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Derivation of flood hydrographs using SCS synthetic unit hydrograph technique for Housha catchment area

Amjed Shatnawi [a,*] and Majed Ibrahim [b]

[a] Earth and Environmental Sciences Department, Al al-Bayt University, Al-Mafraq, Jordan
[b] Geographic Information System and Remote Sensing, Al al-Bayt University, Mafraq, Jordan
*Corresponding author. E-mail: amjedshatnawi@yahoo.com

AS, 0000-0003-2193-1093; MI, 0000-0001-9841-9747

ABSTRACT

SCS (Soil Conservation Service) synthetic unit hydrograph technique was used to estimate the storm runoff overflows entering the Housha tunnel. The flood hydrographs were derived under different storm event durations for the ungauged Husha Catchment area. Geomorphological and hydrological parameters of the watershed were extracted using GIS measurement tools. The data identified various parameters (time to peak, time of base, and peak flow) of the synthetic unit hydrograph. The peak discharge (Q_p in $m^3 s^{-1} cm^{-1}$) of rainfall excess for different time durations (5, 10, 20, 30, 60, 120, 180, 360, and 720 minutes) was estimated. The results revealed that the peak discharge (Q_p) decreased with the increase in time of rainfall excess. The maximum peak discharge (27.5 in $m^3 s^{-1} cm^{-1}$) was reached 84 minutes after the beginning of the rainfall storm for 5 minutes of rainfall excess whereas the minimum peak discharge (5.2 in $m^3 s^{-1} cm^{-1}$) was reached after 7 hours and 22 minutes for 12 hours of rainfall excess. Geographic information system (GIS) data-based SCS synthetic unit hydrograph model was verified by comparing the simulated runoff with the estimated runoff from measured rainfall data of the watershed.

Key words: catchment, curve number, GIS, hydrograph, SCS

HIGHLIGHTS

- The study is focusing on areas with undeveloped basins in Jordan.
- SCS synthetic unit hydrograph technique was used for an arid region.
- The flood hydrographs were derived for ungauged catchment.
- Geomorphological and hydrological parameters of the watershed were extracted using GIS measurement tools.
- A digital elevation model (DEM) data set was used in this study.

1. INTRODUCTION

Jordan suffers from water scarcity. Water availability has become a serious issue that urgently requires the development of sustainable solutions. Water budget inputs can be increased by controlling the surface water through the development of water management facilities and other hydraulic structures. The areas with undeveloped basins in Jordan with insufficient basic flow and rainfall data should be the focus of study (Shatnawi & Diabat 2016). Synthetic unit hydrograph methods are generally followed to determine a unit hydrograph for a catchment area similar to the current study area. However, the hydrologic parameters of the watershed must be identified to accurately design the intended synthetic unit hydrograph for a basin. A runoff hydrograph expresses the surface water discharge over time. This reflection of the watershed characteristics influences the relationship between rainfall and the resulting hydrograph. Watershed characteristics such as channel area, area of the watershed, vegetation cover, overland slope, soil type, channel slope, basin length, channel roughness, watershed shape, and stream pattern affect the synthetic methods. Each characteristic of the watersheds is crucial for shaping the watershed hydrograph (López *et al.* 2005; Singh *et al.* 2014).

Storm pattern affecting the watershed is also important for developing a hydrograph. Rainfall excess represents the volume of rainfall available for on-site surface storage and the greater volumes become site runoff. Runoff is assessed as the flow rate of rainfall excess discharge from an area. The runoff coefficient relates precipitation rate, runoff rate, and rainfall excess to precipitation volume (Déry *et al.* 2009). Direct runoff hydrograph (DRH) of a river with regular rainfall over the area of its basin at an equal intensity to unit length and duration is considered a unit hydrograph of a drainage basin. It represents surface runoff (1 cm of excess rainfall) as an increase from seepage and other losses per unit time. A unit hydrograph is used to calculate the maximum flow and other runoff rates from the observed rainfall (Adeyi *et al.* 2020). Hydrologic literature has proposed several synthetic unit-hydrograph methods to develop hydrographs for ungauged watersheds. These methods have been reported in detail by Dayani & Mohamadi (2002) and Singh *et al.* (2014). Snyder was among the first hydrologists who developed these methods by relating features of a unit hydrograph to watershed characteristics (Snyder 1938, 1955). Singh (1988) has described other methods for measuring ungauged watersheds including unit hydrograph, rational hydrograph, discrete unit-time hydrograph, Santa Barbara urban hydrograph (SBUH), Gray method, Nash's synthetic hydrograph, and Clark's instantaneous unit hydrograph (IUH).

SCS (Soil Conservation Service) curvilinear synthetic unit hydrograph method has been previously applied in Jordan (Ataany 2013) to determine that the Wadi Rajil catchment is characterized by a peak value of 1,146 m^3/s per 1 cm of rainfall excess. Most of these synthetic methods require some coefficients to study a basin. Due to the absence of these coefficients in countries like Jordan, they are generally taken from the studies conducted in other specific regions of the world. Hammouri & El-Naqa (2007) have presented a model for the rainfall-runoff process in an ungauged basin for artificial recharging of groundwater. The model simulation was based on the hydrological modeling system assisted by geographic information systems (GIS). GIS technique has been applied in several hydrogeology, hydrology, surface, and groundwater studies (Ibrahim 2014; Al-Harahsheh *et al.* 2019; Al-Raggad *et al.* 2021). Two model runs were carried out using precipitation data of the intensity-duration-frequency (IDF) curves at Zarqa rainfall station for 10 years and 50 years return periods. The first model run revealed the total direct runoff volume and the peak discharge for the 10 years return period as 151,000 m^3 and 5.43 m^3/s, respectively, whereas these values were found to be 280,000 m^3 and 12.77 m^3/s, respectively, for the 50 years return period. In this study unit hydrograph parameters were determined for un-gagged Housha catchment area in the northern part of Jordan, using SCS synthetic unit hydrograph method and GIS techniques. Modeling system (HEC-HMS) was applied for estimation of runoff during a storm event between 1 and 4 of January 2000. Estimated unit hydrographs from runoffs for the same storm duration and catchment area were obtained to optimize the model.

