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HYDROLOGICAL MODELLING OF UNGAUGED ARID VOLCANIC ENVIRONMENTS AT UPPER BATHAN CATCHMENT, MADINAH, SAUDI ARABIA

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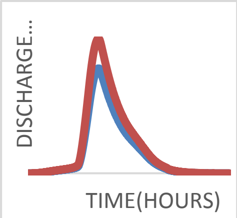
Graphical abstract



Abstract

Hydrological modelling of ungauged catchments is still a challenging task especially in arid regions with a unique land cover features such as highly fracture volcanic basalt rocks. In this study, upper Bathan catchment (103 km^2) in Madinah, western of Saudi Arabia is selected. The aim of this paper is to simulate the hydrological responses of volcanic catchment to daily design storm events. The weighted areal average of two daily design rainfall depth scenarios are computed, which are 50 years and 100 years return period and correspondent predicted rainfall are 80.6 mm and 94.1 mm, respectively. SCS Type II temporal synthetic distribution of daily rainfall is selected to disaggregate the daily rainfall into smaller time interval. Excess rainfall is computed using Soil Conservation Services Curve Number (SCS-CN) method based on Land Cover and Land Use (LCLU) and hydrological soil groups (HSG) maps, while direct runoff hydrograph is developed using Soil Conservation Services dimensionless unit hydrograph (SCS-UH) method using lag time equation. HEC-HMS software is used, and it showed that the runoff volumes of the two rainfall scenarios are 50% and 54% of the total rainfall depth, and the peak discharges are 123 m^3/sec and 158 m^3/sec. This study provided an indication of the hydrograph characteristics of basaltic catchments and the result of this paper can be used for further flood studies in arid ungauged volcanic catchments.

Keywords: Rainfall-runoff modelling; SCS method; arid regions; ungauged; volcanic catchments

Abstrak

Pemodelan hidrologi pada kawasan tadahan tanpa pengukuran masih menjadi cabaran terutamanya di kawasan gersang dengan ciri-ciri permukaan tanah yang unik seperti rekahan batu gunung berapi basalt. Dalam kajian ini, kawasan atas tadahan Bathan (103 km2) di Madinah, bahagian barat Arab Saudi telah dipilih. Tujuan kertas kerja ini untuk simulasi tindakbalas hidrologi di tadahan gunung berapi berdasarkan corak kejadian rekabentuk ribut-hujan harian. Purata kawasan pemberat daripada dua senario rekabentuk kedalaman hujan harian telah dikira, iaitu 50 tahun dan 100 tahun tempoh kembali dan jangkaan hujan adalah 80.6 mm dan 94.1 mm. SCS Jenis II pengagihan sintetik sementara bagi hujan harian dipilih untuk memisahkan taburan hujan harian kepada selang masa yang lebih kecil. Hujan yang berlebihan telah dikira dengan kaedah Nombor Lengkuk, Perkhidmatan Konservasi Tanah (SCS-CN) berdasarkan Litupan Bumi dan Penggunaan Tanah (LCLU) dan peta hidrologi jenis tanah (HSG), manakala hidrograf air larian terus dibangunkan menggunakan Perkhidmatan Konservasi Tanah tanpa dimensi kaedah unit hidrograf (SCS -UH) melalui persamaan lag masa. Perisian HEC-HMS digunakan dan ianya menunjukkan bahawa jumlah air larian daripada dua senario hujan adalah 50% dan 54% daripada jumlah kedalaman hujan dan pelepasan kadaralir puncak adalah 123 m3/ saat dan 158 m3/ saat. Kajian ini memberi petunjuk mengenai ciri-ciri hidrograf kawasan tadahan basalt dan hasil kajian boleh digunakan untuk kajian banjir akan datang di kawasan tadahan tanpa pengukuran gunung berapi gersang.

Kata kunci: Model hujan-air larian; kaedah SCS; rantau gersang; kawasan tanpa pengukuran gunung berapi

1.0 INTRODUCTION

Flood is one of the most frequent occurring and higher impact natural disasters, caused losing of lives and properties, and it can be the highest killer weather phenomena. In arid regions, flood can be considered as one of the major challenging topic in the urban hydrologic system. Saudi Arabia, which is one of the arid region countries, faced many urban flood disasters in the last decade located in the most populated areas (i.e. Riyadh, Jeddah, Makkah, Madinah, Dammam, and Tabuk). In Madinah, significant floods occurred in almost every 10 years (1974, 1982, 1993, 2005, 2014), flood historical events at Wadi Bathan affect Masjid Nabawi and the highly populated surrounding areas (central area).

