

Intelligent estimation of the discharge peak in Al Aqiq drainage basin: A case study in Al Madinah Munwwarah region

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Abstract. The NRCS-CN model is one of the commonly used models for the estimation of discharge peak in a watershed in Saudi Arabia using the DEM outputs and daily rainfall data. The current study aims to classify the sub-basins using rainfall volume, rain off volume and estimate the discharge peak using NRCS-CN method. The drainage map of the studied sub-basin areas was extracted from SRTM Dem 30 m outputs. To estimate the surface runoff and its discharge peak, the drainage area was divided into four tributary basins for Wadi Al-Aqiq using the WMS software outputs from SRTM Dem 30 m. The extracted sub-basins were Wadis Rim, Al Yitimah, Al Ishsh and Sha'ib Ruwawah. The results indicate the importance of the integrated use of the digital processing outputs of the DEM in extracting the morphometric variables necessary in calculating the concentration-time, unit peak discharge and the land resources map in determining the runoff curve. In addition, the weighted curve numbers were ranged between 88.4, 89.9, and 92.1 in Wadi Al Ishsh, wadi Rim, and wadi Al Aqiq watersheds, respectively. It was evident that the attained results can be calibrated by the actual recorded discharge and related to several watersheds.

Keywords: NRCS method; curve number; maximum daily rainfall; runoff depth; discharge peak; sub basins; Wadi Al Aqiq; Saudi Arabia

1. Introduction

In the watershed analysis, developing reliable hydraulic flood models that offer precise estimations of flood threats and risks in urban regions is vital to define the best approaches for flood hazard mitigation, river morphology, and sediment transport (Ballesteros *et al.* 2011, Haghazari *et al.* 2020). The morphometric analysis used the micro-watersheds for studying different linear and aerial parameters (Li *et al.* 2018, Chen *et al.* 2019, Liu *et al.* 2020d, Shen *et al.* 2020, Zuo *et al.* 2020a, b, Jia *et al.* 2021, Wang *et al.* 2021). The morphometric analysis is an essential tool for prioritization of micro-watersheds, even without considering the soil map (Biswas *et al.* 1999, Magesh *et al.* 2013, Yang *et al.* 2015, 2020a, Ding *et al.* 2019, Liu *et al.* 2020f, Lv *et al.* 2020b, Wang *et al.* 2020f, Xu *et al.* 2020c, Zuo *et al.* 2020c). Earlier morphometric analysis has been performed by several researchers using topographic maps (Azab 2009, Ismail *et al.* 2010). The study of the hydrogeological behaviour of the drainage basin requires the morphometric analysis of a drainage basin, using climate, geology, and geomorphology variables (Stralher 1964, Shi *et al.* 2017a, 2018, Chao *et al.* 2018, Liu *et al.* 2019, Su *et al.* 2019b, Zhao *et al.* 2019, Hu *et al.*

2020b, Peng *et al.* 2020). Some empirical relations between landform characteristics and the controlling variable of climate, hydrology, vegetation, and soil properties were proposed by Horton (1945). These empirical relations became the basis of the quantitative description of the form and process of the drainage basin network and their interrelationships (Shi *et al.* 2017b, Li *et al.* 2019b, Xue *et al.* 2019, Chen *et al.* 2020, Cheng and Liu 2020, Hu *et al.* 2020a, Ren *et al.* 2020, Wang *et al.* 2020g, Bai *et al.* 2021). Remote sensing and GIS have contributed to the development of morphometric analyzing using the DEM outputs (Abou El-Magd *et al.* 2010, Arnous *et al.* 2011, Youssef *et al.* 2011, Tera'at El Mansuriyah St 2012, Magesh *et al.* 2013, He *et al.* 2019, Su *et al.* 2019a, Li *et al.* 2020b, Zhang *et al.* 2020d). In hydrology, the term "peak discharge" refers to the maximum concentration of runoff from the basin region (Huang *et al.* 2019, Wang *et al.* 2019b, Duan *et al.* 2020, Jia *et al.* 2020, Mi *et al.* 2020, Zhong *et al.* 2020). The concentrated flow of the basin highly inflated and overtops the natural or artificial bank, and this might be termed flood (Roy and Mistri 2013, Gao *et al.* 2016, He *et al.* 2018b, Liu *et al.* 2018, 2020c, g, Zhu *et al.* 2018a, Wang *et al.* 2019a, Bao *et al.* 2020). In general, the drainage area of Al Aqiq wadi was not subjected before for the studies concerning morphometric and their relations to estimate the discharge peak (Hu *et al.* 2020c, Lei *et al.* 2020, Li *et al.* 2020d, Lv *et al.* 2020a, Shi *et al.* 2020a, b, Zhao *et al.* 2020b, c). Therefore, the main purpose of the present study is to use the morphometric parameters for understanding the hydrological behaviour of Al Aqiq wadi.

