

Estimation of Runoff in Data Scarce Watershed of Middle Gujarat, India Using HEC-HMS Model

Abstract

The accurate estimation of the hydrologic response in water resources planning and development is crucial. In this study, the rainfall-runoff relationship and hydrologic response of the Devgadhi Baria watershed in the Panam river catchment were investigated. Due to limited availability and accuracy of runoff data, Clark UH, and SCS UH models were explored for runoff estimation. Remote sensing and GIS techniques were integrated to assess the ungauged watershed in the Middle Gujarat region.

Rainfall and discharge data, Sentinel-2 data, 12.5m×12.5m Palsar DEM, base maps, and soil maps were collected from various sources. The study area's five different events were randomly selected, and a Thiessen map was prepared to calculate weighted rainfall. Geomorphological parameters and Horton's ratios were estimated using remote sensing and GIS software ILWIS.

The composite curve number (CN) for the watershed was found to be 77.69. Excess-rainfall hyetographs were separated using the SCS-loss method, and the time to peak estimated by the models matched well with observed data, except for a one-day delay in the HEC-HMS based Clark UH model.

Four performance indices, namely NSE, PBIAS, RMSE, and d, were used to compare model performance. The SCS UH model demonstrated the highest NSE value (-0.28) for event-1, while the HEC-HMS based SCS UH model showed the lowest NSE value (-0.28) for event-1. The SCS model outperformed the other models based on performance indicators NSE, RMSE, and d. Overall, the SCS UH approach provided the best estimation of peak discharge and time to peak discharge. The direct surface runoff hydrographs estimated using

Keywords: HEC-HMS, Clark UH, SCS UH, GIS, ArcGIS, DSRO, rainfall-runoff, Ungauged Catchment.

1. Introduction

Assessing water resources is a crucial task that involves observing hydrological processes and utilizing hydrological modeling. However, the current hydrological monitoring network is limited, with only a few stations representing vast areas. This lack of monitoring results in insufficient discharge data for many small watersheds, making water resource assessment challenging for those areas (Amisigo et al., 2008; Taylor et al., 2006). Rainfall-runoff processes in surface hydrology are complex and involve various factors such as climate, topography, soil, land use etc.

Hydrological models can be broadly classified as empirical, conceptual, lumped, or physically based distributed models. In recent years, computer-aided hydrological modeling software has been increasingly used for runoff estimation based on the available data and research objectives. One of the widely adopted software for rainfall-runoff modeling is the Hydrologic Engineering Centre-Hydrologic Modelling System (HEC-HMS), developed by the U.S. Army Corps of Engineers. HEC-HMS allows simulation of rainfall-runoff processes

in diverse geographic areas, solving a wide range of problems (Al-Abed et al., 2005; Azmat et al., 2017; Derdour et al., 2018; Bennett & Peters, 2000).

HEC-HMS is a reliable tool that requires minimal input data and can simulate floods in both short-term and long-term events. It has been successfully used to estimate runoff in different parts of the world but has seen limited application in Indian catchments. Despite its global use, few studies have been conducted in Indian catchments (Putty and Prasad, 2000; Verma et al., 2010; Rathod et al., 2015; Sintayehu, 2015).

The study aims to fill the knowledge gap by estimating runoff in previously unaddressed watersheds. By estimating excess rainfall resulting from intense storms and implementing watershed interventions, it is possible to mitigate water scarcity. Water scarcity is a critical issue in the selected semi-arid region, and effective water resource planning and management are essential.

Hence, this study was conducted in the Middle Gujarat region, a data scarce was selected to analyze the rainfall-runoff relationship using HEC-HMS and remote sensing and GIS techniques. The objective of the study was to estimate runoff using the HEC-HMS based SCS UH and Clark model and compare the results of these transformation methods.

2. MATERIALS AND METHODS

2.1 Study Area

The area selected for present study is a Devgadhi Baria watershed of Middle Gujarat presented in Fig. 1. The Devgadhi Baria watershed is a sub-catchment of Panam river up to Devgadhi Baria taluka of Dahod District located in the middle Gujarat region of India and lies between 22°41'22" to 22°54'00" N latitude and 73°35' to 73°49'1" E longitude. The Panam rises near Bhabra in Jhabua district of Madhya Pradesh joining Mahi from left in Panchmahals district of Gujarat (NRSC & CWC, 2014). Devgadhi Baria watershed has catchment area of 598.89 km², approximately rectangular in shape with a minimum elevation of 114 m at the outlet and a maximum of 597 m above mean sea level at the upstream end of the catchment. Average annual rainfall in the catchment area is 980 mm. About 80% of the rainfall occurs during July and August whereas 20% is distributed over the remaining months of the year.