Pilgrim et al. [1] have discussed some problems related to the rainfall-runoff modeling in arid region, and they found that the lack of observed data provides the major problem for runoff modeling in arid regions. McIntyre and Al-Qurashi [2] evaluated ten rainfall-runoff models in arid catchments in Oman. While Subyani and Alahmadi [3] analyzed 16 rainfall stations in Madinah region, west of Saudi Arabia and used them to predict rainfall for different return periods. SCS method was used in their study to develop runoff hydrographs and regional maps of maximum probable precipitation and probable maximum flood were produced for the study area. El-Hames [4] applied SCS method to reconstruct the flood hydrograph and flood characteristics of the devastating flood event of 25 November 2009 on East Jeddah Western Saudi Arabia. In this study, Digital Elevation Model (DEM) with Aquaveo WMS software [5] was used to extract the catchment geomorphological properties, and the hydrological conceptual model is built in HEC-HMS software [6] to develop the runoff hydrograph. The main objective of this study was to determine the flood hydrograph characteristics of arid ungauged volcanic catchment.

1.1 Study Area

Madinah, the fourth largest city in the Kingdom of Saudi Arabia (KSA), is located at 24°28'N latitude and 39°36'E longitudes (Figure 1). The city lies approximately 160 km inland from the Red Sea coast, at an average elevation of about 600 m above mean sea level (a.m.s.l.). Madinah area is characterized by an arid climate where the rainfall with high temporal and spatial variability takes place primarily during winter and spring. The winter and spring rainfall events are caused by a combination of disturbances from the winter Mediterranean and the Sudan trough [7] usually generate extreme rainfall convective events over Madinah and surrounding areas. The average annual rainfall depth is estimated as 55 mm.

Upper Bathan catchment is selected, which is located in southern part of the city, geologically the basin is almost fully covered by volcanic basaltic rocks that are highly weathered and fractured. 15% of these volcanic rocks are covered with thin layer of sandy clay soils near the outlet of the basin (Figure 5b). Land use activities (i.e. agricultural land and urbanized areas) are located near the outlet with very small portion < 1% (Figure 5a).

2.0 METHODOLOGY

DEM with 10-meter pixel size produced from Geoeye satellite images was processed to delineate the catchment boundary and the streams network using Aquaveo Watershed Modeling System (WMS) software. The morphometric parameters were also automatically computed. Design daily rainfall of 50 years and 100 years return period were predicted using extreme value approach and Peak over threshold (POT) data series of two rainfall stations, this synthetic 24 hour storms are disaggregated into 6-minute time interval using hypothetical temporal distribution SCS type II.

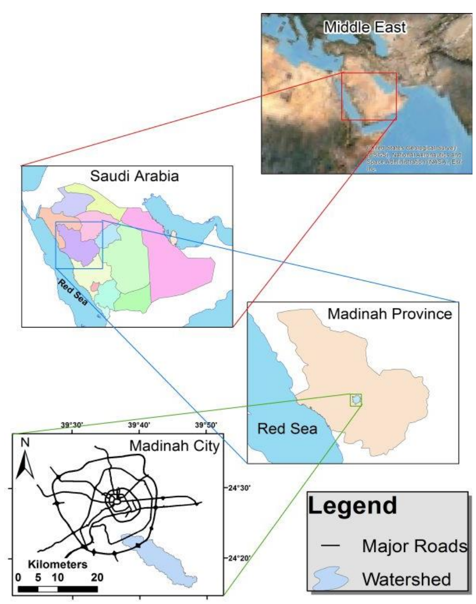


Figure 1 General location of study area

In runoff modeling, effective rainfall (excess rainfall) was computed using SCS Curve number method, which needs mainly two types of data; Land cover and land use information (LCLU) and Hydrological Soil Group (HSG). ESRI ArcGIS software [8] was used to develop these two GIS layers using satellite images, topographic maps, and geological maps. LCLU values for volcanic basaltic rocks were obtained from Sen [9] who developed SCS curve number values of volcanic rocks for different HSG based on intensive rainfall-runoff studies in Saudi Arabia. Composite SCS Curve number was computed automatically from LCLU and HSG layers in Aquaveo WMS software. Then the potential maximum retention (S) and the initial abstraction (I_a) were computed using the following equations:

$$S = \frac{25400-254CN}{CN} \quad (1)$$

$$I_a = 0.2\,S \quad (2)$$

where CN is the composite SCS Curve Number computed from LCLU and HSG layers, the effective rainfall (excess rainfall) depth is computed using the following equation:

$$R_e = \frac{(P-0.2S)^2}{(P+0.8S)} \quad (3)$$

where R_e is the effective rainfall in mm, and S is the potential maximum retention.

Direct runoff hydrograph process was used to transfer excess rainfall to point runoff hydrograph, In the case of ungauged catchment, synthetic unit hydrograph (SUH) methods was used to compute the direct runoff. SUH uses the watershed characteristics to compute travel time parameter, which influences the shape and peak of runoff hydrograph. Usually watershed traveling time parameter can be expressed as lag time or time of concentration, which are indication of the response time at the outlet of the watershed for the rainfall event. In this study, the direct runoff hydrograph is computed using SCS dimensionless unit hydrograph method using lag time (T_{lag}) equation, which can be expressed as:

$$T_{lag} = L^{0.8}\frac{\left[\left(\frac{25400}{CN}-254\right)+25.4\right]^{0.7}}{4238*So^{0.5}} \quad (4)$$

where L is the flow length in meter, CN is the SCS curve number, and So is the average watershed land slope in percentage. Aquaveo WMS software automatically computes these morphometric parameters from DEM.

3.0 RESULTS AND DISCUSSIONS

3.1 Geometric and Morphometric Features

Processing of DEM showed that the area of Upper Bathan catchment is about 103 km^2, the main channel length is about 25 km, and the average slope of the main channel is about 0.01, the maximum elevation is about 1354 m (a.m.s.l), and the minimum elevation is about 659 m (a.m.s.l). Figure 2 shows the DEM of Upper Bathan, catchment boundary, and stream network, while Table 1 shows the automatically computed morphometric parameters.

The computed morphometric parameters of Upper Bathan shown in Table 1 indicates that the catchment has moderate relief and low drainage density with elongated shape (elongation value is less than 1.0), circularity was computed as 7.57 which confirming the elongation of the catchment. The drainage pattern of the Wadi has dendritic shape with drainage density as 0.56 km/km^2, which may indicate a highly permeable landscape with small potential for runoff. Relief ratio is 0.03, which indicates that the host rocks are more resistant to physical geological processes.

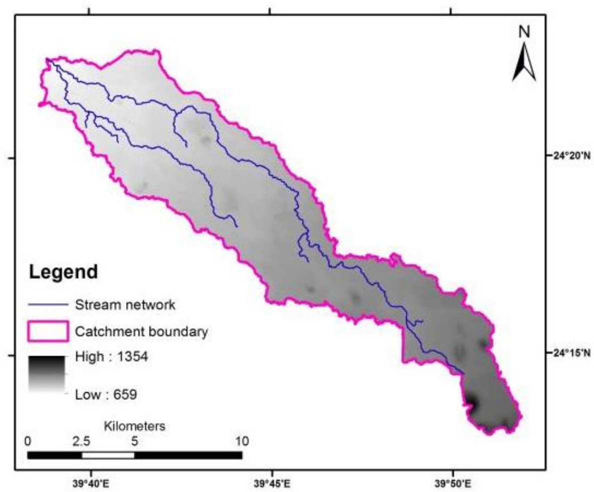


Figure 2 Upper Bathan DEM, boundary and stream network

Table 1 Upper Bathan morphometric parameters

Morphometric parameter	value
Basin area (km^2)	103
Total stream length (m)	58132
Basin slope (m/m)	0.0775
Maximum stream length (m)	37121
Circularity (mi^2/mi^2)	7.57
Sinuosity factor (msl/l)	1.33
Mean basin elevation (m)	875
Average streams slopes (m/m)	0.0101
Drainage density (km/km^2)	0.56
Relief (m)	1063
Relief ratio (-)	0.03
Elongation (-)	0.36

3.2 Rainfall Representation

Two daily rainfall stations with 45 years of records were selected for frequency analysis. Madinah meteorological station (M001) in the north and Bir Almashi daily rainfall station (M103) in the south. Figure 3 shows the location of these two rainfall stations.