2. MATERIALS AND METHODS

2.1. Study area

The study area is located in the northern part of Jordan on the Mafraq highway to Irbid city. Housha catchment area lies between 36°4′11.88″ to 36°7′11.40″ E and 32°26′59.68″ to 32°26′59.32″ N. According to Palestine Grid, the catchment area of the tunnel entrance is about 18.4 km^2 (Figure 1). Digital elevation model (DEM) revealed the elevation of the study area from 599 to 765 m above sea level (Figure 2). The annual rainfall of the area is about 149 mm during the winter months (October to April). Therefore, the area is considered as strongly arid as the mean annual rainfall is less than 150 mm (Salahat & Al-Qinna 2015). Arid climate, atmospheric dust, and low precipitation impact the water quality leading to increased salt content whereas most of the geologic formations consist of marly layers (Eraifej & Abu-Jaber 1999; Ibrahim *et al.* 2019).

2.2. Digital elevation model

Digital elevation model data set was used in this study. DEM was acquired from United States Geological Survey (USGS) with a spatial resolution equal to 30 meters**.** The suitability of DEM from Shuttle Radar Topography Mission (SRTM), Global Digital Elevation Model Version 3 (GDEM 003), and Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) in geomorphology and hydrological studies have been confirmed (Ibrahim *et al.* 2020). The other datasets including water streams networks, contours, soil, land use maps, and geological settings were also collected. GIS technique was employed to delineate the main catchment areas in Housha based on the available DEM from SRTM DEM. The topographic map further validated the dataset, which was used for estimating the watershed parameters.

2.3. Land use and cover

The satellites Landsat 8 OLI (Operational Land Imager) and TIRS (Thermal Infrared Sensor) were used in this study in May 2020 (path 169 and row 45). The image was obtained from the USGS Global Visualization (GloVis) site and geometrically

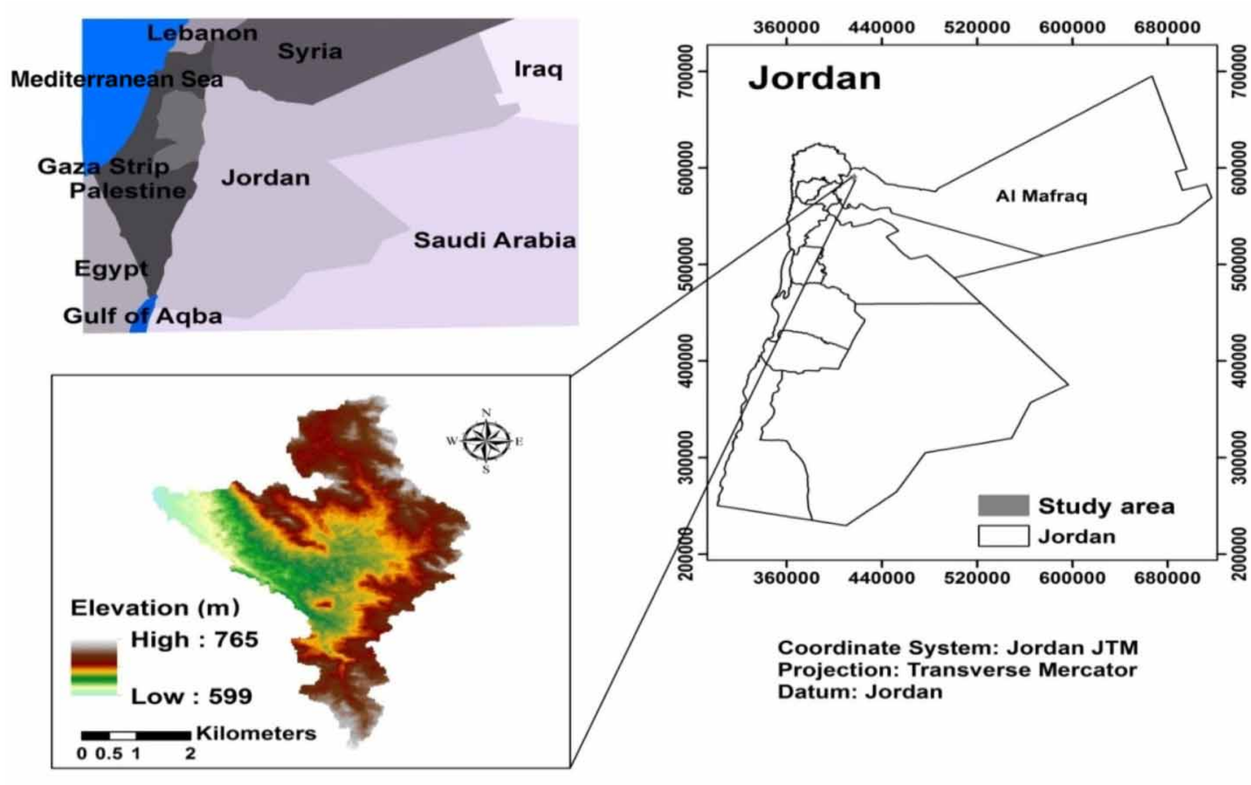

Figure 1 | Location of the study area.