2.2 Data Acquisition

Hydro-meteorological data play a significant role in runoff estimation as it gives an indication of the rainfall depth within the simulation period which directly affect the amount of runoff generated. The daily rainfall and runoff data of the watershed have been collected from were collected from the State Water Data Centre Gandhinagar for the year 2019. Three different isolated storms are selected for the study. The remote sensing information like sentinel 2 data was downloaded from Copernicus Open access hub (Table 1). The DEM is a crucial dataset used to generate the morphometric characteristics of the watershed needed in hydrological modelling. ALOS PALSAR 12.5 m digital elevation model was used for elevation data. This is the basic data that will be used for watershed delineation, generation of the stream network. It is the basic input for HEC-HMS, to find the longest flow path, basin slope, basin elevation etc. These parameters will be used to calculate loss parameters, transform parameters like, time of concentration. The topographical map, drainage network, watershed boundary etc. for the watershed were extracted using Survey of India maps Ahmedabad. The soil data was obtained from the FAO (Food and Agricultural Organisation). ArcGIS(v10.0) is used to create the basin model input for HEC-HMS. The software used for the present study is HEC-HMS (v4.9) available in public domain on USACE website.

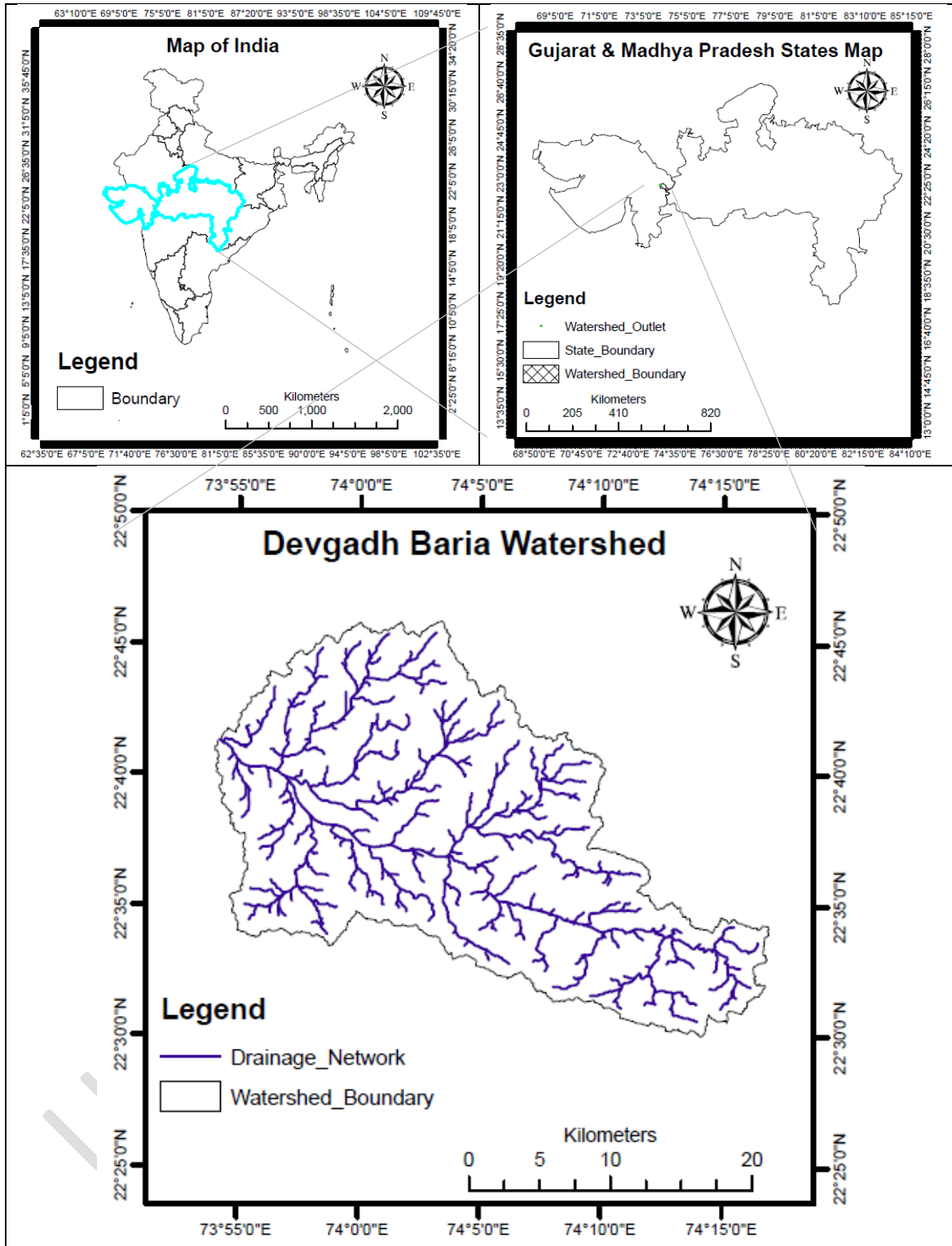


Fig. 1: Location map of Devgad Baria watershed

Table 1 :- Hydro-meteorological and remote sensing data

Data	Description	Source of Data
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Hydrological and meteorological data	Daily Rainfall, Daily Discharge	➤ State Water Data Centre, Gandhinagar.
Remote Sensing data	Sentinel 2 data	➤ Copernicus Open Access Hub
	12.5m×12.5m Digital elevation model (DEM)	➤ Also Palsar DEM downloaded from Alaska Satellite Facility
Maps	Base map/ Topography sheet	➤ Survey of India, Ahmedabad
	Soil Map	➤ Food and Agricultural Organization