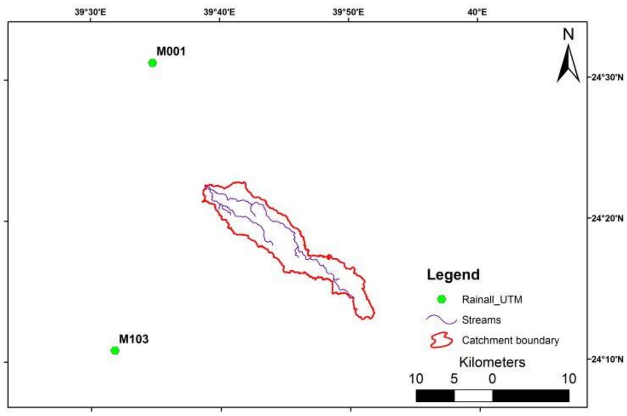


Figure 3 Upper Bathan effective rainfall station location

Peak Over Threshold (POT) series was applied for the two rainfall stations. Nine statistical probability distribution functions (PDFs) were used, which are Exponential (EXP), Gamma (GAM), Generalized Extreme Value (GEV), Generalized Logistic (GLO), Generalized Pareto (GPA), Gumble (GUM), Normal (NOR), Pearson Type III (PE3), and Wakeby (WAK) distributions. These PDFs were evaluated using two methods which are Anderson-Darling (A-D) Goodness of fit test and Root Mean Squared Error (RMSE).

A-D test showed that PE3, GEV, and GLO were the best for station M001, while PE3, GPA, and WAK were the best for station M103. Table 2 shows the best three PDFs with lowest A-D values. The three best PDFs were evaluated using RMSE which showed that PE3 had the lowest error and can be considered as the best fit PDF. Table 3 shows the computed RMSE of the three PDFs.

Table 2 A-D test for the best three PDFs

Station M001		
PDF	Statistic	Rank
PE3	*0.30774*	*1*
GEV	*0.43382*	*2*
GLO	*0.47158*	*3*

Station M103		
PDF	Statistic	Rank
PE3	*0.63486*	*1*
GPA	*0.85844*	*2*
WAK	*0.85844*	*3*

Rainfall depth of 50 years and 100 years return periods were selected and the areal weighted average rainfall was computed for Upper Bathan as 80.6 mm and 94.1 mm, for 50 years and 100 years, respectively. More details of the computation of rainfall frequency analysis of this study can be referred in Alahmadi and Abd Rahman [10].

Table 3 RMSE for the best three PDFs

Station M001		
PE3	GEV	GLO
4.99	*7.5`*	*7.72*

Station M103		
PE3	GPA	WAK
2.62	2.96	2.96

The computed design storms of 24 hours rainfall depth is disaggregated to 6-minute time interval using hypothetical temporal distribution, SCS Type-II which is considered as one of the most conservative disaggregation approach because most intensive rainfall occur in the middle of the storm. Figure 4 showed the cumulative hypothetical temporal rainfall distribution for 100 years return periods using 6-minute time interval.

3.3 Composite SCS Curve Number Computation

Land cover and land used (LCLU) of Upper Bathan catchment is fully covered by volcanic basaltic rocks with minor portion of agriculture land and urban areas in the lower part of the catchment. HSG is a measure of the land surface potentiality to runoff.