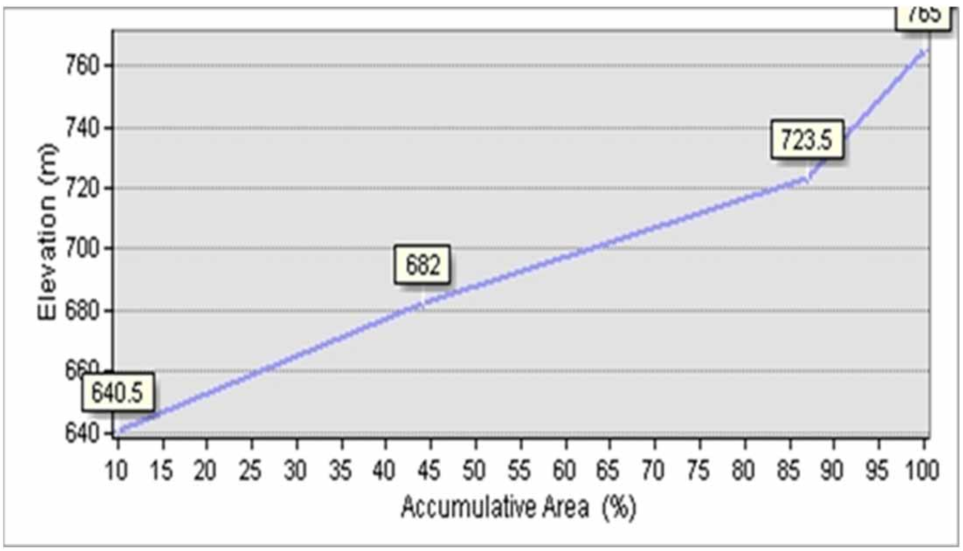

Figure 2 | The relation between elevation and area of Housha basin.

corrected and rectified to UTM zone 36. ERDAS IMAGINE 2014 software was used to import and enhance the image for mapping the land use of the study area. The study area was distinguished into three types (Figure 3).

A supervised classification that classifies the unknown-identity pixels by using samples of known identity was applied for land mapping between two different periods. These pixels are located within training-set statistics for image classification whereas the maximum likelihood algorithm (MLA) of ERDAS software was used for the land use/land cover mapping

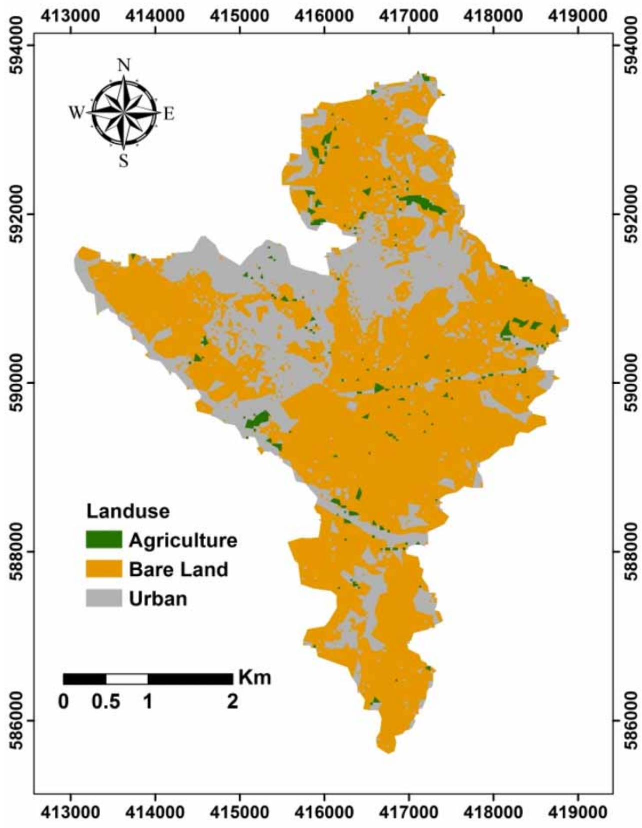

Figure 3 | Land use/land cover map.

(Ibrahim 2014, 2016; Ibrahim & Al-Mashagbah 2016). The MLA compares the upper and lower limits of data values for all candidate-unit pixels (image spatial resolution and truth ground control points (GCPs)) for the interpretation of remote sensor data at various scales. It classified the land into three main land use classes: (1) Urban areas (built-up areas) including towns, villages, power, and transportation; (2) Vegetation areas including agricultural land, forest, pasture, cropland, and grassland; and (3) Bare land having thin soil, rock, or sand including bare exposed rock, mixed barren land, and transitional area. Accuracy assessment of satellite image classification was carried out as well. Accuracy refers to the compatibility level between the signs (as assigned by the analyst) and ground locations of the classes (truth points). It reveals accurate conclusions about samples based accuracy of the map, which is important for the validation of results. Three standard criteria were used to assess the accuracy of the different classifications (overall accuracy, producer's accuracy, and user's accuracy) (Lillesand *et al.* 2015).

$$\text{Overall accuracy} = \frac{\text{total number correct}}{\text{total reference or total classified}} * 100$$

$$\text{Producer's accuracy} = \frac{\text{number correct}}{\text{total reference}}$$

$$\text{User's accuracy} = \frac{\text{number correct}}{\text{total classified}}$$

2.4. Soil cover data

The grain size gives varying characteristics to the soils including different infiltration rates of precipitation during a rain event (Chow *et al.* 1988; Al-Harahsheh *et al.* 2019). The digital data depicted the dominance of clay loam texture in the study area (Figure 4). The soil map was obtained based on the National Soil Map and Land-Use Project (Ministry of Agriculture 1993).