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The intention is to study the flood phenomenon and its environmental and economic impact on the urban cities located near the outlet of the drainage areas or in the drainage areas of the different Wadi in the Kingdom of Saudi Arabia, which is increasing, especially after the losses due to the floods that struck Jeddah on 6/12/2008. The number of deaths was 117, and material losses have been estimated at about 2.8 billion Saudi riyals. Also, the flood that happened on 25/11/2009 in Mecca caused 48 deaths and about 900 people were saved. The flood of 17/02/2005 and 18/02/2005 in Medina prevented pilgrims from entering the city by the road of Medina-Mecca (Hijra Road) on the Aqiq Wadi and caused 29 deaths with material losses estimated at 500 million riyals. The study of the floods and their impact is a big problem for the researcher due to the absence of hydrometric stations and the actual measurements of the flow on the Wadis (Gao *et al.* 2018a, b, c, d, 2019a, Gao and Zhang 2019, Wang *et al.* 2018, Yang *et al.* 2020c). The absence of the hydrological data is a significant obstacle in understanding and analyzing the surface drainage system of the Wadis (Gao *et al.* 2019b, Guo *et al.* 2019, 2020, Liu *et al.* 2020a, Qu *et al.* 2020, Yan *et al.* 2020, Yang *et al.* 2020d). It makes difficult the application of hydrological models to estimate the flow one regarding the possible alternatives which can help us to study the phenomenon of flooding in the dry basins like the Aqiq Basin in Madinah (Wang *et al.* 2015, Feng *et al.* 2020a, Li *et al.* 2020c, Lin *et al.* 2020, Yu *et al.* 2020, Zhang *et al.* 2020e). Many studies have tried to analyze the properties of the surface drainage system for some Wadis in the Kingdom of Saudi Arabia, like studies of (Sorman 1993, Sorman *et al.* 1994). Pavement materials always play a main role in runoff discharge and researchers have typically tried to enhance the water penetration rate and permeability of pavement (Wu *et al.* 2019a, Cheng *et al.* 2016, Chen *et al.* 2017, 2018, Al Kajbaf *et al.* 2018, Dinh-Cong *et al.* 2018, He *et al.* 2018a, Zhu *et al.* 2019b). Porous concrete has been employed in the road pavement due to the promising permeability and considerable mechanical properties (Long *et al.* 2015, Afsar Dizaj *et al.* 2018, Zhu *et al.* 2018b, 2020b, Dinh-Cong *et al.* 2019, Ju *et al.* 2020, Ni *et al.* 2020, Yang *et al.* 2020b, Chen *et al.* 2021). In terms of rainfall management, various methods have been introduced to dispatch input flood. During heavy rains, piping is proven to be an effective technique (Xiong *et al.* 2016, He *et al.* 2018c, Lu *et al.* 2019, Zhu 2019, Asadolahi and Fanaie 2020, Ganesan *et al.* 2020, Sun *et al.* 2020b, Zhang 2020). Also, pipe net can be a reliable solution, but some problems such as difficult installation and high cost in construction are challenging factors (Fanaie *et al.* 2016, Xu *et al.* 2018b, Yang *et al.* 2018, Hu *et al.* 2019, Huynh-Van and Tran-Thanh 2019, Wu *et al.* 2019a, b, 2020b, Dong and Cui 2021). The annual rainfall may experience different values in each year, hitherto terrain shapes and sizes may not be stable in decades and these differences always impose difficulties for infrastructure design and constructions (Fanaie *et al.* 2015, Jiang *et al.* 2018, Xu *et al.* 2018a, Qi and Fourie 2019, Tsai *et al.* 2019, Zhang *et al.* 2019, Zhu *et al.* 2019a, Wang *et al.* 2020e, Zhang *et al.* 2020c). Water transfer structures are designed in both

underground and above ground categorize (Liu *et al.* 2015, Guan *et al.* 2019, Ni *et al.* 2019b, Feng *et al.* 2020b, c). Underground structures are always in low danger from flood, overflow and other types of runoff outburst than above ground structures (Singh *et al.* 2011, Fanaie and Ezzatshoar 2014, Afrazi and Rouhanifar 2019, Fanaie *et al.* 2019, Ni *et al.* 2019a, Han *et al.* 2020, Huang *et al.* 2020a, Qi *et al.* 2020, Xu *et al.* 2020b, d). Therefore, engineers are always in trouble to build optimum drainage facilities especially when the hydrological studies, input value, and other data are insufficient (Fanaie *et al.* 2017, He *et al.* 2020, Wu *et al.* 2020a, Xiong *et al.* 2020, Zhang *et al.* 2020b, d, Zhao *et al.* 2020a, Zhu *et al.* 2020a). Basin topology has been always an interesting topic for studies about hydrological problems (Abedini *et al.* 2020, Gholipour *et al.* 2020, Li *et al.* 2020a, Zhang *et al.* 2020a, Zhang and Mousavi 2020, Zheng *et al.* 2020). Drainage properties of the basin depend on different characteristics of the terrain and hydrological lines that are different along a season (Afrazi *et al.* 2017, Abedini *et al.* 2019, Fanaie and Moghadam 2019b, Li *et al.* 2019a, Zhang *et al.* 2019, Jin *et al.* 2020, Wang *et al.* 2020a, b, Xu *et al.* 2020a). These challenging points have attracted scholars' attention to find a reliable way for prediction and estimation of the discharge peak of the drainage basin (Fanaie and Tahriri 2017b, Abedini and Zhang 2020a, Huang *et al.* 2020b, Liu *et al.* 2020e, Lu *et al.* 2020, Sun *et al.* 2020a, Wang *et al.* 2020c, d). In recent years, considerable progress in the development of hydrological models has been observed. In this regard, different techniques have been proposed for hydrological modeling. Artificial intelligence (AI) as one of the reliable methods has shown its ability in data prediction and estimation in various fields such as engineering, medical diagnosis, decision making etc. (Mohammadhassani *et al.* 2013, 2014, Toghroli *et al.* 2014, 2016, Safa *et al.* 2016, Afrazi *et al.* 2018, Sadeghipour Chahnasir *et al.* 2018, Sedghi *et al.* 2018, Katebi *et al.* 2019, Mansouri *et al.* 2019, Shariati *et al.* 2019c). In terms of hydrologic modeling, several investigations have been performed using AI-based models. Particularly, Evolutionary computation, Fuzzy logic and Classifiers and statistical learning methods as three subsets of AI are extensively applied in hydrological and environmental applications (Shariati *et al.* 2019c, Afrazi *et al.* 2017a, Shariati *et al.* 2019a, b, Trung *et al.* 2019, Alabduljabbar *et al.* 2020, Alaskar *et al.* 2020a, b, Alyousef *et al.* 2020, Cao *et al.* 2020a, b, c, d, Liu *et al.* 2020b, Safa *et al.* 2020, Shariati *et al.* 2020a, b, c). The absence of hydrometric stations presents an essential problem for identifying and analyzing the characteristics of the hydrological system in the drainage basins of Saudi Arabia. Therefore, this research uses the NRCS-CN method to provide the runoff depth and discharge peak of Al Aqiq drainage basin located in Al Madinah Munawwarah area. The principal aim of this research is to estimate the runoff depth and discharge peak using the maximum daily rainfall recorded during 1070-2017 in wadi Rim, Shai'ib Ruwawah, Wadi Al Yitimah and Wadi Al Ishsh, tributaries of Wadi Al Aqiq.