2.3 Mean Precipitation using Thiessen-mean Method

The rain gauges represent only point sampling of the areal distribution of a storm. In practice, however, hydrological analysis requires a knowledge of the rainfall over an area, such as over a catchment. To convert the point rainfall values at various stations into an average value over a catchment, the Thiessen-polygon method is used in this study to convert rainfall values into an average value over the catchment. This method attempts to allow for non-uniform distribution of gauges by providing a weighting factor for each gauge. The results obtained are usually more accurate than those obtained by simple arithmetic averaging. The gauges should be properly located over the catchment to get regular shaped polygons. However, one of the serious limitations of the Thiessen method is its non-flexibility since a new Thiessen diagram to be constructed every time if there is a change in the rain gauge network. (Raghunath, 2006).

2.4 HEC-HMS Hydrological modelling

The HEC-HMS model was developed by the US Army Corps of Engineers (USACE) Hydrologic Engineering Center's (HEC) and is well known hydrological model of the most widely used rainfall-runoff models. The model is suitable for small and larger catchment hydrologic applications in addition to lumped and distributed rainfall-runoff modelling such as water balance studies, flood studies, impact of land use and climate change on runoff generation and flooding. Before going to HEC-HMS the input data files are prepared using HEC-GeoHMS and Arc-GIS.

2.4.1 Loss Rate Method : SCS-CN

The SCS-CN method, developed by the USDA's Soil Conservation Service, estimates direct runoff from rainfall in small agricultural watersheds. It considers interception, storage, and infiltration volume, with an initial abstraction threshold before runoff occurs. Additional losses due to infiltration and increasing runoff with rainfall are incorporated. The method is widely used and described in the USDA-NRCS Technical Release 55: "Urban Hydrology for Small Watersheds." (Soil Conservation Service Engineering Division. (1986).

$$Q = \begin{cases} \frac{(P - I_a)^2}{P - I_a + S} & P > I_a \\ 0 & P \leq I_a \end{cases} \quad (3.30)$$

Where, S (mm) is potential maximum retention after runoff begins. I_a is all loss before runoff begins. It includes water retained in surface depressions, water intercepted by vegetation, evaporation, and infiltration. I_a is highly variable but generally is correlated with soil and land cover parameters. To remove the necessity for an independent estimation of I_a , a linear relationship between I_a and S was suggested by Soil conservation service engineering division

(1986) as: $I_a = S\lambda$, where λ is an initial abstraction ratio. The values of λ vary in the range of 0 to 0.3 and have been documented in a number of studies encompassing various geographic locations in the United States and other countries (Shrestha, 2003). Through studies of many small agricultural catchments, I_a was found to be approximated by empirical equations such as $I_a = 0.2S$.

By removing I_a as an independent parameter, a combination of S and P to produce a unique runoff amount can be approximated. Substituting $I_a = 0.2S$ give

$$Q = \frac{(P - 0.2S)^2}{P + 0.8S} \quad (3.31)$$

The variable S , which varies with antecedent soil moisture and other variables, can be estimated as

$$S = \frac{25400}{CN} - 254 \quad (3.32)$$

Where, CN is a dimensionless catchment parameter ranging from 0 to 100. A CN of 100 represents a limiting condition of a perfectly impermeable catchment with zero retention, in which all rainfall becomes runoff. A CN of zero conceptually represents the other extreme, with the catchment abstracting all rainfall and with no runoff regardless of the rainfall amount.

2.4.2 Unit Hydrograph Transforms Methods

When rainfall occurs, it satisfies all the basin requirement such as infiltration, initial abstraction, storage, etc. and the remaining portion is drained through the watershed outlet and is called as direct runoff. To calculate the direct runoff Clark's Unit Hydrograph Method and SCS Unit hydrograph Method equipped in HEC-HMS is used for this study.

2.4.2.1 SCS unit hydrograph

The Soil Conservation Service (SCS) proposed a parametric UH model; this model is included in HEC-HMS. The model is based upon averages of UH derived from gauged rainfall and runoff for many small agricultural watersheds throughout the US.

(a) SCS unit hydrograph method

The SCS UH lag can be estimated via calibration for gauged headwater sub watersheds. For ungauged watersheds, the SCS suggests that the UH lag time may be related to time of concentration, t_c as:

$$t_{lag} = 0.6 t_c$$

(b) Clark unit hydrograph method

The Clark Unit Hydrograph Method requires a specified duration, the Clark Unit Hydrograph (CUH) was developed using a time-area method (Viessman and Lewis 2003). This method considers an instantaneous unit hydrograph, which is similar to a regular unit hydrograph except that it is assumed that effective precipitation is applied to a drainage basin in an infinitely short period of time.

Storage effect or attenuation is accounted for by a built-in storage coefficient. Many studies have found that the storage coefficient, divided by the sum of time of concentration and storage coefficient, is reasonably constant over a region (USACE-HEC, 2021) shows this relationship.

$$\frac{R}{R + T_c}$$

The storage coefficient (R) measures the storage of rainfall in the watershed before it can drain to the outlet point. It is measured in units of time. The higher the storage coefficient

in comparison to the time of concentration, the higher the storage within the watershed (Sabot 1988).