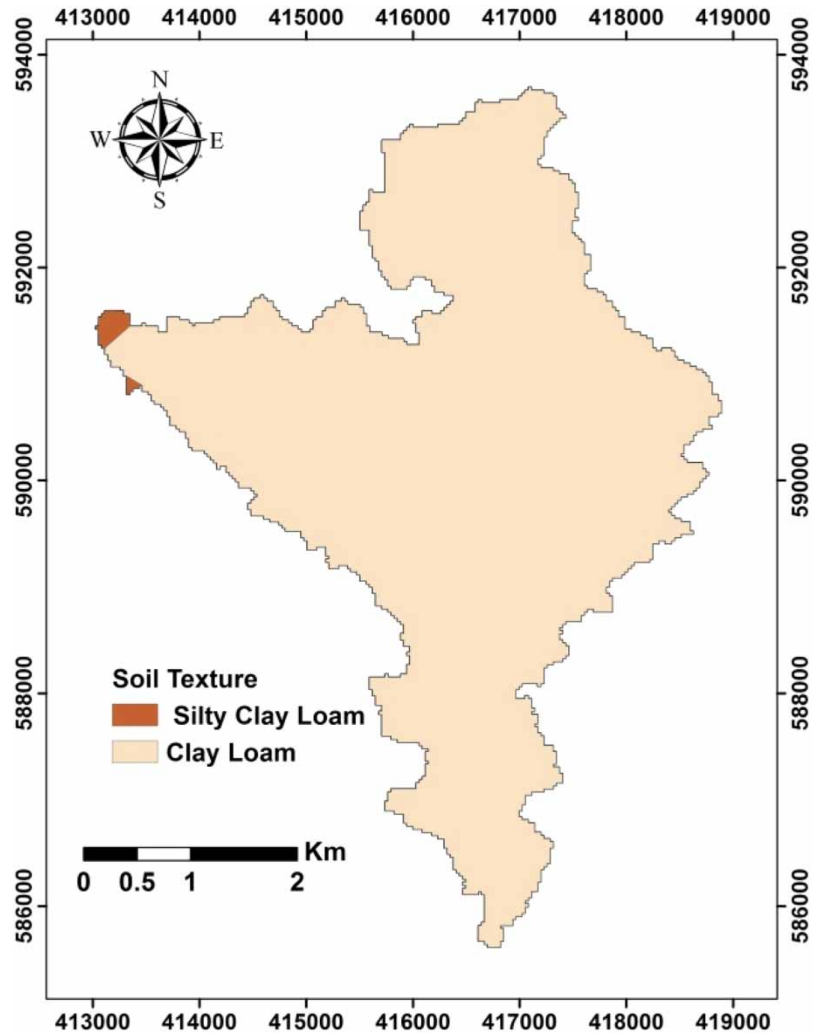

Figure 4 | Soil texture map.

2.5. Estimation of watershed parameters

GIS technique was used for calculating the parameters of the watershed area where the watershed occurs from the highest elevation and drains to a common outlet point. Elevation DEMs are necessary for delineating the watershed areas using GIS (Ibrahim *et al.* 2020). ArcGIS software, which is a widely used GIS tool, was applied to assess watershed parameters (Table 1). Hydrological parameters and streams network was extracted using GIS measurement tools.

Table 1 | Hydrological parameters extracted using GIS tools

No	Parameters, Symbol	Description	Value
1	Drainage area (A_d)	The area that drains to a point (stream-gauge station) on a stream in square meters.	18.43 km^2
2	Basin average slope (S)	Main channel 10–95 slope (the difference in elevation between points 10% and 85% of the distance along the mainstream channel.	10.5%
3	Channel length (L) for the whole area	Main channel stream length in km	4.5 km
4	Main channel length (Lc)	Length from the main channel outlet to the catchment centroid, Lc (km)	3.5 km
5	Height H_{outlet}	Height of the basin outlet	640.5 m
6	Mid-height H_{mid} (m)	The mid-height of watershed area	690 m
7	Max height H_{Max} (m)	The maximum height of the basin	765 m

The stream ordering concept proposed by Horton (1945) and modified by Strahler (1957) has become a conceptual and organizational tool in river science. It is commonly used for determining the habitat and physical character of entire stream networks. However, during this study, the GIS environment was used to generate a stream network having a total length of 14 km including two streams orders whereas minor details were ignored. One first-order tributary (10 km) was found (Figure 5). The stream network was extracted through flow accumulation in the GIS environment. The digital elevation model served as the resource data for generating a stream network with 30 m resolution (USGS earthexplore.org).

2.6. Synthetic unit hydrograph

In case of the nonexistence of rainfall-runoff data in un-gauged watersheds of the study area, the Soil Conservation Service (SCS synthetic unit hydrograph) method originally developed by Victor Mockus in 1957 (Mockus 1957) and U. S. Soil Conservation Service in 1972 is widely applied for the estimation of small watersheds runoff (Singh *et al.* 2014; Monajemi *et al.* 2021). This method requires geographical parameters which can be easily obtained by using GIS techniques. The SCS method synthesizes the unit hydrograph (UH) using a specific average dimensionless UH derived from the analysis of a large number of natural UHs for watersheds of varying sizes and geographic locations (Singh 1988; Singh & Frevert 2003; Singh *et al.* 2014; Shaikh Mohamed Maroof *et al.* 2021). To enable the definition of the time base (t_b) in terms of time to peak (T_p) and time to recession (t_{rc}), the SCS method represents the dimensionless UH as a triangular UH (Figure 6), which further facilitates the computation of the runoff volume (V) and peak discharge (q_p). The following equations were developed by Natural Resources