2. Materials and methods

To achieve the objectives of the study, the SRTM Dem 30 m method was used to compute the relief and morphometric variables applied in the hydrological model of NRCS-CN. This model has been employed using the maximum daily rainfall recorded in the rainfall stations of Um Al Birak (J112), Al Madinah Munawwara (M001), Bir Al Mashī (M103) and Al Faqir (J109) during the 31 years from 1974 to 2004. The drainage area of wadi Aqiq watershed (5130.8 km²) has been divided into four sub-basins tributaries. These sub-basins are wadi Rim (776.1 km²), wadi Al Yitimah (1037.5 km²), wadi Al Ishsh (1193.0 km²) and Sha'ib Ruwawah (527.9 km²). The hydrologic parameters of the storm type II are used to determine the equations for predicting the discharge peak related to the rainstorms of 25 mm, 40 mm, 50 mm and 100 mm in each studied sub-basin. Al Aqiq watershed is selected because of its hydrological importance with a drainage area of 5130.8 km² and an outlet oversees on the urban area of the Madinah Munawwara city. The total drainage area of the sub-basins is 3534.5 km², equivalent to 68.9% of the total drainage area of the Wadi Aqiq basin.

2.1 Study area

Al Aqiq wadi is one of the most famous Madinah wadis. It has called the blessed wadi by the Prophet Muhammad. It meets with Btahan and Qana at Moujama'a Al Assial. These wadis flow into Hamadh wadi, which is towards the Red Sea. Al Aqiq drainage basin is located in geological Arabian Shield in the western part of Saudi Arabia in the region of the Madinah. The catchment of Wadi Aqiq lies between the following geographic coordinates: 39°16'13.2"E; 40°05'8.5"E and 23°32'50.4"N; 24°31'41.1"N (Fig. 1). The drainage basin area of Wadi Al Aqiq is characterized by arid climate rainfall pattern with high temporal and spatial variability that takes place primarily during the winter and spring seasons (Subyani *et al.* 2010, Alahmadi *et al.* 2016). The seasonal rainfall events are caused by the combination of disturbances from the winter Mediterranean and the Sudan trough, which usually generate extreme rainfall convective events over Madinah region and its surrounding areas (Subyani and Al-Ahmadi 2011, Alahmadi *et al.* 2016). The geological properties of Al Aqiq drainage basin were extracted from the Umm Al Birak geological quadrangle (Sheet 23D, GM-87C) and Al Madinah geological quadrangle (Sheet 24D, GM-52C). The geological map of Al Aqiq drainage basin contains different volcanic, metamorphic and intrusive rocks with sedimentary formations crossed by some faults. The geology of the studied basin includes the geologic formations from the Precambrian to the Quaternary, as shown in the geological map, as shown in Fig. 2. The catchment is one of the significant five catchments in the central part of the Tihamah-Hijaz (the middle part of the Arabian Shield) region. It is bounded from the east by Qa'a Hadawda'a; from the north by Chaib Bathane drainage basin and Wadi El Aqoul drainage basin; from the south by El Yatama

drainage basin, Kathara (1235 m), and the Riba'a (1528 m) mountains; and from the west by Wadi Malal drainage basin. Al-Aqiq Valley floods in winter like a large river. It flows to the west of Mount Eir, and passes through Thul Hulaifa, until it reaches the end of Eir, to turn eastwards and meet Bathan Valley near the Qiblatain area. Then heads north-west a little, then north, to meet Qanat Valley, coming from the east of Medina at Zaghaba area. The Wadi Aqiq basin, as a typical hydrologic system in the western part of the Arabian Peninsula, is composed of a funnel-like shape catchment. The general flow direction of the streams in Al-aqiq basin goes from southwest to northeast following the main direction of the Arabian Shield structure. The morphometric parameters of Al-aqiq basin imply that the basin has the largest area with about 5130.8 km²; the perimeter is about 534 km, and the total mainstream length is about 108.5 km. The relief altitudes are ranging from 2362 m on Jabal Wergane and 580.5 m at the outlet. Al Aqiq main stream descends from the Qadas and Wergane mountains with a length of 163.2 km. These mountains are located in Harat El Hijaz in the south and range about 82 km from Madinah. Wadi Aqiq takes many names along its



