	4	0.70
Event 2	0.66	0.01	1	0.87
Event 3	0.55	0	0.03	0.70
Event 4	0.60	0.01	1	0.68

3.2 Derivation of Synthetic Unit Hydrographs

Based on analyzing Section 2.4.4, two one-hour SUH graphs were derived for Al-Bathan sub-catchment. (Figures 3.B and 3.C) illustrate the one-hour Snyder UH and one-hour SCS-UH, and by using them, could derive one-hour SUHs for any rainfall storm. And also, one-hour SUHs could be used for Al-Bathan sub-catchment to develop SUHs at different durations by using two methods (superposition and S-curve) (Adeyi et al., 2020; Fang et al., 2005). The ordinates of one- hour Snyder UH and one-hour SCS-UH were tabulated in Appendix A (Tab. 10 and 11).

Figure 7.B

One-Hour Snyder Hydrograph for Al-Bathan Sub-Catchment

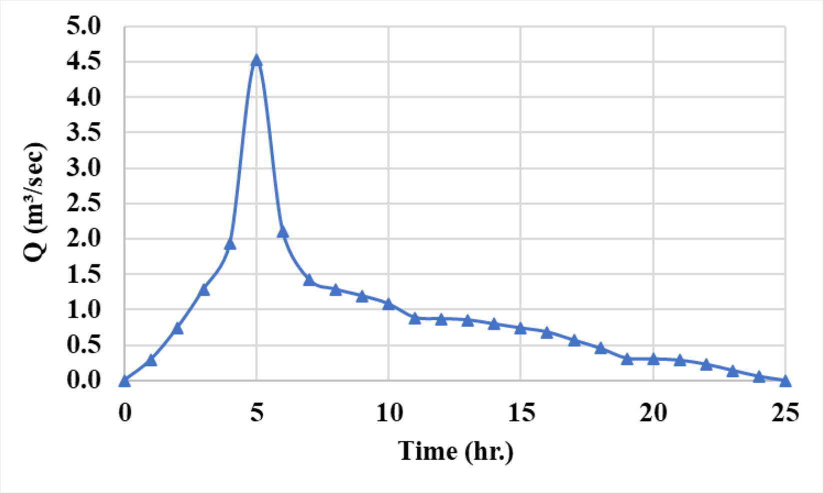
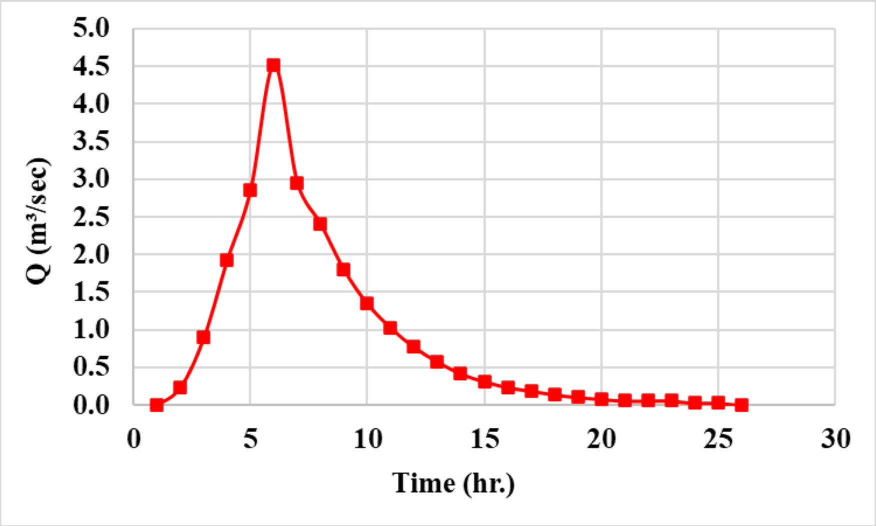


Figure 7.C

One-Hour Soil Conservation Service Unit Hydrograph for Al-Bathan Sub-Catchment



3.3 Synthetic Unit Hydrographs Parameters Estimations

Based on the characteristics of the one-hour average UH and by using the equations mentioned in 2.4.4 that relate to the derivation of one-hour Snyder and one-hour SCS SUHs for Al-Bathan sub-catchment, the parameters derived that relate to Q_p and T_p in both SHUs are determined to suit Al-Bathan 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.

3.4 Verification of the Simulated Results

The one-hour average UH was used to obtain DRH for both "Event 5" and "Event 6" through the convolution method discussed in Section 2.4.3. The observed and average-simulated DRHs are shown in (Figure 7.D).

The parameters of Q_p and T_p and runoff volume of observed and average-simulated DRHs for "Events 5 and 6" were compared and shown in (Table 7).

Table 7

Peak Discharges and Time to Peaks of Observed and Average-Simulated Direct Runoff Hydrograph for Events [5-6]

Parameter	Observed DRH	Average-Simulated DRH	Observed DRH	Average-Simulated DRH
	Event 5		Event 6	
T_p (hr)	6	5	10	10
Q_p (m^3/sec)	4.52	5.92	5.89	8.32
Runoff Volume (m^3)	93,168	106,128	173,916	172,260

As shown in (Table 7), the T_p was close to or the same in the same event storm, but the Q_p also differed in the same event storm. In general, as ER increases, so does Q_p (Shadeed et al., 2007). In addition, this difference is natural because it resulted from complex mathematical calculations (For example, it assumed the φ-Index losses for events might not equal the actual losses) and is also attributed to the average UH resulting from one extreme storm whose characteristics differ from those of the other storms. However, it is also possible that the recorded observed DR contains an error or that part of the runoff did not pass through the flume, which would constitute an error in the recording the streamflow values. The performance measurements of "Events 5 and 6" were tabulated in (Table 8).