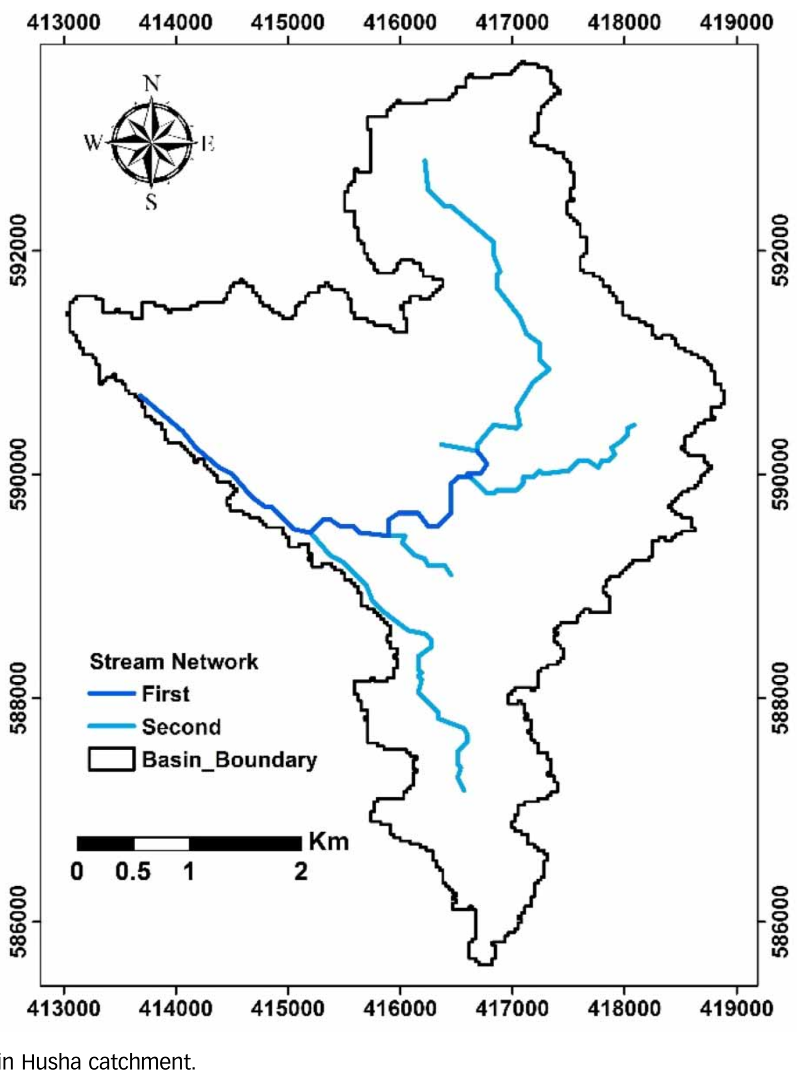

Figure 5 | Stream network in Husha catchment.

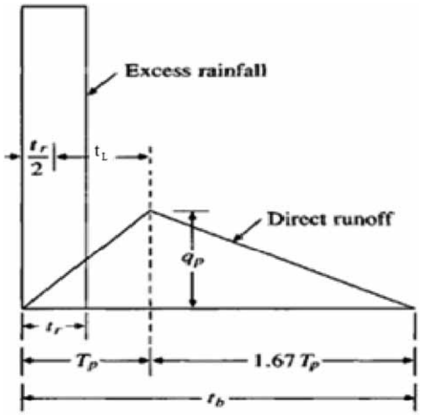

Figure 6 | Triangular unit hydrograph (Chow *et al.* 1988).

Conservation Service (NRCS) (formerly Soil Conservation Service (SCS)) in 1972, known as Watershed Lag Method (Kent *et al.* 2010).

$$V = 0.5\ ((q_p)(t_b)) \tag{1}$$

$$V = 0.5\ q_p\ (T_p + t_{rc}) \tag{2}$$

$$t_b = T_p + t_{rc} \tag{3}$$

$$t_{rc} = 1.67T_p \tag{4}$$

$$t_b = T_p + 1.67T_p \tag{5}$$

$$t_b = 2.67T_p \tag{6}$$

$$q_p = V/0.5(2.67T_p) \tag{7}$$

$$q_p = 0.749\left(\frac{V}{T_p}\right) \tag{8}$$

where q_p is expressed as mm h^{-1} mm^{-1}; V is expressed as mm; T_p and t_{rc} are expressed as hours. To determine the complete shape of the synthetic unit hydrograph from the non-dimensional (q/q_p versus t/t_p) hydrograph, the time to peak was computed as follows

$$T_p = (t_L) + (t_e/2) \tag{9}$$

where t_L is lag time (h) from the centroid of rainfall excess to peak discharge (q_p) and t_e is the excess rainfall duration (unit duration) (h) (Figure 6). The lag time (t_L) can be estimated either directly from the watershed characteristics using the curve number (CN) (Table 2) or by using the time of concentration, which is the time required for a certain catchment area to completely contribute to the discharge at the outlet (time required for the most remote drop of water to reach the catchment outlet). The time of concentration varies with the type of surface, ground slope, size and shape of drainage area, length of the flow line, rainfall intensity, and vegetation cover of the catchment area. Time of concentration (t_c) was calculated by applying the following SCS lag equation

$$t_L = \frac{L^{0.8}\ (1000/\mathrm{CN}) - 9)^{0.7}}{441\ (Y^{0.5})} \tag{10}$$

$$t_L = 0.6t_c \tag{11}$$

Table 2 | Curve numbers according to land use description and hydrological soil group (USSCSE 1986)

Land use description	Hydrological soil group A	B	C	D
Commercial, raw houses, and townhouses	80	85	90	95
Fallow, poor condition	77	86	91	94
Cultivated with conventional tillage	72	81	88	91
Cultivated with conservation tillage	62	71	78	81
Lawns, poor condition	58	74	82	86
Lawns, good condition	39	61	74	80
Pasture or range, poor condition	68	79	86	89
Pasture or range, good condition	39	61	74	80
Meadow	30	58	71	78
Pavement and roofs	100	100	100	100
Woods or forest thin stand, poor cover	45	66	77	83
Woods or forest, good cover	25	55	70	77
Farmsteads	59	74	82	86
Residential 1/4 acre lot, poor condition	73	83	88	91
Residential 1/4 acre lot, good condition	61	75	83	78
Residential 1/2 acre lot, poor condition	67	80	86	89
Residential 1/2 acre lot, good condition	53	70	80	85
Residential 2 acre lot, poor condition	63	77	84	87
Residential 2 acre lot, good condition	47	66	77	81
Roads	74	84	90	92

Note: 1 acre = 4,047 m^2

where L is the length of the mainstream or hydraulic length of the watershed (m), CN is the curve number for various soil/land use combinations ($50 \leq 95$), and Y is the average catchment slope (m/m). The equation can also be expressed as:

$$Q_p = 2.08\left(\frac{A_w}{T_p}\right) \tag{12}$$

where Q_p is the peak discharge of rainfall excess ($m^3\ s^{-1}\ cm^{-1}$), A_w is the watershed area (km^2), and T_p is expressed as hours. Synthetic unit hydrograph could be derived from known q_p, T_p, and a specified dimensionless UH.

