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RAINFALL RUNOFF MODELLING USING HEC-HMS MODEL: CASE STUDY OF PURNA RIVER BASIN

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ABSTRACT

The runoff estimation process is extremely complicated, nonlinear, and dynamic in nature, which depends on the meteorological and various physical features of the catchment area. Rainfall causes runoff, and the occurrence and quantity of runoff are determined by the features of the rainfall event, which is the most significant hydrological process. Water resource planners typically utilize hydrological modelling to simulate the hydrological response in a basin according to the precipitation. The objective of the study is to develop a rainfall runoff model for Purna River basin using HEC-HMS model. In this study, Digital elevation model was used to delineate the watershed and consider outlet at Mahuwa gauging site, also prepared a thematic map by using Arc-GIS (10.3). HEC-HMS 4.6.1 model is used to rainfall runoff process. The Green Ampt method was utilized in this research to account for loss. SCS unit hydrograph and Synder Unit hydrograph methods are compared and both methods used for accounting the transform method and best suitable method is being used for final simulation. After optimization of the model result shows that, in SCS unit hydrograph, coefficient of determination (R-squared) was 0.9680 for year 2007 and value of Nash–Sutcliffe efficiency (NSE) and Root mean squared standard deviation (RMSE std. dev.) at Mahuwa outlet were 0.928 and 0.3 respectively. Whereas, the performance of the model was evaluated by Synder unit hydrograph which gave R-squared value varies between 0.7 to 0.9. Regression analysis indicate that both the methods have shown the good performance in predicting the runoff events in the study area based on the rainfall events. However, performance of the SCS unit hydrograph is better than Synder unit hydrograph. Thus, SCS unit hydrograph can be applied for the accurate prediction of the runoff.

Keywords: Arc-GIS (10.3), HEC-HMS, Green Ampt, SCS unit hydrograph, Synder unit hydrograph, Purna River.

INTRODUCTION

Rainfall runoff is an important aspect of water resource planning and management (Benkaci and Dechemi, 2018; Zeggane et al., 2021; Rouissat and Smail, 2022). A thorough understanding of the rainfall runoff mechanism is required to estimate the runoff which is produced within a specific catchment (Darji et al., 2019). Runoff computation from ungauged or poorly gauged catchment is a serious challenge in developing countries like India in which has higher operation and maintenance costs differed gauging on small as well as medium rivers (Sahu et al., 2020; Kumar et al., 2023a; Kumar et al., 2023b). To find out the runoff, not only precipitation is responsible itself but also other various kind of meteorological parameters are being used (Koua et al., 2019). In the other words, rainfall runoff is impacted by all physical qualities of the catchment, and generalizing all physical parameters of the catchment is a challenging operation (Mistry et al., 2017; Riahi et al., 2020; Baudhanwala et al., 2024; Atallah et al., 2024). Consider the phenomena of infiltration, which has a direct impact on the runoff process, but when you examine infiltration at different places in the catchment, you will see a broad range of infiltration rates (Rathod et al., 2015; Mehta et al., 2023a; Verma et al., 2024).

Many watershed models have been created to describe rainfall processes based on a conceptual depiction of the physical water flow mechanism throughout the whole basin region (Sampath et al., 2015; Faregh and Benkhaled, 2016; Kantharia et al., 2024). Collection and calculation of runoff is one of the remedy to save water; there are various Hydrological models are available for calculation of runoff but HEC -HMS is a choice of suitable one which is important of accurate prediction. The hydrologic modeling system is designed to simulate intact hydrologic processes of watershed system (Patil et al., 2019; Mehta et al., 2023b; Kapadia et al., 2023). HEC-HMS is a hydrologic model that provides many simulation options for rainfall-runoff processes, and it has been widely used to analyze hydrologic processes and forecast hydrologic outcomes in a catchment (Atallah et al., 2024). For this study, the integration of the HEC-HMS model with the Geographic Information System (GIS) and remote sensing imagery is employed to enhance better output performance (El Hmaidi et al., 2015; Armain et al., 2021; Umrigar et al., 2023; Berrezel et al., 2023).

The HEC-HMS model is a simple representation of real-world system (Fernando et al., 2021). The best model is one that produces outcomes that are similar to the original while using least parameters and more complexity (Ibrahim et al., 2021). Models are primarily used to forecast behaviour of the system and to comprehend various hydrological processes. Various model parameters that define the model's properties. A runoff models can be defined as set of equations which helps in the estimation of runoff as a function of various parameters used for describing watershed characteristics (Devia et al., 2015; Benkaci and Dechemi, 2018; Mehta et al., 2022; Patel et al., 2024). In this paper, The Green Ampt method was used as a loss model in the study. SCS unit hydrograph and Snyder unit hydrograph methods are compared for better runoff estimation, and the best acceptable method for the study region is chosen for the final simulation.