2.5 PERFORMANCE INDICATORS

The performance of the HEC-HMS models was evaluated using five performance indices, namely: Nash-Sutcliffe efficiency (NSE), Percentage Bias (PBIAS), root mean square error (RMSE), and Index of Agreement measure (d) as defined below (Moriassi *et al.*, 2015). The range of optimal values for these performance indicators are given in Table 2.

Table 2: Performance indicators (Moriassi *et al.*, 2015)

Sr. No.	Static	Formula	Range	Optimal Value
1	NSE	$E = 1 - \frac{\sum_{i=1}^n (O_i - P_i)^2}{\sum_{i=1}^n (O_i - \bar{O}_i)^2}$	$-\infty$ to 1.0	1.0
2	PBIAS	$PBIAS = \frac{\sum_{i=1}^n (O_i - P_i) \times 100}{\sum_{i=1}^n (O_i)}$	$-\infty$ to ∞	0.0
3	RMSE	$RMSE = \sqrt{\frac{1}{n} \sum_{i=1}^n (O_i - P_i)^2}$	0.0 to ∞	0.0
4	d	$1 - \frac{\sum_{i=1}^n (O_i - P_i)^2}{\sum_{i=1}^n (P_i - \bar{d} + O_i - \bar{d})^2}$	0.0 to 1.0	1.0

3 RESULTS AND DISCUSSION

3.1 DEM Processing and Watershed Delineation

The 12.5 m Alos Palsar DEM was used to delineate the Devgadha Baria watershed using ArcGIS software. The DEM map of Devgadha Baria watershed imported in ArcGIS software to delineate watershed using different steps such as fill, flow direction, flow accumulation, stream definition, stream segmentation, catchment grid delineation, catchment polygon processing, drainage line processing, catchment merging etc. The stream ordering map of the catchment is shown in Fig. 2 and the river is found to be 5th order according to the Strahler stream ordering definition.

3.2 Thiessen polygon

The Thiessen polygon map for weighted rainfall is prepared using ArcGIS software. The watershed area covered by Devgadha Baria, Devhat and Rangpur rain gauges are found to be 405.24, 108.40 and 85.25 km² respectively. Therefore, the weightage factor of Devgadha Baria, Devhat and Rangpur rain gauges are found to be 0.68, 0.18 and 0.14 respectively.

3.3 Curve Number (CN) Generation

The SCS has developed standard Tables of curve number values as functions of catchment land use/cover conditions and HSG (hydrologic soil group). Land use/cover map and HSG map for watershed is prepared details are below:

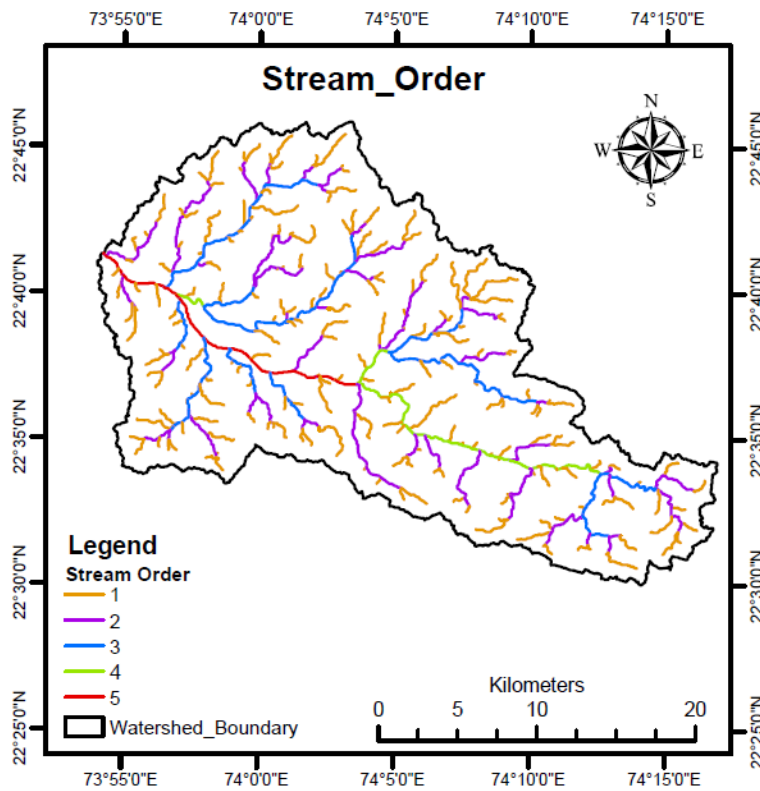


Fig. 2: Stream Order map

3.3.1 Land use map

Land use is one of the most important parameters affecting the surface runoff generation process. To incorporate the effect of land use, the watershed is classified into five dominant land use land cover categories viz. Agriculture, Bare land, Built up Forest, and Water. To prepare land use maps remote sensing image Sentinel-2 is obtained from Copernicus website for the year 2019, this image is classified using supervised classification. ArcGIS is used to classify these remote sensing images into different land use categories. The overall accuracy of the classification is found as 0.91 for the Sentinel-2 of year 2019. The land use map and the area under different land use types are shown in Fig. 3 and Table 3, respectively.