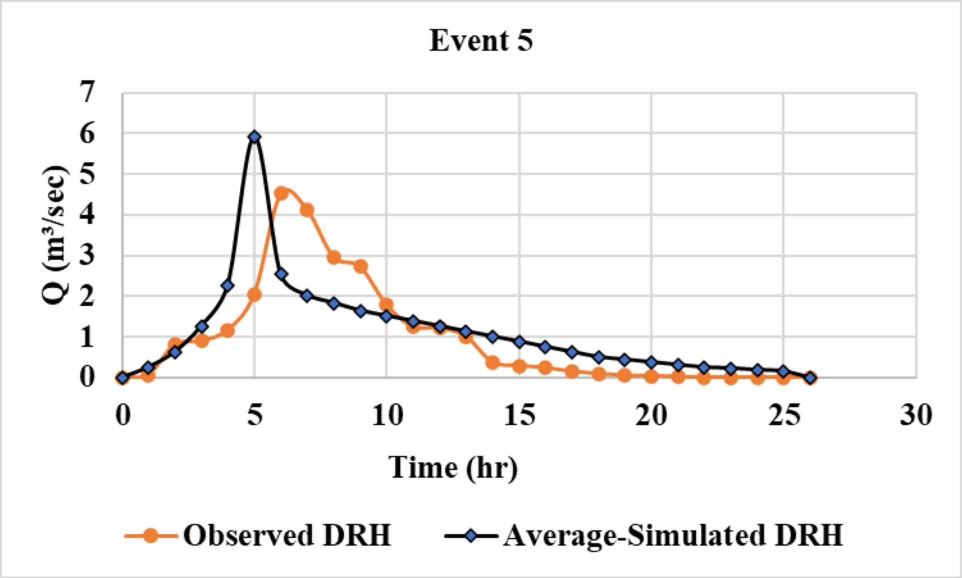
Table 8

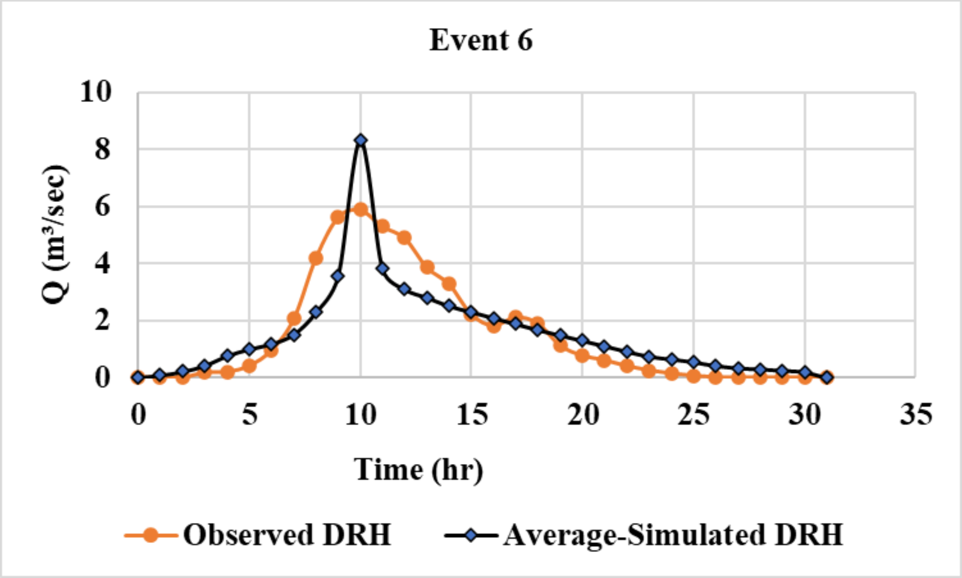
Performance Coefficients of Events [5 and 6] for Observed and Average-Simulated DRHs

Events	EFC	VE	PBIAS (%)	R^2
Event 5	0.33	0.14	-14	0.65
Event 6	0.78	-0.01	1	0.68

Figure 7.D

Observed and Average-Simulated DRHs for Events [5 and 6]





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-Bathan 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 (Table 9). Furthermore, the performance measurements for both events were tabulated in (Table 10) in addition to the illustration of the DRHs for both compared with the observed DRH for each event in (Figure 7.E).

Table 9

Peak Discharges and Time to Peaks of Observed, Snyder and SCS-Simulated Direct Runoff Hydrograph for Events [5-6]

Parameter	Observed DRH	Snyder-Simulated DRH	SCS-Simulated DRH	Observed DRH	Snyder-Simulated DRH	SCS-Simulated DRH
	Event 5			Event 6		
T_p (hr)	6	5	5	10	10	10
Q_p (m^3/sec)	4.52	5.92	5.92	5.89	8.30	8.28
Runoff volume (m^3)	93,168	108,756	108,720	173,916	177,696	178,344

Table 10

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

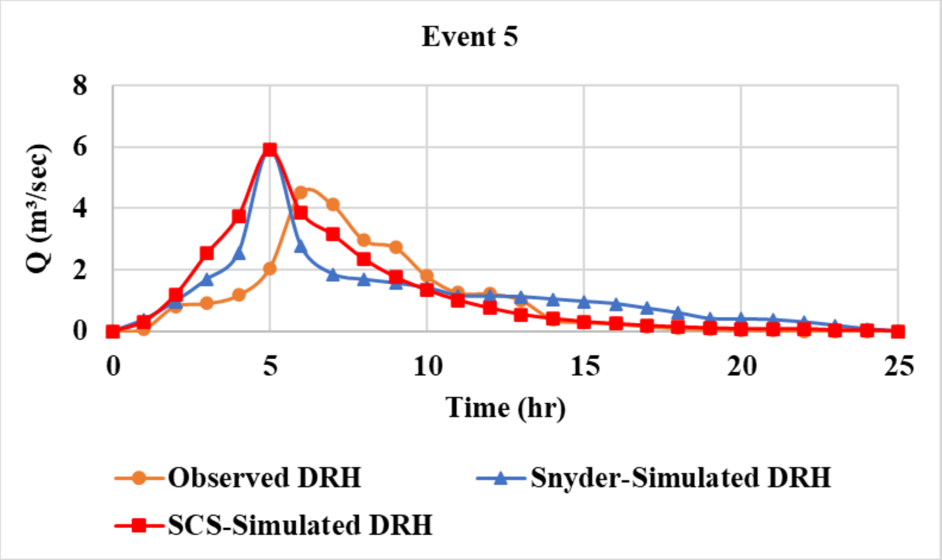
Events	Snyder				SCS			
	EFC	VE	PBIAS (%)	R^2	EFC	VE	PBIAS (%)	R^2
Event 5	0.26	0.16	-16.7	0.67	0.35	0.16	-16.6	0.84
Event 6	0.79	0.02	-2.17	0.69	0.87	0.02	-2.15	0.88