Fig. 1 The geographic location of Wadi Al Aqiq drainage basin

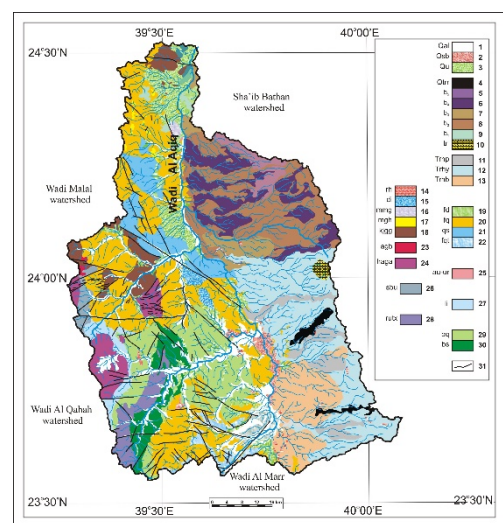


Fig. 2 Geological map of Wadi Al Aqiq drainage basin

course; Naqi' in the high stream, Al Asad Al Hassi between Eir mountain, and Hamra'a and Aqiq next Dhou Al Halifa. Many of tributaries wadis flow into Wadi Aqiq, like Chaabine, Dhalama, Al Ouch, El Yatama, Dhaf, Malaha, Rym, Naqi', Khanga, Hadha and Sudayr. Also, many tributaries feed Wadi Aqiq like Al lihyane, Arar, Nakhal Malha and Slayem Massaid. The drainage basin system is internal and characterized by the dendritic pattern flowing into the inland basins. The ratio topographic slope of the Aqiq basin varies between 30% in the high relief and 3% along the mainstream (even the outlet). The drainage basin has medium drainage density with a value of 1.72 km/km², a relief ratio of 0.1, and a circularity of 0.73 and drainage pattern has a high dendritic shape. These ratios indicate a high permeable landscape in Al Aqiq drainage basin (Mahmoud and Alazba 2015). Rainfall record plays a significant role in the assessment of discharge peak using The SCS Dimensionless Unit Hydrograph method. In the arid region, studies on rainfall are rather scarce due to intricacy and constraint of the available data. Therefore, this study uses maximum daily rainfall extracted from historical precipitation records during 1974-2004 in 5 rainfall stations in and around Wadi Al-Aqiq basin. The rain analysis of the Al-Aqiq basin was the subject of studies on hydrological modelling (Alahmadi *et al.* 2016) and climate change (Abd Rahman *et al.* 2017, Tian *et al.* 2020). Also, Al-Aqiq wadi and surrounding Madina area were the subjects of the environmental rehabilitation project. Besides, Ibrahim *et al.* (Ibrahim *et al.* 2015) used the integration of Point and Remote Sensing Data for Monitoring Surface Runoff around Madinah City.

Note:

Holocene deposits:

1- Qal: sand, grave and silt deposits in wadis, 2- Qsb: sabkhah and kahbrah deposits, 3- Qu: slope scree, terrace, fan and dune deposits.

Tertiary-Quaternary volcanic rocks:

5- Qtrr: Rashid formation, 5- b₅, 6- b₄: Quaternary basalt, 7- b₃, 8- b₂, 9- b₁: Tertiary basalt, 10- tr: volcanoc rocks, 11- Trhp: least weathered flows, 12- Trhy: moderately weathered flows, 13- Trhb: highly weathered flows, Intrusive rocks (14- rh: granophyre and subvolcanic rhyolite, 15- di: diabase and diorite, 16- mmg: microgranite,

17- mgh: granophyre, rhyolite and microgranite, 18- kjgg: Jayyah complex), Furayh group (19- fd: Dawnak formation, 20- fq: Qidirah formation, 21- qs: Dehial sedimentary member), 22- fqt: terraceous member, Intrusive rocks (23- agb: gabbro, 24- haga: Awf complex), 25- au-ur: Al Ays group, Intrusive rocks (26- sbu: gabbro and diorite), 27- li: Milhah formation, Intrusive rocks (28- rutx: tonalite - rhyolite suite), Birak group (29- bq: Qahah formation, 30- bs: Suri formation. Birak), 31- Fault.

2.2 Materials

The present study aims to classify the sub-basins using rainfall volume, rain off volume and estimate the discharge peak using NRCS-CN method. The drainage map of the studied sub-basin areas was extracted from SRTM Dem 30m outputs available in King Abdulaziz City for Science and Technology. To estimate the surface runoff and its discharge peak, the drainage area was divided into four tributary basins for Wadi Al-Aqiq using the WMS software outputs from SRTM Dem 30 m. The extracted sub-basins were Wadis Rim, Al Yitimah, Al Ishsh and Sha'ib Ruwawah, as shown in Fig. 3. Moreover, ArcGIS 10.1 software was used to extract drainage networks from the DEM using WMS software. The morphometric parameters



Fig. 3 The studied sub-basins of Wadi Al Aqiq

Table 1 Morphometric parameters of studied sub-basins

Morphometric parameter	Sub Basins				Al Aqiq basin
	Al Ishsh	Ruwawah	Al Yitimah	Rim	
Basin area (km ²)	1193.0	527.9	1037.5	776.1	5130.8
Basin perimeter (km)	251.2	153.6	240.9	193.3	534.0
Basin length (km)	41.8	39.0	48.1	37.2	108.5
Maximum elevation (m)	1726.0	1270.0	2124.0	2304.0	2304.0
Minimum elevation (m)	851.0	690.0	851.0	720.0	589.0
Mean elevation (m)	1012.1	912.1	1139.9	1044.8	971.2
Mean width (km)	28.5	13.5	21.6	20.9	47.3
Mean slope (%)	5.0	3.3	18.0	16.8	9.5

of each sub-basin were computed using the WMS outputs and are given in Table 1.

2.3 Hydrologic model

The hydrologic model used in this study was followed by the NRCS-CN model application, which is containing the methodological steps, as follow:

2.3.1 Runoff depth estimation

In ungauged watersheds, the estimation of the expected runoff resulting from rainfall is essential for flood hazards studies. In arid regions, the direct runoff estimation and flood analysis are often related to rainfall, in the absence of hydrometric. Many hydrological models have been derived to predict. Among them is the Soil Conservation Service Curve Number (SCS-CN) method renamed Natural Resources Conservation Service (NRCS) method in 1994 (Ferguson 1998). The NRCS-CN method is widely used, is the estimates runoff depth by the following equations

$$Q = \frac{[P - I_a]^2}{[P - I_a] + S}, \text{ if } P > I_a \quad (1)$$

$$Q = 0, \text{ if } P < I_a \quad (2)$$

$$I_a = 0.2S \quad (3)$$

where P is the rainfall depth (mm), Q is the Runoff depth (mm), I_a the initial abstraction (mm) and S is the maximum

potential storage which is given by

$$S = \frac{25400}{CN} - 254 \quad (4)$$

where CN is the curve number parameter.