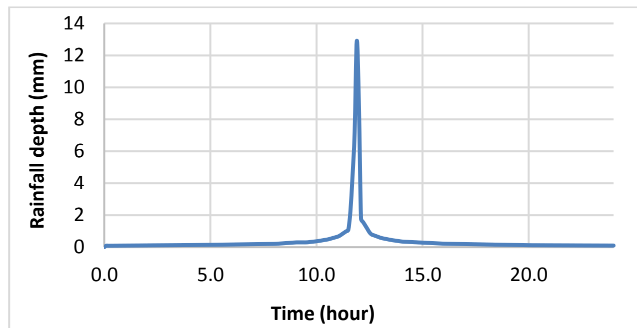
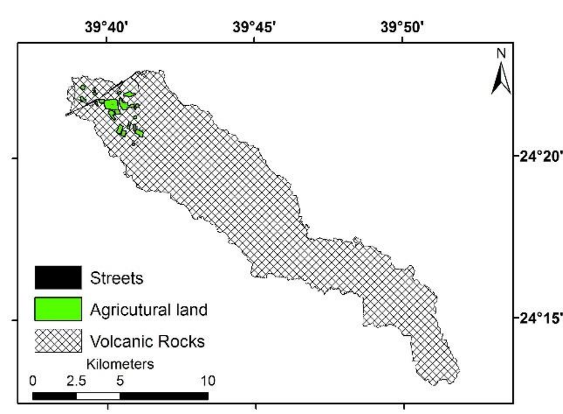
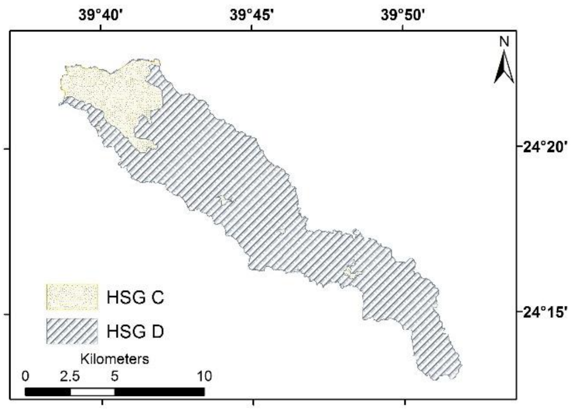


Figure 4 Cumulative hypothetical temporal rainfall distribution of 100 years using SCS-Type-II

Upper Bathan catchment consists mainly of two types HSG, the volcanic rocks, which can be considered as Type D with 85% of the catchment area, and sandy clay soils, which can be considered as Type C with 15% of the catchment area in the lower part. Satellite images, topographic maps and geological maps were used to delineate Upper Bathan LCLU and HSG features. Figure 5 shows the development of LCLU and HSG by GIS layers. While Table 4 shows the Upper Bathan HSG type for LCLU features.



(a) Land cover and Land Use



(b) Hydrological Soil Groups

Figure 5 Upper Bathan (a) LCLU and (b) HSG

Table 4 Upper Bathan HSG types of LCLU features

Land cover land use (LCLU feature)	Hydrological soil groups (HSG)			
	A	B	C	D
Urban and built-up land	81	88	91	93
Farms and agriculture land	45	66	77	83
Transportation	83	89	92	93
Volcanic basalt rocks	60	65	70	80

Source: [11] and [9]

After developing LCLU and HSG GIS layers, Aquaveo WMS software was used to compute the composite SCS Curve Number automatically, which is an areal weighted average of different SCS curve numbers for the different regions within the basin. Table 5 summarizes the results of processing LCLU and HSG layers and as a result, the computed composite SCS-CN of Upper Bathan is 78.5, which can be considered as relatively moderate to high potential to runoff.

3.4 Effective Rainfall and Initial Abstraction Computation

After computing SCS-CN, the potential maximum retention (S) was computed as in equation (1), and initial abstraction is estimated as in equation (2) which is 20% of potential maximum retention (S), the effective rainfall depth was computed using equation (3). Table 6 shows these computed values for Upper Bathan catchment using 50 years and 100 years rainfall scenarios.

Table 5 Upper Bathan composite SCS-CN computation

LCLU Features	Hydrological Soil Groups	Area (km²)	Area %	SCS -CN
Volcanic Basalt rocks	D	86.86	99.7	80
Volcanic Basalt rocks	C	15.46	9	70
Farms and agriculture land	C	0.043	0.04	77
Transportation	C	0.085	0.08	92
Mixed Urban and Built-up land	C	0.085	0.08	91
Composite (Weighted average) SCS Curve Number				**78.5**

The total loses for 50 years and 100 years ranges between 48% and 51% of the total rainfall depth, where the initial abstraction ranges between 15% to 17%, and the continues loss ranges from 37 mm to 40 mm. The computed effective rainfall depth using SCS-CN method ranges between 32.6 mm and 42.9 mm for 50 years and 100 years, respectively.