Table 3: Land use/land cover in watershed

Land use class	Area (km ²)	Area (%)
Agriculture	252.34	42.13
Bare land	0.14	0.03
Built up	18.47	3.08
Forest	320.69	53.55
Water	7.25	1.21
Total	598.89	100

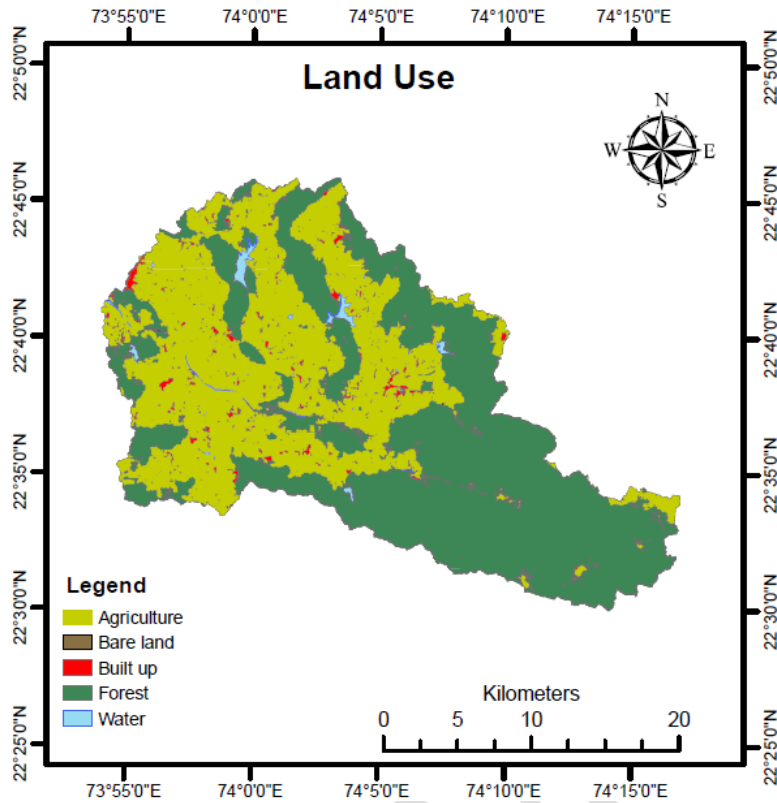


Fig. 3: Land Use Map

3.3.2 Soil map

Soil texture in the watershed is another factor affecting the conversion of rainfall into runoff. Soil series map at 1:250,000 scale for watershed downloaded from FAO website, is used as the source of soil database and soil grid in this study. After pre-processing of soil maps using GIS the soil types obtained for the study area are clayey and loamy soil. In which the clayey and loamy soil cover an area of 51.90 and 546.99 km², respectively. The soil map and the area under different soil types are shown in Fig. 4 and Table 4, respectively.

Table 4: Soil type in watershed

Soil Type	Area (km ²)	Area (%)
Loamy	546.99	91.33
Clayey	51.90	8.67
Total	598.89	100.00

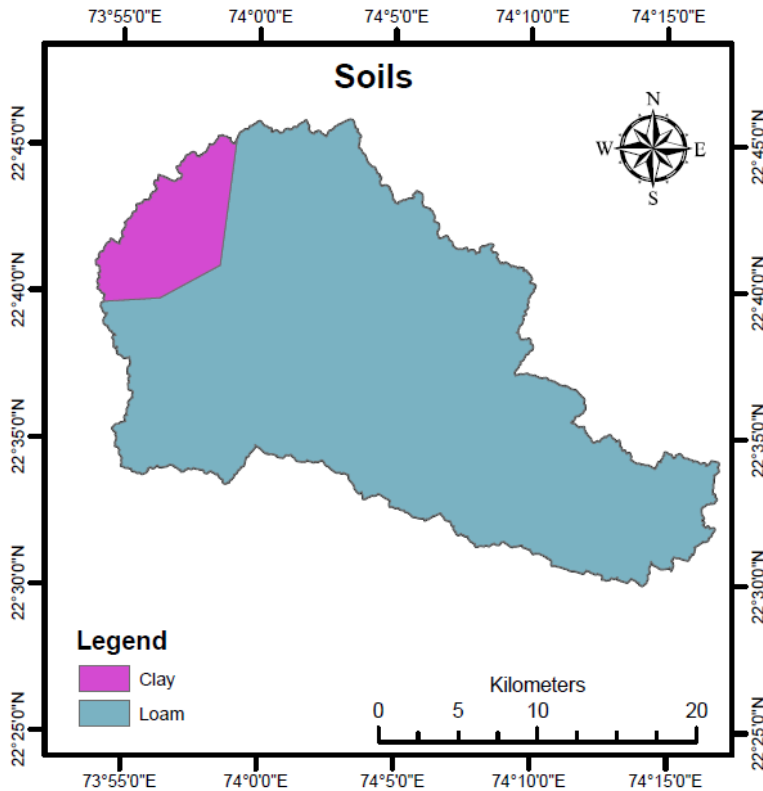


Fig. 4: Soil map

3.3.3 Curve Number (CN) generation

CN is used for loss model in HEC-HMS model. Primarily it is prepared from the combination of land use and soil map. The CN grid map of year 2019 is presented in Fig. 5 and CN values are presented in Table 5. The following steps are done to get a Curve Number grid for the area of interest from land use and soil maps:

- Vectorization of both the land use and soil maps.
- Table or vector operation (Union) to get polygons of unique combination of both the maps in Arc-GIS.
- CN value generation from unique polygons by query operation in Arc-GIS and create the gridMap.
- CN value determination polygon of watershed.