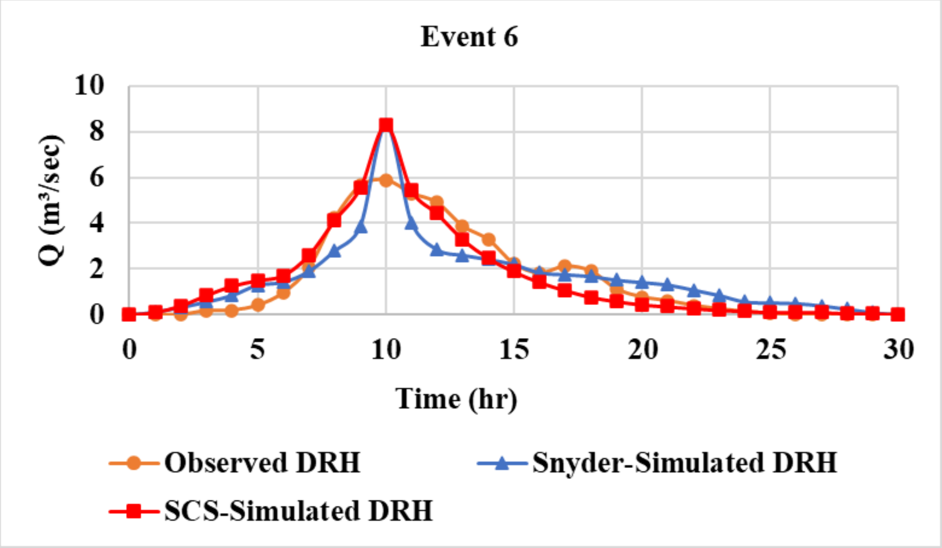
Through (Table 9), notice that the parameters Q_p and T_p in both methods were the same for each event. Furthermore, the performance measurement results for both "Event 5" and "Event 6" were acceptable and within the percent error range.

The performance of the SCS method was more accurate than Snyder in the same event, indicating that the SCS method is more acceptable and precise when used to predict the runoff volume in the catchment, and also that the performance of "Event 6" is higher than "Event 5", indicating that we need and require more rainfall storms to develop a one-hour average UH to be situatable for any events that have different characteristics than others.

Figure 7.E

Observed, Snyder and SCS Simulated DRHs for Events [5 and 6]





Chapter Four

Conclusions, Limitations and Recommendations

4.1 Conclusions

Al-Bathan sub-catchment is located in the northeastern part of the West Bank in Palestine and has an area of about 83 km^2, as well as it has some physical characteristics such as the length of the mainstream at 19 km with a slope of 4%.

Runoff estimation in an ungauged catchment is one of the most challenging tasks in surface water hydrology. Therefore, this research aims to parameterize the SUHs and obtain the DRHs for known rainfall storms based on rainfall and runoff analysis.

A one-hour average UH was calculated using rainfall and runoff data from selected rain storm events between (2005-2007). The two essential characteristics of the average UH of Al-Bathan 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 UH is a simple linear method that can help derive a DRH from an ER hyetograph.

The theory of UH for gauged catchments can be extended to predict hydrological systems in ungauged catchments based on physical characteristics by using SUH, especially Snyder and SCS methods.

The Snyder UH derived for Al-Bathan 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 [0.3-6.0], 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.

In this study, two events, "Event 5" and "Event 6 " in [2017-2018] and [2018-2019], respectively, were examined, and Q_p and T_p were simulated for both. The simulated results were then compared to the observed value. The statistical analysis mentions to the SCS method as more effective and accurate in the same event; the R^2 in "Event 5" reaches 0.84, and in "Event 6" reaches 0.88.

This study helps manage water resources, which is a complex issue with outstanding challenges, and also helps design suitable hydraulic structures.

4.2 Limitations

- There are limitations to sources of information, and they are not always available.
- Rainfall and runoff record values are not available for several years.
- The observed measurement of runoff is not always accurate.
- Some of UH theory’s restrictive such as do not apply to the study area, affecting the result.
- The estimated losses (φ-Index) do not represent the exact actual hydrological losses.

4.3 Recommendations

Based on the finding of this work, the following points can be recommended for future research in the field of rainfall-runoff analysis hydrology in Al-Bathan sub-catchment:

- Apply the simulated results of this study in similar hydrological and meteorological catchments, this in turn will enhance the proper design of hydraulic structures.
- Maintain the Parshall flume and TBRs in Al-Bathan sub-catchment to continue collecting more rainfall and runoff data for further improvement of the simulated results.
- Once more rainfall and runoff data are being collected, it is recommended to classify the rainstorm events based on their durations and intensities to develop different average UHs (1 hr, 2 hr, etc.).
- Install proper devices that are required to estimate the hydrological abstractions (evaporation, infiltration, etc.) to accurately estimate excess rainfall from gross rainfall.

List of Abbreviations

Abbreviation	Meaning
$[P]$	Matrix of the excess rainfall
$[P^T]$	Transpose matrix of the excess rainfall
$[P^TP]^{-1}$	Inverse matrix of the transpose matrix of the excess rainfall multiplied by matrix of the excess rainfall
$[Q]$	Matrix of the direct runoff
$[U]$	Matrix of the unit hydrograph
BF	Base Flow
C_p	Peaking coefficient depending on the storage capacity of the catchment
C_t	Non-dimensional regional coefficient representing catchment storage effects and slope
C_w	Constant of widths
DR	Direct Runoff
DRH	Direct Runoff Hydrograph
ER	Excess rainfall or Effective rainfall
GIS	Geographic Information System
HEC-HMS	Hydrologic Engineering Center-Hydrologic Modeling System
i	The time step
IDF	Intensity Duration Frequency
KW-GIUH	Kinematic Wave based Geomorphological Instantaneous Unit Hydrograph
L	Length of main stream of the catchment
L_{ca}	The distance from the outlet to the point on the main stream which is nearest to the centroid of catchment
m	Pluses of unit hydrograph
M	Pulses of the excess rainfall
n	Pulses of the direct runoff
NRCS	Natural Resources Conservation Service
P	The total rainfall depth
PBIAS	Percentage of Bias
Q	Discharge
Q_{oi}	The observed runoff