Furthermore, the CN values are ranged from 30 to 100 and are extracted from the tables formulated by the NRCS (1986). The minimum values indicate low runoff. However,

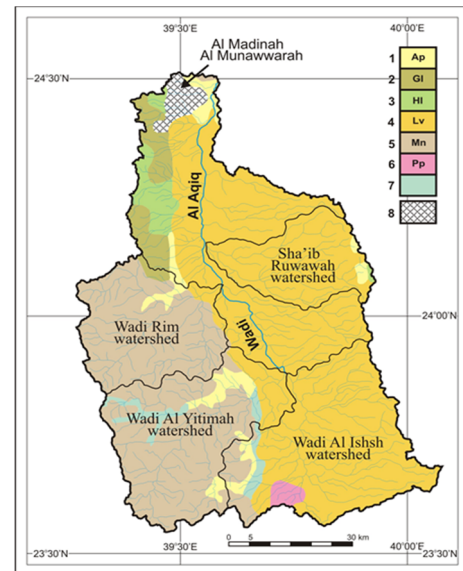


Fig. 4 Land resources map of Wadi Al Aqiq watershed

Table 2 Estimated weighted curve numbers of studied sub-basins

SB	Variable	Ap	GI	Lv	Mn	Pp	HI	Wd	Total
Wadi Ruwawah	A (km ²)	15.8	0	512.1	0	0	0	0	527.9
	%	3.0	0.0	96.8	0.0	0.0	0.0	0.0	100
	CN	55	0	91	0	0	0	0	---
	CNw	1.6	0.0	88.1	0.0	0.0	0.0	0.0	89.7
Wadi Rim	A (km ²)	19.4	6.3	11.6	738.8	0	0	0	776.1
	%	2.5	0.8	1.5	95.2	0.0	0.0	0.0	100.0
	CN	55	55	91	91	0	0	0	---
	CNw	1.4	0.4	1.4	86.6	0.0	0.0	0.0	89.8
Wadi Al Yitimah	A (km ²)	28.0	0	108.9	867.4	0	0	33.2	1037.5
	%	2.7	0.0	10.5	83.6	0.0	0.0	3.2	100.0
	CN	55	0	91	91	0	0	55	---
	CNw	1.5	0.0	9.6	76.1	0.0	0.0	1.8	88.9
Wadi Al Ishsh	A (km ²)	26.2	0	1045.1	52.5	46.5	0	22.7	1193.0
	%	2.2	0.0	87.6	4.4	3.9	0.0	1.9	100.0
	CN	55	0	91	91	63	0	55	---
	CNw	1.2	0.0	79.7	4.0	2.5	0.0	1.0	88.4
Total Wadi Al Aqiq	A (km ²)	107.1	31.5	2770.1	2089.1	46.5	29.6	55.9	5130.8
	%	2.1	0.6	57.0	40.7	0.9	0.6	1.1	100
	CN	55	55	91	91	63	91	55	---
	CNw	1.2	0.3	51.9	37.0	0.6	0.5	0.6	92.1

high values express high runoff. The curve number is dependent on multi factors, such as land use, soil type, and moisture condition. These factors are incorporated into a single CN parameter.

2.3.2 Curve number determination

To estimate the runoff from storm rainfall, NRCS uses the runoff curve number (CN) method. Determination of CN depends on the watershed's soil and cover conditions, which the model represents as hydrologic soil group, cover type, treatment, and hydrologic condition (NRCS 1986). In this study, the NRCS-CN of studied sub-basins is determined from the land resources map (1:500,000, Sheet 47) published in 1994 by the Land Resources Department of Agriculture and Water Ministry and illustrated in Fig. 4.

Besides, the land resources map was used to calculate the weighted CN curve of each sub-basin and the data are given in Table 2.

Note:

1: Alluvial plain, 2: Alluvial fans, 3: Hills and rock outcrops, 4: Lava fields and volcanic hills, 5: Mountains, 6: Pediplain with deep soils, 7: Wadi deposits, 8: Urban area.

Source: Land resources map, 1:500000, Sheet 47, Land Resources Department, Ministry of Agriculture and Water, Kingdom of Saudi Arabia.

2.3.3 Discharge peak estimation

The peak discharge validation has been performed through the NRCS for TR-55 (NRCS 1986) model given by the following formulae

$$Q_{peak}(m^3/s) = q_u A Q \quad (5)$$

where Q_{peak} is the peak discharge (m^3/s), A is the drainage area (km^2), and Q is the depth of runoff (mm). Q is calculated from the curve number NRCS equation and q_u is the unit peak discharge ($m^3/s/km^2/mm$), which is calculated from

Table 3 Coordinates of rainfall stations

Station code	Station name	Longitude (E)	Latitude (N)	Elevation (m)
J 109	Al Faqir	39°42'	23°25'	682
J 112	Umm Al Birak	39°14'	23°26'	210
M 001	Madinah Munawara	39°35'	24°31'	590
M 103	Bir Al Mashi	39°32'	24°11'	660

Table 4 Maximum daily rainfall in studied stations

Year	M103	M001	J109	J112	Year	M103	M001	J109	J112
1970	16.9	2.8	34.5	27.5	1995	16.0	27.4	38.0	17.0
1971	20.0	43.6	45.0	4.8	1996	15.5	12.6	21.0	42.0
1972	20.5	16.0	34.0	38.5	1997	27.5	14.8	50.0	23.0
1973	10.0	1.4	6.3	4.5	1998	18.0	21.0	22.0	15.6
1974	22.0	13.4	48.0	15.1	1999	33.0	2.5	28.0	10.0
1975	21.0	8.6	36.0	35.8	2000	49.5	55.0	53.0	10.0
1976	21.0	12.2	29.0	15.5	2001	23.0	23.2	38.0	49.0
1977	22.0	2.0	58.0	8.2	2002	45.0	32.0	20.0	50.0
1978	66.0	5.4	12.0	14.0	2003	6.0	14.8	10.0	11.0
1979	4.3	17.8	25.5	35.5	2004	29.0	27.8	22.0	20.0
1980	8.6	8.8	12.0	8.5	2005	57.0	15.0	10.0	53.0
1981	24.0	26.4	14.0	23.2	2006	16.0	10.5	10.0	27.0
1982	25.0	85.2	48.0	15.3	2007	5.9	6.0	3.0	2.1
1983	23.7	24.2	6.0	14.2	2008	14.0	26.0	16.0	11.4
1984	25.0	18.2	6.0	16.0	2009	11.0	16.3	6.0	4.3
1985	28.0	27.4	21.0	22.2	2010	12.0	14.8	32.0	22.7
1986	21.0	16.6	49.0	20.1	2011	1.5	4.7	37.5	26.6
1987	4.3	4.4	58.0	9.2	2012	18.0	26.5	48.0	76.0
1988	8.0	8.2	9.0	9.0	2013	14.5	13.5	15.0	10.7
1989	10.0	22.3	10.0	0.0	2014	12.5	19.5	19.0	20.0
1990	15.0	17.3	6.0	10.0	2015	10.8	20.0	30.0	21.3
1991	5.0	6.6	33.0	22.0	2016	16.5	15.7	23.0	16.3
1992	21.5	12.8	71.0	22.0	2017	42.0	26.0	20.0	55.0
1993	22.0	89.6	35.0	50.0	Aver	20.2	20.1	26.8	22.1
1994	11.6	29.8	10.0	25.0	SD	13.4	17.7	17.0	16.0