3.5 Unit Hydrograph Parameter Compotation

In this study synthetic unit hydrograph approach is used, and SCS–UH method was selected to compute the Lag Time (T_{lag}), which is based on SCS-CN, flow length, and watershed slope. Composite SCS-CN was developed in the previous section to compute the effective rainfall, while the last two morphometric parameters were computed automatically from DEM using Aquaveo WMS software. Table 7 shows the input parameters and the computed SCS lag time, which is about 6 hours.

Table 6 Effective rainfall computation

Parameter	50yr	100yr
Total rainfall depth (*P*) (mm)	80.6	94.1
Composite SCS-CN	78.5	
Potential maximum retention (*S*) (mm)	69.6	
Initial abstraction (I_a) (mm)	13.90	
Total Loss (mm)	48.0	51.2
Continues loss (mm)	39.5	37.3
Effective rainfall depth (P_e) (mm)	32.6	42.9

Table 7 SCS Lag time computation

Parameter	Value
Composite curve number	78.5
Flow Length (L) in meter	38518.8
Average watershed lands slope (S) in %	7.06
SCS lag time (hour)	6.01
SCS lag time (min)	361

3.6 Direct Runoff Hydrograph Characteristics

The conceptual hydrological model of the study area was built in HEC-HMS software [5], to develop runoff hydrograph using 5 minutes time interval of the hydrograph construction. Therefore, Table 8 shows the characteristics of the resultant hydrographs based on the design rainfall of 50 years and 100 years, while Figure 6 shows the simulated flood hydrographs. The resultant peak discharge for 50 and 100 years rainfall design storm is about 123 m^3/sec and 158 m^3/sec.

Table 8 Upper Bathan hydrograph characteristics

Hydrograph characteristics	50yrs	100yrs
Peak discharge (m^3/sec)	123	158
Runoff volume (Mm^3)	4.1	5.2
Loss (%)	50.6	46.2

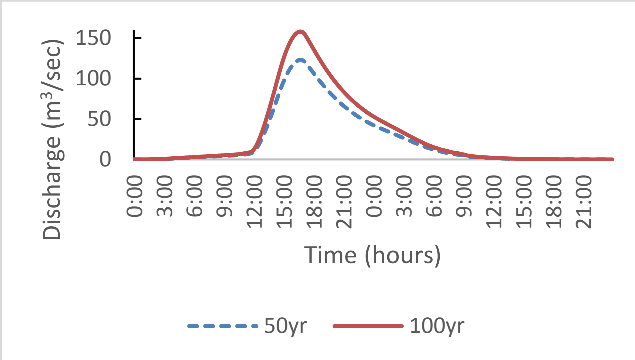


Figure 6 Upper Bathan hydrograph based on 100 years rainfall

4.0 CONCLUSION

In this study, urban arid volcanic of Upper Bathan catchment with 103 km^2 was selected for rainfall-runoff modeling. Digital Elevation Model was processed to extract the geomorphological features and to compute the morphometric parameters automatically. Design daily rainfall amounts for 50 years and 100 years return periods are selected which are equal to 80.1 mm and 94.1 mm, respectively. SCS Curve number (SCS-CN) method was implemented to compute the excess rainfall and the composite SCS Curve Number of upper Bathan catchment is about 78.5. Synthetic unit hydrograph approach was used, and SCS dimensionless unit hydrograph (SCS-UH) is selected to compute the lag time (T_{lag}). Therefore, SCS-CN method indicated that the 46% to 50% of the total rainfall depth were extracted as losses and 40% to 46% of the total rainfall depth was considered as effective (excess) rainfall. The initial abstraction is about 13.9 mm of the total rainfall depth. The computed lag time (T_{lag}) using SCS-UH method is about 6.01 hour, which is reasonable for moderate slope catchment, the peak discharges for 50 years and 100 years are 123 m^3/sec and 158 m^3/sec, respectively. This study provides an indication of the hydrograph characteristics of basaltic catchments and the result of this paper can be used for further flood studies in arid ungauged volcanic catchments.

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