Q_p	Peak discharge or peak flow
Q_{ps}	Standard peak discharge
Q_{si}	The simulated or simulated runoff
R	The total runoff depth
R^2	Coefficient of determination (square ratio)
s	Slope of the catchment
SCS	Soil conservation services
SUH	Synthetic unit hydrograph
T_b	Time Base
TBR	Tipping Bucket Rain Gauges
t_c	Time of concentration
T_P	Time to Peak
t_p	Lag Time
$t_{p'}$	Modify of lag time
TR	Total Runoff
t_r	Standard duration of excess rainfall
t_R	Duration of desired UH
TRH	Total Runoff Hydrograph
UH	Unit hydrograph
USA	United State of America
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 depth of the rainfall equals the depth of the runoff

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Appendices

Appendix A

Tables

Table A. 1

Rainfall Data of Event 1 in the Rainy Seasons2005-2006

Time (hr)	*Stations*				*Time (hr)*	*Stations*				*Time (hr)*	*Stations*			
	Nablus	*Taluza*	*Bait Dajan*	*Salim*		*Nablus*	*Taluza*	*Bait Dajan*	*Salim*		*Nablus*	*Taluza*	*Bait Dajan*	*Salim*
1	*0.00*	*0.00*	*0.00*	*0.00*	*12*	*0.00*	*0.00*	*0.00*	*0.00*	*23*	*2.34*	*2.40*	*1.38*	*3.00*
2	*0.00*	*0.00*	*0.00*	*0.00*	*13*	*0.00*	*0.00*	*0.00*	*0.00*	*24*	*9.86*	*13.20*	*5.82*	*4.60*
3	*0.00*	*0.00*	*0.00*	*0.00*	*14*	*0.00*	*0.00*	*0.00*	*0.00*	*25*	*8.17*	*9.60*	*4.82*	*7.20*
4	*0.00*	*0.00*	*0.00*	*0.00*	*15*	*0.00*	*0.00*	*0.00*	*0.00*	*26*	*0.60*	*0.80*	*0.35*	*0.60*
5	*0.00*	*0.00*	*0.00*	*0.00*	*16*	*0.00*	*0.00*	*0.00*	*0.00*	*27*	*0.16*	*0.20*	*0.09*	*0.40*
6	*0.00*	*0.00*	*0.00*	*0.00*	*17*	*0.00*	*0.00*	*0.00*	*0.00*	*28*	*0.32*	*0.60*	*0.19*	*0.60*
7	*0.00*	*0.00*	*0.00*	*0.00*	*18*	*0.00*	*0.00*	*0.00*	*0.00*	*29*	*0.67*	*1.20*	*0.39*	*0.40*
8	*0.00*	*0.00*	*0.00*	*0.00*	*19*	*0.00*	*0.00*	*0.00*	*0.00*	*30*	*7.35*	*7.80*	*4.33*	*4.60*
9	*0.00*	*0.00*	*0.00*	*0.00*	*20*	*0.00*	*0.00*	*0.00*	*0.00*	*31*	*0.81*	*0.20*	*0.48*	*2.80*

10	*0.05*	*0.20*	*0.03*	*0.00*	*21*	*2.35*	*1.20*	*1.39*	*1.00*	*32*	*1.71*	*2.20*	*1.01*	*3.00*
11	*0.00*	*0.00*	*0.00*	*0.00*	*22*	*8.64*	*8.60*	*5.10*	*5.40*	*33*	*4.76*	*7.80*	*2.81*	*3.20*
Time	*Stations*				*Time*	*Stations*				*Time*	*Stations*			
(hr)	*Nablus*	*Taluza*	*Bait Dajan*	*Salim*	*(hr)*	*Nablus*	*Taluza*	*Bait Dajan*	*Salim*	*(hr)*	*Nablus*	*Taluza*	*Bait Dajan*	*Salim*
34	*3.11*	*3.20*	*1.83*	*2.60*	*43*	*0.15*	*0.00*	*0.09*	*0.00*	*52*	*0.00*	*0.00*	*0.00*	*0.00*
35	*4.16*	*2.80*	*2.45*	*2.20*	*44*	*0.00*	*0.00*	*0.00*	*0.00*	*53*	*0.11*	*0.00*	*0.06*	*0.40*
36	*7.48*	*9.60*	*4.41*	*8.20*	*45*	*0.67*	*0.20*	*0.40*	*0.00*	*54*	*0.00*	*0.00*	*0.00*	*0.00*
37	*11.02*	*12.80*	*6.50*	*7.20*	*46*	*1.07*	*1.60*	*0.63*	*0.20*	*55*	*0.00*	*0.00*	*0.00*	*0.00*
38	*7.95*	*10.00*	*4.69*	*7.80*	*47*	*0.20*	*0.00*	*0.12*	*0.00*	*56*	*0.00*	*0.00*	*0.00*	*0.00*
39	*9.82*	*12.80*	*5.79*	*4.20*	*48*	*0.22*	*0.00*	*0.13*	*0.80*	*57*	*0.00*	*0.00*	*0.00*	*0.00*
40	*11.08*	*10.40*	*6.54*	*15.00*	*49*	*0.15*	*0.00*	*0.09*	*0.00*	*58*	*0.00*	*0.00*	*0.00*	*0.00*
41	*3.52*	*2.80*	*2.08*	*6.20*	*50*	*0.00*	*0.00*	*0.00*	*0.00*	*59*	*0.00*	*0.00*	*0.00*	*0.00*
42	*1.49*	*0.20*	*0.88*	*0.00*	*51*	*0.00*	*0.00*	*0.00*	*0.00*	*60*	*0.00*	*0.00*	*0.00*	*0.00*