$$q_u = \alpha 10^{[C_0 + C_1 \log t_c + C_2 (\log t_c)^2]} \quad (6)$$

where, α is the conversion parameter (0.000431 in metric units), t_c is the time of concentration, and C_0 , C_1 and C_2 are constants based on the storm type.

The time of concentration, t_c , has been calculated by the equation

$$t_c = 1.67 t_{Lag} \quad (7)$$

$$t_{Lag} = \frac{2.587 L^{0.8} \left[\frac{1000}{CN} - 9 \right]^{0.7}}{1900 H^{0.5}} \quad (8)$$

where t_{Lag} is the lag time (hr), L is the watershed length (m), CN is the curve number, and H is the average watershed land slope (%).

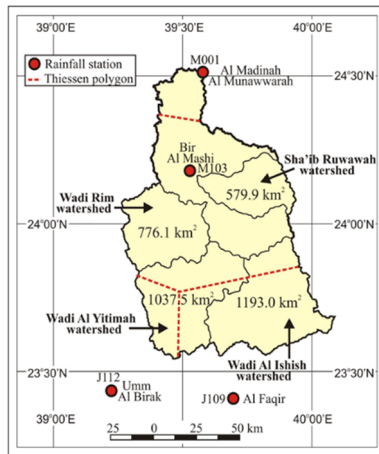


Fig. 5 Thiessen polygons of the studied rainfall stations

2.4 Data collection

In this study, the data which consists of maximum daily rainfall recorded from 1970 to 2017 in four rainfall stations were used and given in Tables 3 and 4. The studied stations of Um Al Birak (J112), Al Madinah Munawwara (M001), Bir Al Mashi (M103) and Al Faqir (J109) contain an integrated and common time series of maximum daily rainfall data recorded during the period 1970–2017. The rain data of these stations contain a common, integrated and continuous time series from January 1970 to December 2017. The selected data can help to predict the runoff depth and discharge peak of wadi Rim (776.1 km²), wadi Al Yitimah (1037.5 km²), wadi Al Ishsh (1193.0 km²) and Shai'ib Ruwawah (527.9 km²), tributaries of Wadi Al Aqiq. These stations were selected because they are surrounding the drainage basin of Wadi Al Aqiq. Fig. 5 illustrates the location of the studied runoff stations.

3. Results and discussion

3.1 Estimation of the model parameters

The NRCS method has been performed to compute the peak discharge using the available rainfall data of four sub-basins area tributaries of Wadi Al Aqiq. The first stage of the results is the estimation of the weighted mean rainfall (P_w) using the Thiessen method as shown in Fig. 5. The results of this stage are given in Table 5. It can be seen that the maximum average of peak discharge was noted for the Wadi Al Ishsh sub-basin. Moreover, the second stage of the results includes the estimation of the maximum potential storage (S) and the initial abstraction (I_a) using the weighted CN_w and the weighted mean rainfall P_w of the studied

Table 5 The weighted mean rainfall of the studied sub-basins

Station	Variable	Wadi Ruwawah	Wadi Rim	Wadi Al Yitimah	Wadi Al Ishsh	Wadi Al Aqiq
M103	km ²	527.9	776.1	485.6	162.2	3250.6
	%	100.0	100.0	46.8	13.6	63.4
	P	20.2	20.2	20.2	20.2	20.2
	P_w	20.2	20.2	9.5	2.7	12.8
J112	km ²	---	---	250.0	---	250.0
	%	---	---	24.1	---	4.9
	P	---	---	22.1	---	22.1
	P_w	---	---	5.3	---	1.1
J109	km ²	---	---	301.9	1030.8	1332.7
	%	---	---	29.1	86.4	26.0
	P	---	---	26.8	26.8	26.8
	P_w	---	---	7.8	23.2	7.0
M001	km ²	---	---	---	---	297.5
	%	---	---	---	---	5.8
	P	---	---	---	---	20.1
	P_w	---	---	---	---	1.2
Mean P_w		20.2	20.2	22.6	25.9	22.0

period 1970-2017. Consequently, the runoff depth is computed and results are given in Table 6.

3.2 Calculate the runoff depth

From the data shown in Table 6, the average of maximum daily rainfall can generate water surplus in sub-basins exceeds 6.7 mm/day in Wadi Al Ishsh, 5.8 mm/day in Shai'ib Ruwawah, 6.3 mm/day in Wadi Al Yitimah, 5.7 mm/day in wadi Rim and 4.4 mm/day in the total drainage area of Wadi Al Aqiq basin. The resulting water surplus can generate surface runoff varies between 4.7 mm/day in the Sha'ib Ruwawah sub-basin and 7.0 mm/day in the wadi Al Ishsh sub-basin. Furthermore, it reaches to 7.9 mm/day in the total drainage area of Wadi Al Aqiq. In addition, the ratio between the mean daily of rainfall and runoff ranges from 23.2% and 27.2% in Sha'ib Ruwawah and Wadi Al Ishsh basins, respectively, and reaches to 35.9% in the total drainage area of the Wadi Al Aqiq basin.