Table 5: Composite Curve Number Calculation

Curve Number (CN)	Area, km ²	CN _i × Area _i	Composite CN = (CN _i × Area _i)/ Total Area
70	309.28	21649.60	77.69
77	11.42	879.34	
85	215.97	18357.45	
88	0.14	12.32	
89	36.35	3235.15	
90	14.95	1345.50	
92	3.53	324.76	
100	7.25	725.00	
Total	598.89	46529.12	

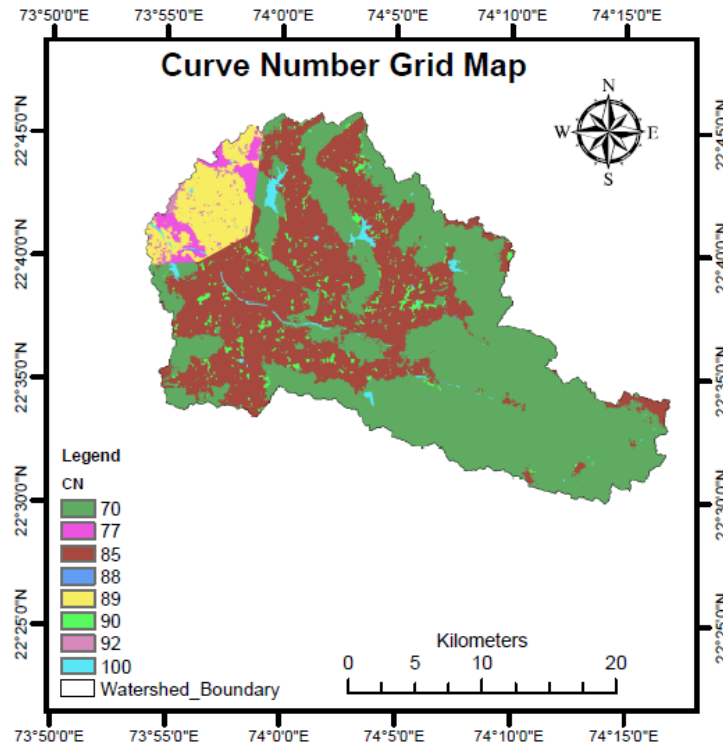


Fig. 5: CN grid map

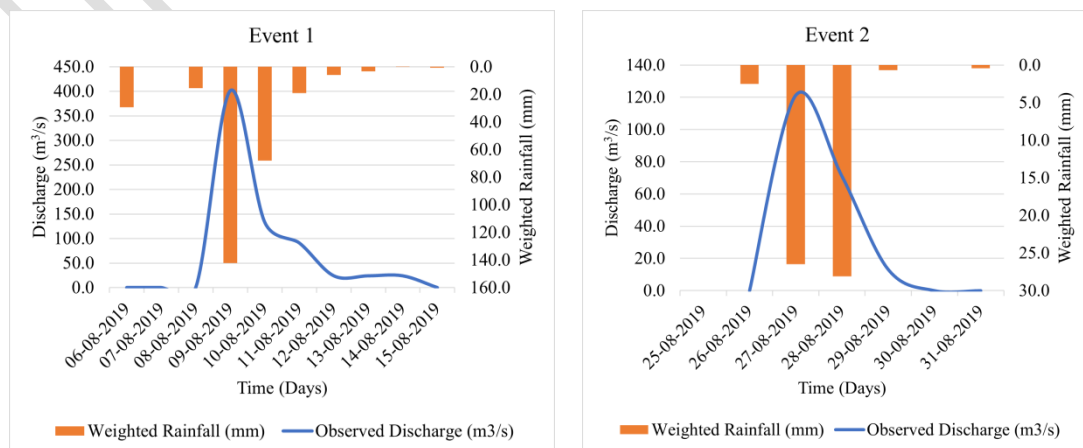
3.4 Selected Events

The discharge/runoff data and corresponding rainfall storm data were collected from the State Water Data Centre, Gandhinagar. The single peaked different five events were selected randomly from the data of the study area and details of the event is given in Table 6.

Table 6: - Different events selected for study

Event No.	Date	
	From	To
1	05-08-2019	17-08-2019
2	24-08-2019	02-09-2019
3	11-09-2019	20-09-2019

The observed direct surface runoff data have been used for the comparison purpose of the runoff hydrographs computed by using HEC-HMS based Clark and SCS model. The weighted rainfall and observed discharge are shown in Fig. 6 (a) to (c) along with the direct surface runoff hydrographs computed by the proposed models.