Table A. 2

Rainfall Data of Event 2 in the Rainy Season 2006-2007

Time (hr)	*Stations*				*Time (hr)*	*Stations*				*Time (hr)*	*Stations*			
	Nablus	*Taluza*	*Bait Dajan*	*Salim*		*Nablus*	*Taluza*	*Bait Dajan*	*Salim*		*Nablus*	*Taluza*	*Bait Dajan*	*Salim*
1	*0.00*	*0.00*	*0.00*	*0.00*	*12*	*1.95*	*1.40*	*1.15*	*2.80*	*23*	*1.37*	*1.40*	*0.81*	*1.00*
2	*0.00*	*0.00*	*0.00*	*0.00*	*13*	*4.24*	*2.20*	*2.50*	*2.00*	*24*	*1.01*	*1.40*	*0.60*	*0.00*
3	*0.00*	*0.00*	*0.00*	*0.00*	*14*	*8.30*	*6.20*	*4.90*	*8.00*	*25*	*1.74*	*1.00*	*1.03*	*1.20*
4	*0.00*	*0.00*	*0.00*	*0.00*	*15*	*5.54*	*4.00*	*3.27*	*6.40*	*26*	*0.05*	*0.00*	*0.03*	*0.20*
5	*0.00*	*0.00*	*0.00*	*0.00*	*16*	*8.70*	*8.20*	*5.14*	*6.20*	*27*	*2.11*	*1.80*	*1.24*	*0.80*
6	*0.00*	*0.00*	*0.00*	*0.00*	*17*	*5.10*	*4.80*	*3.01*	*4.40*	*28*	*9.41*	*7.00*	*5.55*	*5.60*
7	*0.00*	*0.00*	*0.00*	*0.00*	*18*	*6.33*	*8.80*	*3.74*	*4.00*	*29*	*1.08*	*1.60*	*0.64*	*0.60*
8	*0.26*	*0.80*	*0.15*	*0.20*	*19*	*8.81*	*10.20*	*5.20*	*5.20*	*30*	*0.38*	*0.40*	*0.22*	*0.00*
9	*3.15*	*3.40*	*1.86*	*3.80*	*20*	*6.02*	*5.20*	*3.55*	*7.60*	*31*	*1.20*	*1.00*	*0.71*	*0.80*
10	*1.58*	*2.60*	*0.93*	*2.00*	*21*	*9.22*	*10.20*	*5.44*	*5.40*	*32*	*0.41*	*1.40*	*0.24*	*0.20*
11	*5.63*	*3.60*	*3.32*	*3.60*	*22*	*6.06*	*4.00*	*3.58*	*6.00*	*33*	*0.74*	*1.20*	*0.43*	*0.00*

Time (hr)	*Stations*				*Time (hr)*	*Stations*				*Time (hr)*	*Stations*			
	Nablus	*Taluza*	*Bait Dajan*	*Salim*		*Nablus*	*Taluza*	*Bait Dajan*	*Salim*		*Nablus*	*Taluza*	*Bait Dajan*	*Salim*
34	*1.11*	*0.40*	*0.65*	*1.00*	*43*	*0.00*	*0.00*	*0.00*	*0.00*	*52*	*0.00*	*0.00*	*0.00*	*0.00*
35	*0.26*	*0.60*	*0.15*	*0.40*	*44*	*0.38*	*0.20*	*0.23*	*0.00*	*53*	*0.00*	*0.00*	*0.00*	*0.00*
36	*0.00*	*0.00*	*0.00*	*0.00*	*45*	*0.15*	*0.20*	*0.09*	*0.00*	*54*	*0.00*	*0.00*	*0.00*	*0.00*
37	*0.54*	*0.20*	*0.32*	*0.00*	*46*	*0.00*	*0.00*	*0.00*	*0.00*	*55*	*0.00*	*0.00*	*0.00*	*0.00*
38	*1.00*	*0.20*	*0.59*	*0.60*	*47*	*0.32*	*0.60*	*0.19*	*0.60*	*56*	*0.00*	*0.00*	*0.00*	*0.00*
39	*0.00*	*0.00*	*0.00*	*0.00*	*48*	*0.91*	*0.40*	*0.53*	*0.60*	*57*	*0.00*	*0.00*	*0.00*	*0.00*
40	*0.00*	*0.00*	*0.00*	*0.00*	*49*	*0.16*	*0.20*	*0.09*	*0.40*	*58*	*0.00*	*0.00*	*0.00*	*0.00*
41	*0.00*	*0.00*	*0.00*	*0.00*	*50*	*0.00*	*0.00*	*0.00*	*0.00*	*59*	*0.00*	*0.00*	*0.00*	*0.00*
42	*0.00*	*0.00*	*0.00*	*0.00*	*51*	*0.00*	*0.00*	*0.00*	*0.00*	*60*	*0.00*	*0.00*	*0.00*	*0.00*

Table A. 2

Rainfall Data of Event 3 in Rainy Season 2006-2007

Time (hr)	*Stations*				*Time (hr)*	*Stations*				*Time (hr)*	*Stations*			
	Nablus	*Taluza*	*Bait Dajan*	*Salim*		*Nablus*	*Taluza*	*Bait Dajan*	*Salim*		*Nablus*	*Taluza*	*Bait Dajan*	*Salim*
1	*0.00*	*0.00*	*0.00*	*0.00*	*12*	*0.10*	*0.00*	*0.06*	*0.00*	*23*	*0.16*	*0.20*	*0.09*	*0.40*
2	*0.31*	*0.40*	*0.18*	*0.20*	*13*	*0.57*	*1.20*	*0.34*	*0.40*	*24*	*0.08*	*0.00*	*0.05*	*0.00*
3	*0.80*	*0.60*	*0.47*	*0.80*	*14*	*1.44*	*1.40*	*0.85*	*0.80*	*25*	*0.05*	*0.00*	*0.03*	*0.20*
4	*0.11*	*0.20*	*0.06*	*0.20*	*15*	*0.48*	*0.40*	*0.28*	*0.00*	*26*	*0.00*	*0.00*	*0.00*	*0.00*
5	*0.00*	*0.00*	*0.00*	*0.00*	*16*	*0.78*	*1.40*	*0.46*	*1.00*	*27*	*0.00*	*0.00*	*0.00*	*0.00*
6	*0.00*	*0.00*	*0.00*	*0.00*	*17*	*5.80*	*4.40*	*3.42*	*3.40*	*28*	*0.00*	*0.00*	*0.00*	*0.00*
7	*0.00*	*0.00*	*0.00*	*0.00*	*18*	*2.02*	*1.00*	*1.19*	*3.60*	*29*	*2.21*	*2.00*	*1.30*	*1.80*
8	*0.00*	*0.00*	*0.00*	*0.00*	*19*	*1.25*	*2.00*	*0.74*	*1.80*	*30*	*1.56*	*1.60*	*0.92*	*2.00*
9	*0.00*	*0.00*	*0.00*	*0.00*	*20*	*4.89*	*9.20*	*2.89*	*4.80*	*31*	*4.60*	*6.40*	*2.72*	*3.60*
10	*0.00*	*0.00*	*0.00*	*0.00*	*21*	*8.78*	*15.40*	*5.18*	*9.60*	*32*	*1.33*	*0.40*	*0.78*	*0.40*
11	*0.11*	*0.00*	*0.06*	*0.40*	*22*	*3.91*	*4.40*	*2.30*	*3.60*	*33*	*1.80*	*2.60*	*1.06*	*1.20*