Table 6 Estimation of the maximum potential storage and the initial abstraction

Hydrologic variable	Wadi Ruwawah	Wadi Rim	Wadi Al Yitimah	Wadi Al Ishsh	Wadi Al qiq
CNw	88.7	89.8	88.9	88.4	92.1
S (mm)	29.2	28.5	31.7	33.3	21.8
I _a (mm)	5.8	5.7	6.3	6.7	4.4
P _w (mm)	20.2	20.2	22.6	25.9	22.0
Q (mm)	4.7	4.9	5.5	7.0	7.9

3.3 Calculate the discharge peak

The mean discharge peak for each studied sub-basin is calculated using the constants C₀, C₁ and C₂ of the rainstorms type II, and the results are illustrated in Table 7 and Fig. 6. From the results given in Table 7, it can be seen that the mean daily rainfall which generates the surface runoff, is ranged between 20.2 mm/day in the sub-basins of wadi Rim and Sha'ib Ruwawah, and 25.9 mm/day in the sub-basin of Wadi Al Ishsh sub-basin. The runoff depth related to the mean of maximum daily rainfall reached to 4.7 mm/day in Sha'ib Ruwawah sub-basin and 7.0 mm/day in Wadi Al Ishsh watershed. This runoff depth can generate a discharge peak varying between 42.7 m³/s in the Shai'ib Ruwawah sub-basin and 180.2 m³/s in the wadi Al Yitimah watershed.

Besides, based on the unit peak discharge (q_u) and the constants C₀, C₁ and C₂ of the rainstorms type II, the appropriate equations for calculating the discharge peaks

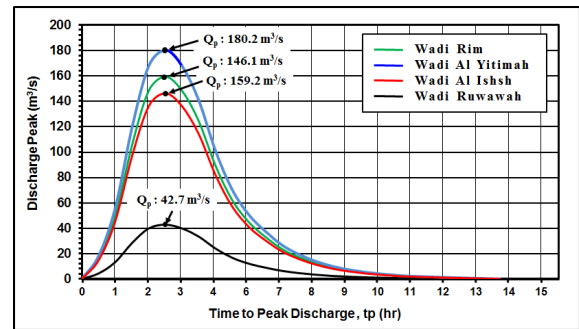


Fig. 6 Hydrographs of mean discharge peak calculated using NRCS-CN method during 1970-2017

Table 7 Estimated discharge peak from the mean of maximum daily rainfall recorded during 1970-2017

Variable	Sub basins				Al Aqiq watershed
	Al Ishsh	Ruwawah	Al Yitimah	Rim	
A (km ²)	1193.0	527.9	1037.5	776.1	5130.8
Q (mm)	7.0	4.7	5.5	4.9	7.9
L (m)	41.8	39.0	48.1	37.2	108.5
H (%)	5.0	3.3	18.0	16.8	9.5
CNw	88.4	89.7	88.9	89.9	92.1
t _{Lag}	5.4	6.0	3.2	2.6	7.3
T _c	9.1	10.1	5.3	4.3	12.1
P _w (mm)	25.9	20.2	22.6	20.2	22.0
I _a (mm)	6.7	5.8	6.3	5.7	4.4
I _a /P	0.26	0.29	0.28	0.28	0.20
C ₀	2.51807	2.54444	2.53565	2.53565	2.47411
C ₁	-0.61959	-0.62183	-0.62108	-0.62108	-0.61587
C ₂	-0.14505	-0.15928	-0.15454	-0.15454	-0.12132
q _u	0.01906	0.01721	0.03157	0.03843	0.01505
Q _p (m ³ /s)	159.2	42.7	180.2	146.1	610.0
Q _{ps} (m ³ /s/km ²)	0.133	0.081	0.174	0.188	0.119

Table 8 Predicted discharge peak of different rainstorms

Model parameters	Sub Basins					
	Wadi Al Ishsh	Wadi Al Ruwawah	Wadi Al Yitimah	Wadi Rim	Wadi Al Aqiq	
A (km ²)	1193.0	527.9	1037.5	776.1	5130.8	
q_u	0.01906	0.01721	0.03157	0.03834	0.01505	
25 mm	Q (mm)	6.5	7.6	6.9	7.8	10.0
	Q_p (m ³ /s)	147.5	69.3	227.4	231.9	772.1
40 mm	Q (mm)	16.6	18.5	22.6	18.7	22.1
	Q_p (m ³ /s)	378.4	167.7	738.6	557.4	1703.8
50 mm	Q (mm)	24.5	26.6	37.9	27.0	30.8
	Q_p (m ³ /s)	556.3	241.9	1242.1	802.1	2380.9
100 mm	Q (mm)	45.9	48.7	47.0	49.1	53.9
	Q_p (m ³ /s)	1043.6	442.3	1540.3	1461.2	4163.6