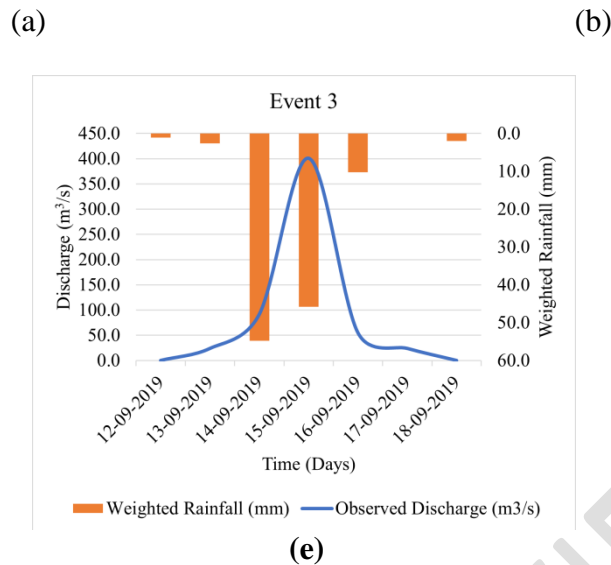


Fig. 6 (a) to (c): Presentation of Discharge and rainfall of selected events

3.5 MODEL APPLICATION

For evaluation of the performances of the unit hydrographs derived using Clark and SCS UH models. All the parameters of the HEC-HMS package Clark and SCS UH models are particularly estimated for the five rainfall runoff events and the same parameters have been used to compute the DSRO hydrographs of the corresponding five rainfall-runoff events.

The DSRO hydrographs computed using the HEC-HMS package Clark and SCS UH models for the five events are shown in Fig. 8 to 10. The maximum discharge (Q_p in m^3/s) and time to peak (t_p in days) values of observed and simulated are presented in the Table 7.

Table 7: Peak discharge and time to peak of the observed and computed DSRO hydrographs

Event. No.	Observed		SCS UH		Clark UH	
	Q_p (m^3/s)	t_p (days)	Q_p (m^3/s)	t_p (days)	Q_p (m^3/s)	t_p (days)
1	400.90	2	495.70	2	316.80	3
2	96.29	3	75.10	3	36.80	4
3	150.90	3	195.30	3	112.50	4

Table 7 shows the peak discharge and time to peak of the observed and the computed DSRO hydrographs. The time to peak discharge of the observed hydrograph is upto three events and that of the, SCS UH, and Clark UH DSRO hydrographs varies from 2 to 5, and 3 to 6. The observed DSRO hydrographs and the computed DSRO hydrographs using the four models are shown in Fig. 8 to 10. It can be observed from the Fig. 8 to 10 and from Table 7 that the time to peak estimated by the models are found same as the as compared to the observed hydrograph except that of the Clark's UH model.