Time (hr)	Stations				Time (hr)	Stations				Time (hr)	Stations			
	Nablus	Taluza	Bait Dajan	Salim		Nablus	Taluza	Bait Dajan	Salim		Nablus	Taluza	Bait Dajan	Salim
34	2.43	3.40	1.44	1.20	43	3.12	2.80	1.84	0.80	52	0.00	0.00	0.00	0.00
35	2.35	3.20	1.39	2.40	44	2.22	2.40	1.31	0.00	53	0.00	0.00	0.00	0.00
36	0.11	0.20	0.06	0.20	45	0.44	0.80	0.26	0.00	54	0.00	0.00	0.00	0.00
37	0.00	0.00	0.00	0.00	46	0.00	0.00	0.00	0.00	55	0.00	0.00	0.00	0.00
38	1.66	3.00	0.98	0.60	47	0.00	0.00	0.00	0.00	56	0.00	0.00	0.00	0.00
39	0.93	1.40	0.55	0.40	48	0.00	0.00	0.00	0.00	57	0.00	0.00	0.00	0.00
40	2.31	2.80	1.36	0.00	49	0.00	0.00	0.00	0.00	58	0.00	0.00	0.00	0.00
41	0.53	0.60	0.31	1.00	50	0.00	0.00	0.00	0.00					
42	3.17	4.60	1.87	3.00	51	0.00	0.00	0.00	0.00					

Table A. 3

Rainfall Data of the Event 4 in the Rainy Season 2006-2007

Time (hr)	*Stations*				*Time (hr)*	*Stations*				*Time (hr)*	*Stations*			
	Nablus	*Taluza*	*Bait Dajan*	*Salim*		*Nablus*	*Taluza*	*Bait Dajan*	*Salim*		*Nablus*	*Taluza*	*Bait Dajan*	*Salim*
1	0.00	0.00	0.00	0.00	12	0.90	1.20	0.53	0.40	23	0.36	1.40	0.21	0.00
2	0.00	0.00	0.00	0.00	13	0.31	0.40	0.18	0.40	24	2.41	1.40	1.42	1.60
3	0.00	0.00	0.00	0.00	14	0.00	0.00	0.00	0.00	25	2.12	3.00	1.25	0.20
4	0.15	0.60	0.09	0.00	15	0.00	0.00	0.00	0.00	26	1.44	1.80	0.85	0.60
5	0.44	1.00	0.26	0.40	16	2.90	6.00	1.71	0.00	27	0.66	0.20	0.09	0.40
6	0.00	0.00	0.00	0.00	17	3.09	4.60	1.82	1.20	28	0.10	0.40	0.06	0.00
7	0.16	0.40	0.09	0.20	18	4.19	5.00	2.47	2.40	29	2.87	1.80	1.70	1.80
8	0.36	0.60	0.21	0.20	19	0.08	0.00	0.05	0.00	30	2.87	1.60	1.69	2.40
9	0.56	1.20	0.33	0.20	20	1.09	0.60	0.65	2.60	31	0.68	0.20	0.40	0.60
10	0.67	1.60	0.40	0.40	21	3.20	4.80	1.89	4.00	32	1.19	1.00	0.70	1.40
11	0.93	0.60	0.55	0.00	22	0.90	0.20	0.53	0.80	33	0.27	0.20	0.16	0.80

Time (hr)	*Stations*				*Time (hr)*	*Stations*				*Time (hr)*	*Stations*			
	Nablus	*Taluza*	*Bait Dajan*	*Salim*		*Nablus*	*Taluza*	*Bait Dajan*	*Salim*		*Nablus*	*Taluza*	*Bait Dajan*	*Salim*
34	*0.00*	*0.00*	*0.00*	*0.00*	*42*	*0.00*	*0.00*	*0.00*	*0.00*	*50*	*0.00*	*0.00*	*0.00*	*0.00*
35	*0.05*	*0.20*	*0.03*	*0.00*	*43*	*0.00*	*0.00*	*0.00*	*0.00*	*51*	*0.00*	*0.00*	*0.00*	*0.00*
36	*0.05*	*0.00*	*0.03*	*0.20*	*44*	*0.00*	*0.00*	*0.00*	*0.00*	*52*	*0.00*	*0.00*	*0.00*	*0.00*
37	*0.27*	*0.40*	*0.16*	*0.60*	*45*	*0.00*	*0.00*	*0.00*	*0.00*	*53*	*0.00*	*0.00*	*0.00*	*0.00*
38	*0.87*	*0.00*	*0.52*	*0.60*	*46*	*0.00*	*0.00*	*0.00*	*0.00*	*54*	*0.00*	*0.00*	*0.00*	*0.00*
39	*0.00*	*0.00*	*0.00*	*0.00*	*47*	*0.00*	*0.00*	*0.00*	*0.00*	*55*	*0.00*	*0.00*	*0.00*	*0.00*
40	*0.00*	*0.00*	*0.00*	*0.00*	*48*	*0.00*	*0.00*	*0.00*	*0.00*	*56*	*0.00*	*0.00*	*0.00*	*0.00*
41	*0.00*	*0.00*	*0.00*	*0.00*	*49*	*0.00*	*0.00*	*0.00*	*0.00*					