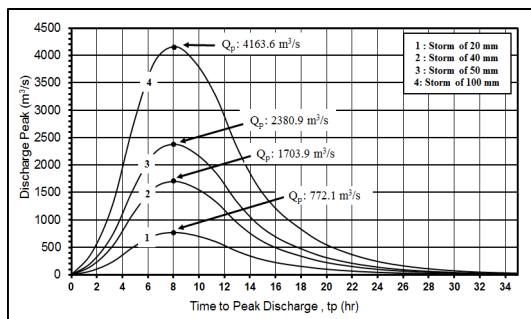


Fig. 7 Hydrographs of predicted storms in Wadi Al Aqiq watershed

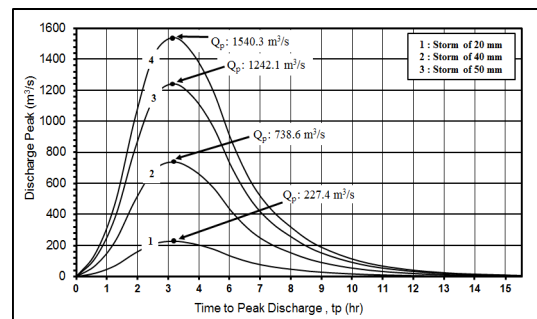


Fig. 9 Hydrographs of predicted storms in Wadi Al Yitimah watershed

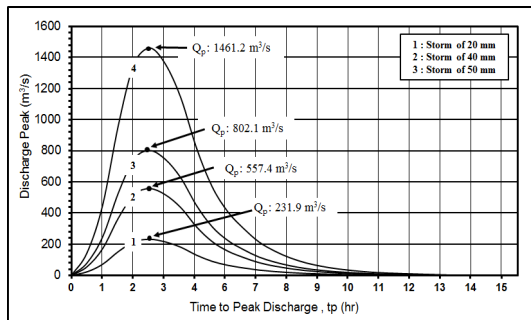


Fig. 8 Hydrographs of predicted storms in Wadi Rim watershed

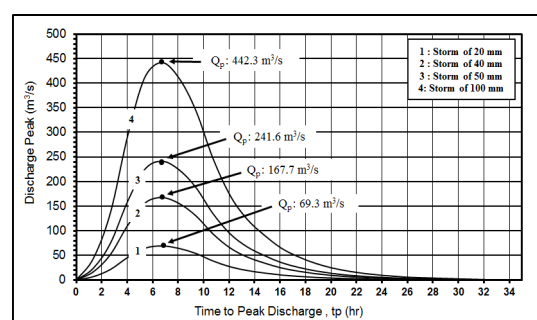


Fig. 10 Hydrographs of predicted storms in Wadi Ruwawah watershed

for each studied sub-basin have been found, and the results are illustrated in Table 8 and Figs. 7-11. The discharge peak formula for each sub-basin can be as follow: For the station of Wadi Al Aqiq, the formula was found as in Eq. (9), and the obtained results are shown in Fig. 7; for the station of wadi Rim, Eq. (10) was originated, and the results are revealed in Fig. 8; Eq. (11) was found for wadi Al Yitimah station, and the outcomes are illustrated in Fig. 9; the obtained Eqs. (12) and (13) were used to calculate the discharge peaks for the stations of Sha'ib Ruwawah and Wadi Al Ishsh with the outcomes exposed in Fig. 10, and Fig. 11, respectively.

$$Q_{peak}(m^3/s) = 0.01505(5130.8 km^2) \times (Q(mm)) \quad (9)$$

$$Q_{peak}(m^3/s) = 0.03843(776.1 km^2) \times (Q(mm)) \quad (10)$$

$$Q_{peak}(m^3/s) = 0.03157(1037.5 km^2) \times (Q(mm)) \quad (11)$$

$$Q_{peak}(m^3/s) = 0.01721(527.9 km^2) \times (Q(mm)) \quad (12)$$

$$Q_{peak}(m^3/s) = 0.01906(1193.0 km^2) \times (Q(mm)) \quad (13)$$

Moreover, the surface runoff depth and peak flow were estimated for four rainstorms of 25, 40, 50, and 100 mm/day,

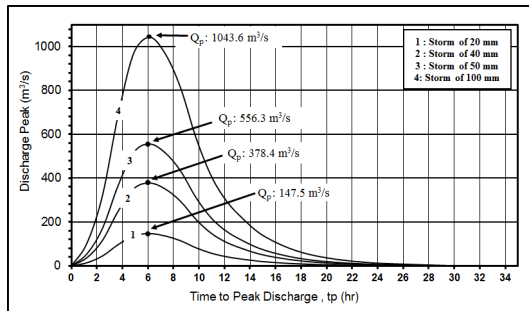


Fig. 11 Hydrographs of predicted storms in Wadi Al Ishsh watershed

and the results are summarized in Table 8. It can be seen that the highest runoff depth and peak flow values were found in the Wadi Al Aqiq sub-basin for rainstorms of 100 mm/day.

4. Conclusions

The current study was developed to estimate the discharge peak of Al Aqiq drainage basin located in Al Madinah Munawwarah region, Saudi Arabia. The SRTM Dem 30 m method was used to compute the relief and morphometric variables used in the hydrological model of NRCS-CN. The following conclusions could be drawn based on the obtained results:

- The outcomes of this study showed the importance of the integrated use of the digital processing outputs of the DEM in extracting the morphometric variables necessary in calculating the concentration-time, unit peak discharge and the land resources map in determining the runoff curve.
- The weighted curve numbers are ranges between 88.4 in Wadi Al Ishsh watershed and 89.9 in wadi Rim watershed. The weighted curve number of Wadi Al Aqiq total drainage area is 92.1.
- The mean daily rainfall can generate surface runoff is ranged between 20.2 mm/day in the sub-basins of wadi Rim and Sha'ib Ruwawah and 25.9 mm/day in the sub-basin of Wadi Al Ishsh sub-basin. Accordingly, the runoff depth related to the mean of maximum daily rainfall reached 4.7 mm/day in Sha'ib Ruwawah sub-basin to 7.0 mm/day in Wadi Al Ishsh watershed.
- The runoff depths can generate a discharge peak varying between 42.7 m³/s in the Shai'ib Ruwawah sub-basin and 180.2 m³/s in the wadi Al Yitimah watershed. Consequently, the comparison between the studied sub-basins shows that the wadi Rim sub-basin is the most capable of generating surface runoff with an average specific discharge of 0.188 m³/s/km².
- The obtained results indicate that the NRCS-CN model can be applied with the caution in the ungauged watersheds of Saudi Arabia using the DEM outputs and daily rainfall data. The NRCS-

CN can be applied according to the morphometric and hydrologic characteristics of each case. The obtained results can be calibrated by the actual recorded discharge and compared with between several watersheds.

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