The determination of the curve number (CN) is crucial as it represents the soil function and land use characteristics of the basin (Figure 7). Curve numbers of the area ranged between 89 and 95. The factors including vegetal cover and antecedent moisture conditions (AMC) during the previous five days are also important for CN estimation. The CN values are documented for the case of normal condition (AMC-II) (USSCSE 1986), therefore this value needs to be adjusted for dry condition (AMC-I) (Hawkins *et al.* 1985).

In addition to CN, information regarding mainstream length and average slope of the basin is also required for the SCS method, which is acquired through GIS techniques.

3. RESULTS AND DISCUSSION

Hydraulic length, slope, and curve number values of the study area were estimated and utilized to calculate the synthetic unit hydrograph model parameters (time of rise and peak flow). A map of the union between soil texture map and land use/land cover of the study area was used to assess CN values based on the tables published by the United States Department of Agriculture (USSCSE 1986) (Table 2). Based on the soil texture, the hydrological soil group of the study area was noted as D

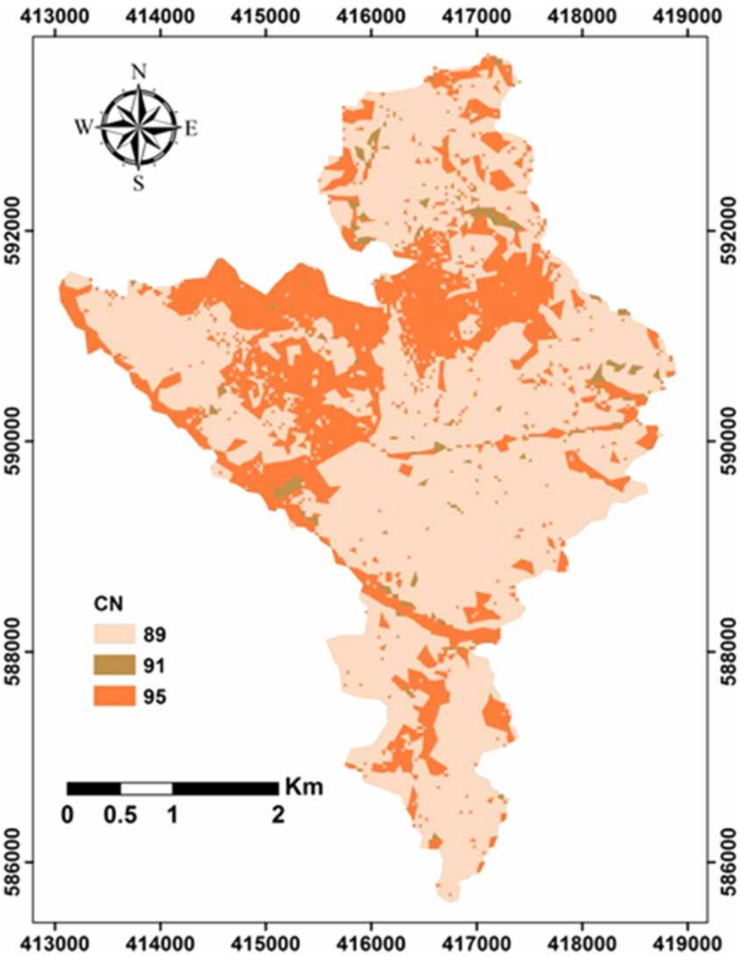

Figure 7 | Curve number values in the study area.

whereas four types (agriculture, soil, urban, and rock) represented the land use (Figure 2). The curve number of the study area was calculated as 81 for the dry condition (AMC-I). The results revealed a high to moderate high runoff potential in the area with a clay loam texture. GIS measurement tools estimated all the hydrological parameters for deriving synthetic unit hydrograph. The results depicted the drainage area of 18.43 square kilometers, mainstream catchment length of 4.5 kilometers, watershed slope of 10.5%, 3.5 km length from the main channel outlet to the catchment centroid, and 4.5 km length of the main channel, whereas the maximum height of the basin H_{Max} was found to be 765 m.

Table 3 represents the peak discharge (Q_p) of rainfall excess ($m^3\ s^{-1}\ cm^{-1}$) for different durations. The peak discharge Q_p decreased with the increased time of excess rainfall. The maximum peak discharge of 27.35 m^3/s for each centimeter of rainfall excess was reached after 84 minutes of starting the rainfall storm for 5 minutes duration of rainfall excess whereas the minimum peak discharge of 5.21 m^3/s for each centimeter of rainfall excess was reached after 7 hours and 22 minutes for a 12 hours duration of rainfall excess (Figures 8(a)–8(d) and 9(a)–9(e)).

Figures 8(a)–8(d) and 9(a)–9(e) depict that the ascending tip of the basin hydrograph possesses a steeper slope than the falling tip. It represents a short concentration time and a high possibility of flooding in the catchment area (Figure 10).