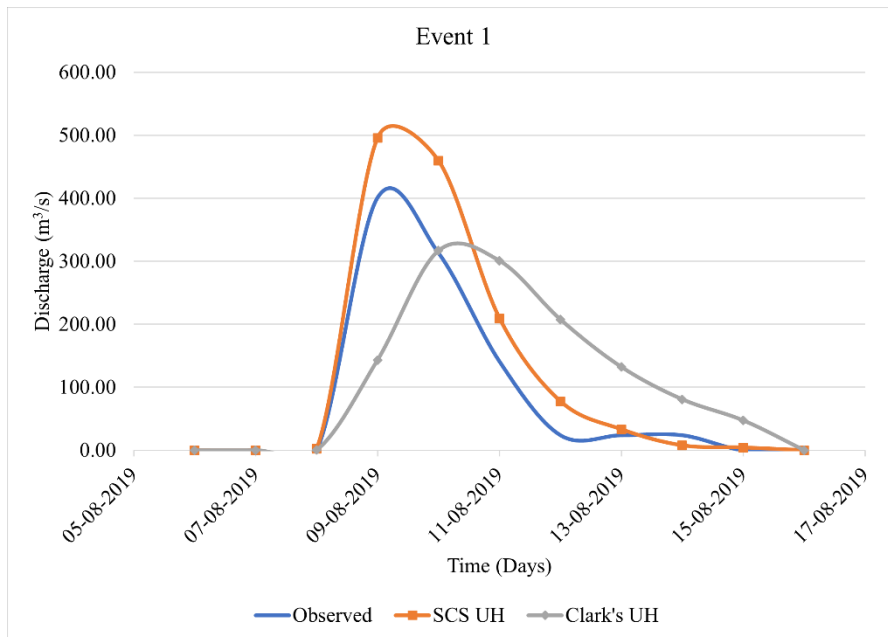


Fig. 8: Comparisons of DSRO hydrographs of Event No. 01

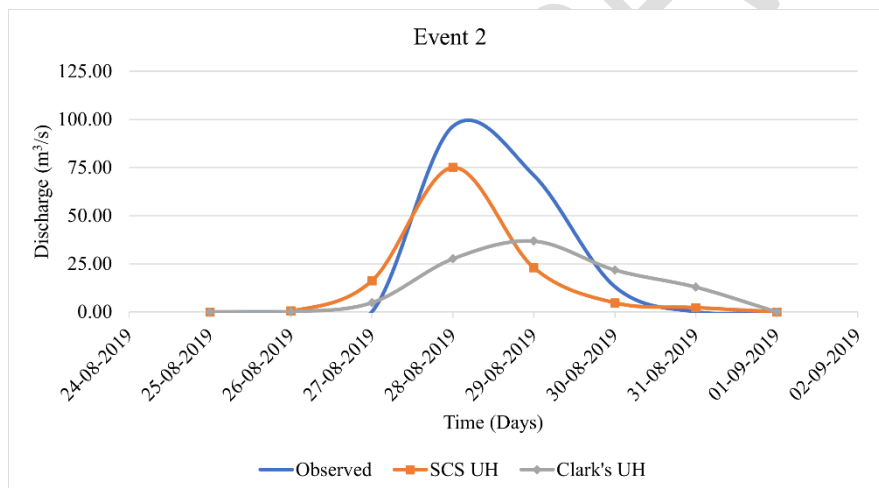


Fig. 9: Comparisons of DSRO hydrographs of Event No. 02

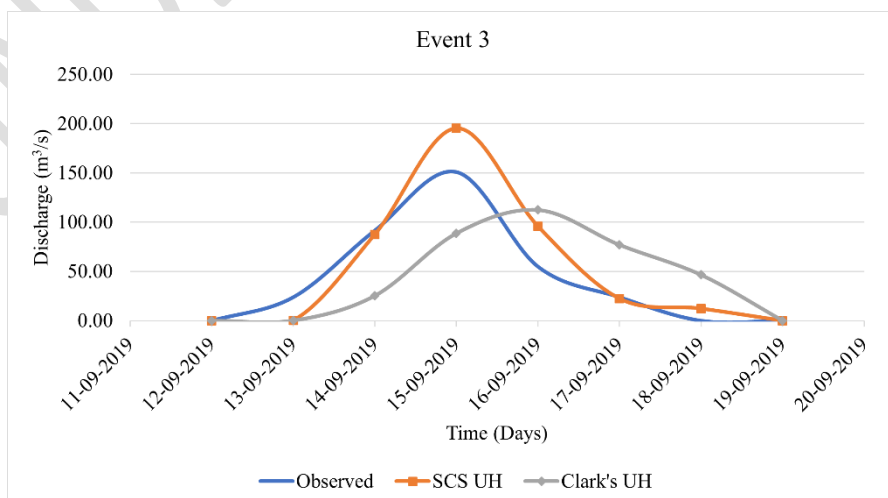


Fig. 10: Comparisons of DSRO hydrographs of Event No. 03

4.4. COMPARISON OF ERROR FUNCTIONS USED FOR EVALUATION

Table 8 shows the values of error functions computed to evaluate the DSRO hydrographs derived using the HEC-HMS based SCS and Clark model. These error functions are: (1) NSE, (2) PBIAS (3) Root mean square error (RMSE), and (4) Index of Agreement measure (d).

It can be observed from the Table 8 that the values of NSE varies from -0.28 to 0.81 for SCS UH model; from -0.11 to 0.41 for Clark UH model.

It can be observed from the Table 8 that the values of PBIAS varies from -32.65% to 108.76% for SCS UH model; from -42.30% to 77.89% for Clark UH model.

It can be observed from the Table 8 that the values of RMSE varies from 19.64 to 59.1 for SCS UH model; from 19.79 to 113.9 for Clark UH model.

It can be observed from the Table 8 that the value of d varies from 0.86 to 0.97 for SCS UH model; from 0.68 to 0.77 for Clark UH model.

Table 8: Error functions computed for DSRO hydrographs

Event No.	Methods	Error functions for DSRO hydrographs			
		NSE	PBIAS	RMSE	d
1	SCS UH	0.81	39.24%	59.10	0.97
	Clark UH	0.29	32.72%	113.93	0.76
2	SCS UH	0.70	-32.65%	19.64	0.89
	Clark UH	0.41	-42.30%	27.72	0.68
3	SCS UH	0.79	19.90%	23.36	0.96
	Clark UH	0.16	1.45%	46.26	0.71

5 CONCLUSIONS

The Land use and land cover in the watershed were classified into agriculture (42.13%), bare land (0.03%), built-up areas (3.08%), forest (53.55%), and water (1.21%). The predominant soil type in the watershed is loamy (91.33%), with some areas having clayey soil (8.67%). FAO soil data and Sentinel-2 remote sensing data in ArcGIS were used to create the soil map and land use map, respectively. The estimated Curve Number for the watershed was found to be 77.69. Weightage factors for calculating weighted rainfall using the Thiessen Polygon method were determined as 0.68, 0.18, and 0.14 for the Devgadh Baria, Devhat, and Rangpur rain gauges, respectively. Excess rainfall estimated using the SCS loss method for three events (event-1, event-2, and event-3) were 186.27 mm, 17.32 mm, and 58.63 mm, respectively. The estimated time to peak using the HEC-HMS based SCS UH model matched well with observed data, while the HEC-HMS based Clark UH model showed a one-day delay in time to peak. The HEC-HMS based SCS UH model outperformed the HEC-HMS based Clark model based on performance indicators such as NSE, RMSE, and d.

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