Table A. 4

Rainfall Data of the Event 5 in the Rainy Season 2017-2018

Time	*Stations*							*Time*	*Stations*						
(hr)	*Nablus*	*Taluza*	*Bait Dajan*	*Salim*	*Badan*	*Beit Furik*	*Lubadi*	*(hr)*	*Nablus*	*Taluza*	*Bait Dajan*	*Salim*	*Badan*	*Beit Furik*	*Lubadi*
1	*4.11*	*9.74*	*4.46*	*2.65*	*4.49*	*2.86*	*3.51*	*12*	*1.62*	*0.99*	*0.42*	*1.37*	*3.39*	*0.21*	*2.68*
2	*5.09*	*2.99*	*0.42*	*1.06*	*1.62*	*1.06*	*1.72*	*13*	*2.40*	*5.08*	*0.63*	*1.48*	*3.39*	*0.63*	*4.30*
3	*1.97*	*2.18*	*1.97*	*3.80*	*3.73*	*3.97*	*1.97*	*14*	*2.11*	*6.35*	*1.48*	*1.80*	*2.61*	*1.90*	*2.83*
4	*2.89*	*3.32*	*1.41*	*2.01*	*2.61*	*1.76*	*2.89*	*15*	*4.86*	*2.75*	*2.82*	*4.01*	*4.23*	*4.65*	*4.72*
5	*0*	*3.32*	*0*	*0*	*0.14*	*0*	*0.14*	*16*	*11.29*	*2.61*	*6.01*	*6.28*	*4.51*	*10.47*	*6.64*
6	*6.36*	*2.94*	*3.52*	*2.96*	*1.90*	*4.72*	*5.57*	*17*	*8.49*	*5.77*	*3.75*	*4.17*	*1.76*	*6.71*	*3.71*
7	*0.49*	*3.87*	*0.99*	*0.85*	*0.70*	*1.06*	*0.70*	*18*	*1.13*	*7.75*	*0.99*	*1.06*	*0.99*	*1.27*	*0.77*
8	*0*	*1.34*	*0*	*0.07*	*0*	*0*	*0.07*	*19*	*0*	*1.58*	*0*	*0*	*0.21*	*0.14*	*0.07*
9	*1.86*	*1.34*	*1.27*	*1.27*	*0.07*	*1.06*	*0.56*	*20*	*0.07*	*0.07*	*0*	*0*	*0.21*	*0*	*0.14*
10	*0.42*	*0.07*	*0*	*0.25*	*0*	*0.07*	*0.07*	*21*	*0*	*0.14*	*0.35*	*0.14*	*0*	*0*	*0*
11	*1.21*	*0*	*2.70*	*1.44*	*0.77*	*2.78*	*2.27*	*22*	*0*	*0.14*	*0*	*0*	*0*	*0*	*0*

Time	*Stations*							*Time*	*Stations*						
(hr)	*Nablus*	*Taluza*	*Bait Dajan*	*Salim*	*Badan*	*Beit Furik*	*Lubadi*	*(hr)*	*Nablus*	*Taluza*	*Bait Dajan*	*Salim*	*Badan*	*Beit Furik*	*Lubadi*
23	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*34*	*0*	*0*	*0*	*0*	*0*	*0*	*0*
24	*0*	*0*	*0.07*	*0*	*0*	*0*	*0.07*	*35*	*0*	*0*	*0*	*0*	*0*	*0*	*0*
25	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*36*	*0*	*0*	*0*	*0*	*0*	*0*	*0*
26	*0.07*	*0*	*0*	*0*	*0*	*0*	*0*	*37*	*0*	*0*	*0*	*0*	*0*	*0*	*0*
27	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*38*	*0*	*0*	*0*	*0*	*0*	*0*	*0*
28	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*39*	*0*	*0*	*0*	*0*	*0*	*0*	*0*
29	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*40*	*0*	*0*	*0*	*0*	*0*	*0*	*0*
30	*0*	*0*	*0*	*0*	*0*	*0*	*0*								
31	*0*	*0*	*0*	*0*	*0*	*0*	*0*								
32	*0*	*0*	*0*	*0*	*0*	*0*	*0*								
33	*0*	*0*	*0*	*0*	*0*	*0*	*0*								

Table A. 5

Rainfall Data of the Event 6 in the Rainy Season 2018-2019

Time (hr)	*Stations*							*Time (hr)*	*Stations*						
	Nablus	*Taluza*	*Bait Dajan*	*Salim*	*Badan*	*Beit Furik*	*Lubadi*		*Nablus*	*Taluza*	*Bait Dajan*	*Salim*	*Badan*	*Beit Furik*	*Lubadi*
1	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*12*	*0*	*3.66*	*2.75*	*3.52*	*2.96*	*2.11*	*2.32*
2	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*13*	*0*	*0.99*	*0.21*	*0.49*	*0.95*	*0.32*	*0.95*
3	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*14*	*0*	*0.07*	*0*	*0*	*0.21*	*0*	*0*
4	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*15*	*0*	*2.49*	*1.48*	*0.63*	*3.11*	*1.58*	*0.85*
5	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*16*	*0*	*2.91*	*1.12*	*0.56*	*2.02*	*0.85*	*0.32*
6	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*17*	*0*	*4.22*	*5.31*	*6.12*	*4.48*	*3.63*	*1.48*
7	*0.11*	*0*	*0*	*0*	*0*	*0*	*0*	*18*	*0*	*0*	*0.63*	*0.78*	*0.21*	*0.74*	*1.06*
8	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*19*	*0*	*0*	*0*	*0.07*	*0*	*0.11*	*1.06*
9	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*20*	*0*	*0*	*0*	*0*	*0*	*0*	*0.85*
10	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*21*	*0*	*0.07*	*0*	*0*	*0*	*0*	*0.85*
11	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*22*	*0*	*0.64*	*0.07*	*0*	*0.53*	*1.44*	*0.21*

Time	*Stations*							*Time*	*Stations*						
(hr)	*Nablus*	*Taluza*	*Bait Dajan*	*Salim*	*Badan*	*Beit Furik*	*Lubadi*	*(hr)*	*Nablus*	*Taluza*	*Bait Dajan*	*Salim*	*Badan*	*Beit Furik*	*Lubadi*
23	*0.11*	*0*	*0*	*0*	*0*	*0*	*0*	*34*	*0*	*0.14*	*0*	*0*	*0*	*0*	*0.21*
24	*0.11*	*0*	*0*	*0*	*0*	*0*	*0*	*35*	*0*	*0*	*0*	*0*	*0*	*0*	*0.11*
25	*0*	*0*	*0*	*0*	*0*	*0*	*0.14*	*36*	*0*	*0*	*0*	*0*	*0*	*0*	*0.74*
26	*0*	*2.06*	*0.66*	*0.57*	*1.65*	*1.77*	*0.49*								
27	*0*	*1.34*	*0.14*	*0.70*	*0.92*	*1.48*	*0.56*								
28	*0*	*0.88*	*0.07*	*0.14*	*0.85*	*0.32*	*0.53*								
29	*0*	*0*	*0*	*0*	*0*	*0.11*	*0.25*								
30	*0*	*0*	*0*	*0*	*0*	*0*	*0.21*								
31	*0*	*0*	*0*	*0*	*0*	*0*	*0.21*								
32	*0*	*0*	*0*	*0*	*0*	*0*	*0.21*								
33	*0*	*0*	*0*	*0*	*0*	*0*	*0.11*								