3.1. SCS synthetic unit hydrographs model verification

Multiple techniques could validate the flood hydrograph parameters. During the current study, the topographic map validated the dataset used for the estimation of watershed parameters. A topographic map could be used to determine the watershed contour lines. The contours refer to the surface of land at a particular elevation, which is important for analyzing the water flow patterns. The water flows downhill and perpendicular to contours, therefore, hydrology parameters of a watershed can

Table 3 | Peak discharge (Q_p) of rainfall excess ($m^3\ s^{-1}\ cm^{-1}$) for different durations of rainfall excess

t_e (h:m)	T_p (h:m) S.U.H	t_{rc} (h:m)	t_b (h:m)	Q_p (m^3/s/cm) S.U.H
00:05	01:24	02:20	03:45	27.35
00:10	01:27	02:25	03:51	26.56
00:20	01:32	02:33	04:05	25.11
00:30	01:37	02:41	04:18	23.81
01:00	01:52	03:07	04:58	20.61
02:00	02:22	03:56	06:18	16.24
03:00	02:52	04:44	07:38	13.40
06:00	04:22	07:07.5	11:38	8.79
12:00	07:22	12:17	19:39	5.21

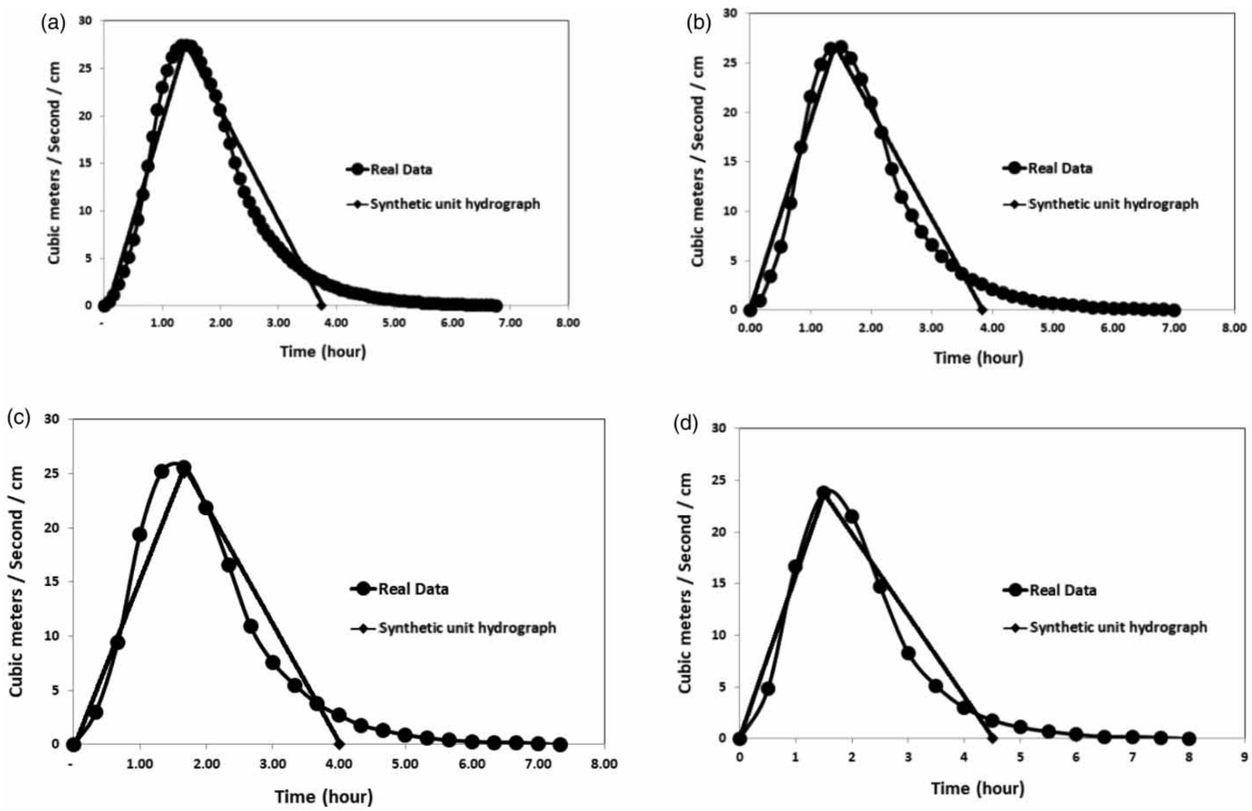

Figure 8 | Triangle unit hydrograph for (a) 5 minutes, (b) 10 minutes, (c) 20 minutes, and (d) 30 minutes of excess rainfall and the estimated hydrograph based on the real rainfall data for the same duration of rainfall excess.

be determined from a topographical map based on the intervals scale. Seventy-nine percent matching percentage of DEM parameters and topographical map parameters efficiently evaluated the DEM dataset used in this study. Kappa coefficient was also applied to assess the accuracy of satellite image classification whereas the error matrices of maximum likelihood classification assessed the classification accuracy of 200 randomly selected samples. The producer's and user's accuracies of both pixel-based classifications revealed a high matching percentage of the vegetation class as it is scattered and could be easily distinguished through satellite images. The vegetation also exhibits a unique spectral reflectance in the thermal bands. The overall accuracies of the maximum likelihood classification remained 82%.