Table. A. 6

Polygon Area Using the Thiessen Polygon Method in Rainy Seasons (2006-2007)

Stations	Nablus	Taluza	Beit Dajan	Salim
Polygon Area (km^2)	20	18	18	27
Total Area (km^2)	83			

Table A. 7

Polygon Area Using the Thiessen polygon Method in Rainy Seasons (2017-2019)

Stations	Nablus	Taluza	Beit Dajan	Salim	Badan	Beit Furik	Lubadi
Polygon Area (km^2)	11.9	4.1	14.7	18.4	6.7	13.6	13.6
Total Area (km^2)	83						

Table A. 8

Coordinates of Soil Conservation Service Dimensionless Unit Hydrograph

$t\backslash T_P$	$Q\backslash Q_P$	$t\backslash T_P$	$Q\backslash Q_P$	$t\backslash T_P$	$Q\backslash Q_P$
0.0	0.000	1.1	0.980	2.4	0.180
0.1	0.015	1.2	0.920	2.6	0.130
0.2	0.075	1.3	0.840	2.8	0.098
0.3	0.160	1.4	0.750	3.0	0.074
0.5	0.430	1.6	0.560	3.5	0.036
0.7	0.770	1.8	0.420	4.0	0.018
0.8	0.890	2.0	0.320	4.5	0.009
1.0	1.000	2.2	0.240	5.0	0.000

(Subramanya, 2003)

Table A. 9

ordinates of Snyder Unit Hydrograph for Al-Bathan Sub-Catchment

Time (hr)	Q (m^3/sec)	Time (hr)	Q (m^3/sec)
0	0	13	0.85
1	0.29	14	0.80
2	0.74	15	0.74
3	1.29	16	0.68
4	1.93	17	0.57
5	4.52	18	0.46
6	2.11	19	0.31
7	1.42	20	0.30
8	1.29	21	0.28
9	1.20	22	0.23
10	1.08	23	0.14
11	0.89	24	0.06
12	0.87	25	0

Table A. 10

ordinates of Soil Conservation Service Unit Hydrograph for Al-Bathan Sub-Catchment

Time (hr)	Q (m^3/sec)	Time (hr)	Q (m^3/sec)
0	0	13	0.42
1	0.24	14	0.31
2	0.90	15	0.24
3	1.93	16	0.19
4	2.86	17	0.14
5	4.52	18	0.10
6	2.96	19	0.08
7	2.41	20	0.06
8	1.80	21	0.06
9	1.35	22	0.06
10	1.03	23	0.03
11	0.77	24	0.03
12	0.58	25	0

جامعة النجاح الوطنية

كلية الدراسات العليا

حساب معاملات الهيدروغراف القياسي المصطنع لحوض وادي الباذان

إعداد

غصون زياد توفيق حمدالله

إشراف

د. سمير شديد

قدمت هذه الرسالة استكمالا لمتطلبات الحصول على درجة الماجستير في هندسة المياه والبيئة، من كلية الدراسات العليا، في جامعة النجاح الوطنية، نابلس– فلسطين.

2023

حساب معاملات الهيدروغراف القياسي المصطنع لحوض وادي الباذان

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د. سمير شديد

الملخص

يعد تطوير وحدات الهيدروغراف القياسية أمراً بالغ الأهمية لتصميم المنشآت الهيدروليكية وإدارة مصادر المياه في الأحواض المائية المعايرة. نظراً لنقص البيانات المحلية (المطر والجريان السطحي)، يجب على المهندسين السعي لتقدير كميات التصريف باستخدام الأساليب الحسابية (الاصطناعية) التي يمكن بواسطتها حساب كميات الجريان السطحي بالاعتماد على كميات هطول الأمطار في الأحواض المائية غير المعايرة.

إن طرق وحدات الهيدروغراف القياسية الاصطناعية، مثل طريقة (Snyder and SCS) تلعبان دوراً مهماً وأساسياً في هذا المجال. تمتاز هذه الطرق بالبساطة وسهولة التعامل معها، حيث أنها تتطلب فقط خصائص الأحواض الفيزيائية مثل المساحة وطول المجرى المائي ومعامل الانحدار السطحي. لذلك، تعمل هذه الطرق كأدوات لحساب كميات الجريان السطحي في الأحواض المائية غير المعايرة للتمكّن من حساب قيمة التصريف القصوى وزمن حدوثها وحجم الجريان السطحي.

تمت هذه الدراسة في حوض وادي الباذان، والذي يقع في الجزء الشمالي الشرقي من الضفة الغربية في فلسطين بمساحة تقريبية 83 كم^2، تم باستخدام المصفوفات الرياضية المتعلّقة بتطوير متوسط وحدة الهيدروغراف القياسية من خلال اختبار أربع عواصف مطرية تقع في الفترة الزمنية (2005-2007) وباستخدام الجريان السطحي المباشر الذي تم قياسه عند مخرج حوض وادي الباذان.

كانت خصائص متوسط وحدة الهيدروغراف في حوض وادي الباذان هي 4.52 م^3/ث عند زمن يساوي 5 ساعات. تم تطوير وحدات الهيدروغراف القياسية الاصطناعية (Snyder and SCS) لتناسب خصائص منطقة الدراسة، حيث كانت قيم معاملات طريقة Snyder هي 0.88 لوحدة ذروة التدفق و1.26 لوحدة ذروة الزمن بينما كانت المعاملات لطريقة SCS هي 1.90 لوحدة ذروة التدفق و2.92 لوحدة ذروة الزمن.

وللتحقق من النتائج السابقة من حيث مدى قابلية تطبيق وحدات الهيدروغراف القياسية الاصطناعية المشتقة لحوض وادي الباذان، تم اختيار عاصفتين مطريتين في الفترة الزمنية (2017–2019) ، حيث تم اختبارهما باستخدام بعض الطرق الاحصائية، وأوضحت النتائج أن الطريقتين (and SCS Snyder) مناسبتان للتطبيق وأن طريقة SCS أعطت نتائج أكثر دقة من طريقة Snyder.

الكلمات المفتاحية: وحدة الهيدروغراف القياسية، وحدة الهيدروغراف القياسية الاصطناعية، وحدة هيدروغراف الجريان السطحي المباشر، الحوض المائي الغير معاير، حوض وادي الباذان، فلسطين.