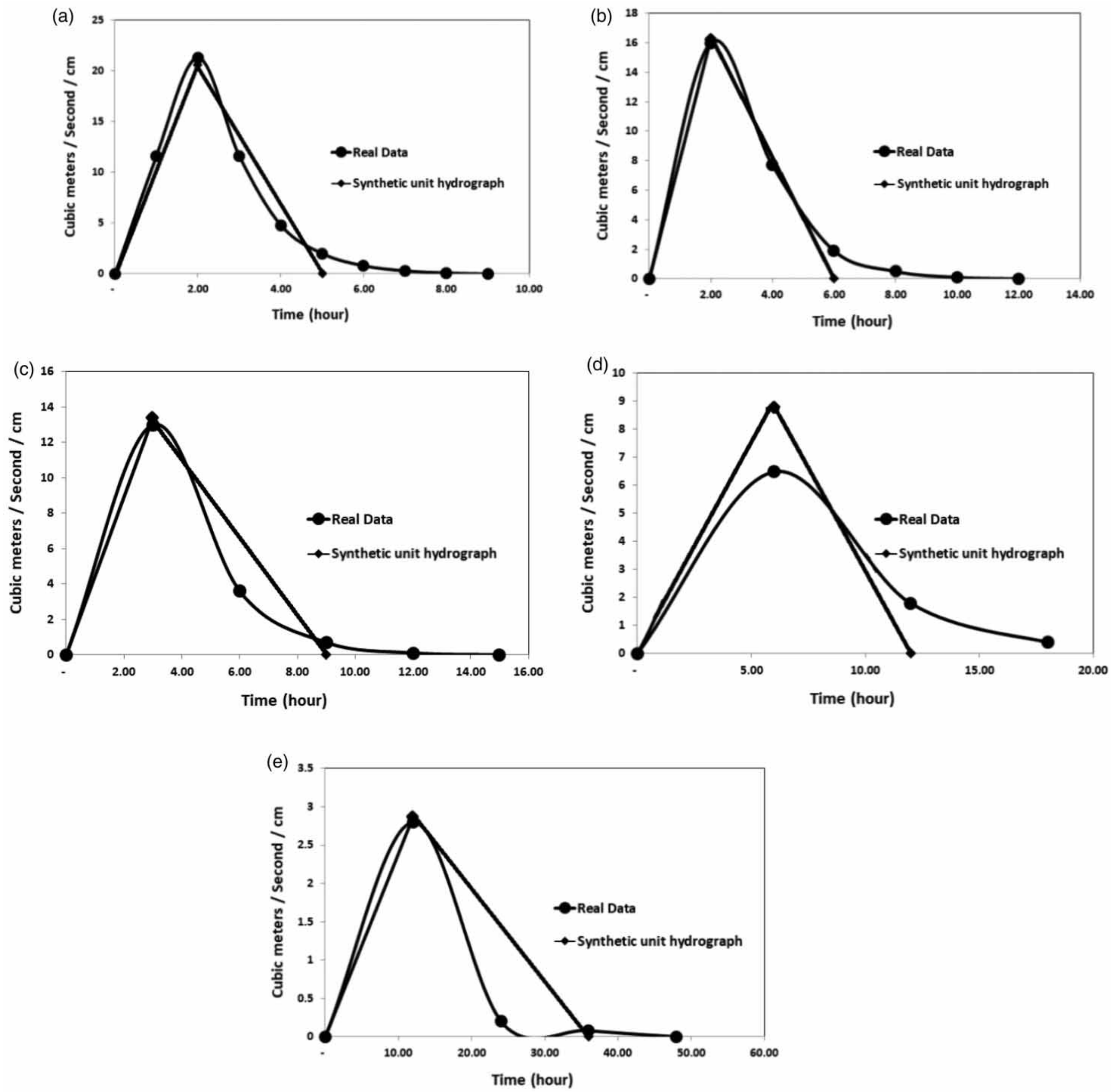

Figure 9 | Triangle unit hydrograph for (a) 1 hour, (b) 2 hours, (c) 3 hours, (d) 6 hours, and (e) 12 hours of excess rainfall and the estimated hydrograph based on the real rainfall data for the same duration of rainfall excess.

SCS synthetic unit hydrograph model parameters (time of rise and peak flow) were validated by selecting nine events of daily rainfall data that occurred during a storm event between 1 and 4 January 2000 in Housha catchment area. Hydrologic modeling system (HEC-HMS), which is a product of the Hydrological Engineering center within the U.S. Army Corps of Engineering, was applied for the runoff estimation from the rainfall data of Housha catchment. The validity and feasibility of the SCS synthetic unit hydrograph model based on the GIS data were further confirmed by comparing the simulated runoff with the estimated runoff process from the measured rainfall data of the watershed (Figures 8(a)–8(d) and 9(a)–9(e)). The results revealed coinciding hydrographs of the simulated runoff process and the estimated runoff process for the two parameters (time of rise and peak flow) (Table 4). The results depicted a high precision and practicability of the SCS synthetic unit hydrograph model used in the Housha catchment area.

Figure 10 | Housha tunnel in November 2019 (Almadenah news 2016).

Table 4 | Peak discharge (Q_p) (m^3 s^{-1} cm^{-1}) and time of peak (T_p) for the SCS synthetic unit hydrographs model and the estimated ones from the measured rainfall data of different durations of rainfall excess (t_e)

t_e (h:m)	T_p (h:m) S.U.H	T_p (h:m) estimated from real data	Q_p (m^3/s/cm) S.U.H	Q_p (m^3/s/cm) estimated from real data
00:05	01:24	01:25	27.35	27.4
00:10	01:27	01:30	26.56	26.6
00:20	01:32	01:40	25.11	25.6
00:30	01:37	01:30	23.81	23.8
01:00	01:52	02:00	20.61	21.3
02:00	02:22	02:00	16.24	16.0
03:00	02:52	03:00	13.40	13.0
06:00	04:22	06:00	8.79	6.5
12:00	07:22	12:00	5.21	2.8

4. CONCLUSION

According to the land-use description and hydrological soil group classification, the soil of the study area was hydrologically classified as D group. The clay loamy soil texture of most of the study area is characterized by a high runoff potential and a very low infiltration rate. Approximately 70% of the total area is considered arid lands. The curve number of the study area was calculated as 81 for dry conditions (AMC-I) whereas the slope values varied between 0 and 35%. Despite the 4.5 kilometers length of the mainstream of the catchment and 10.5% watershed slope, the time of concentration is relatively low as compared to other similar catchments. The fan-shaped topography might be the reason behind this phenomenon. High rainfall intensity for short periods is a characteristic of the area that increases the potential of flood occurrence.

The results revealed a strong alignment of simulated runoff processes of the SCS synthetic unit hydrograph model and estimated runoff process based on the measured rainfall data parameters (time of rise and peak flow). More than 80% accuracy clearly depicts that the integration of remote sensing, GIS, and SCS model could serve as an important tool for the runoff simulation of small ungauged watershed areas such as the Housha catchment area of Jordan. This methodology could also be useful in other ungauged watersheds.

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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