STUDY AREA AND DATA COLLECTION

The study area is located in part of Purna river basin (Dang district, Surat district and Tapi district) Gujarat state (Fig. 1). The river has its origin in Saputara Hill ranges in the Dang district of Gujarat. Drainage area of Purna River basin is 2431 km^2 and its travels 180 km before joining Arabian Sea. Drainage area of Purna River sub-basin (study area) is 1548.45 km^2. The basin lies between 72˚ to 74˚ 00'' East longitude and 20˚41'' to 21˚05'' North latitude. From June through September, the region receives the majority of its rainfall from the south monsoon. The sub-annual basin's rainfall average is 1596.8 mm. The maximum and lowest temperatures of Mahuwa are 27˚ C to 46 ˚C and 30˚ C to 10˚ C, respectively. The wind direction that is most prevalent is NE, followed by SE and W. Wind speed is often greater during the pre- and post-monsoon season.

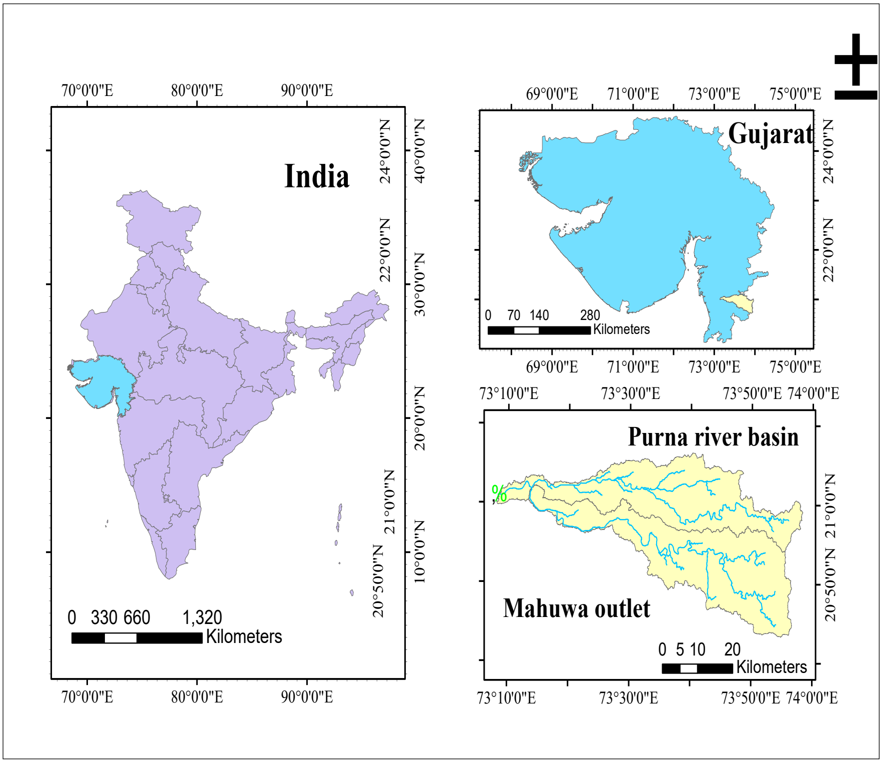

Figure 1: Location of Purna river basin

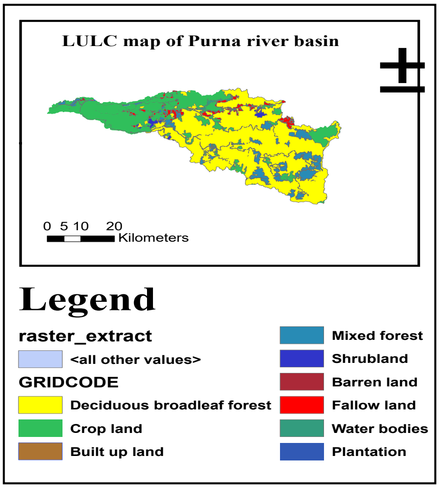

Figure 2: LULC map

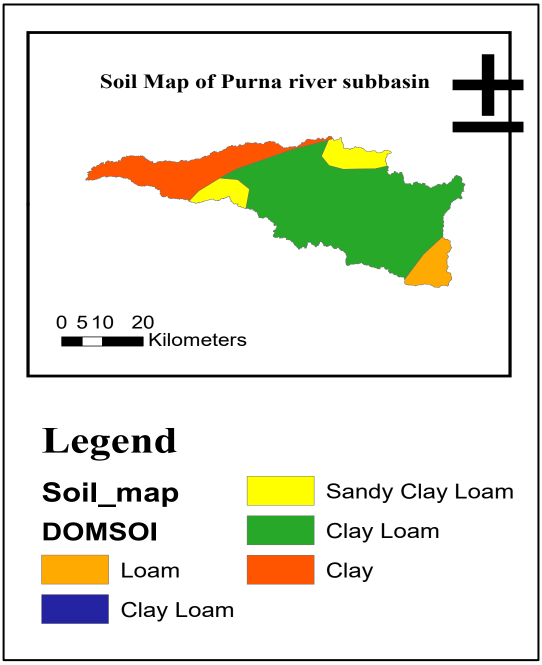

Figure 3: Soil map

DATA COLLECTION

The data used in present study is obtained from the different sources. Temperature, wind speed, humidity data and daily discharge data of the discharge gauging station (mahuwa) is procured from Central water commission, Surat (CWC). For the present study, there are two rainfall station Wankla and Kalibel. And daily rainfall data has been collected from the State Water Data Centre (SWDC) Gandhinagar. The data is collected for the period of 2004, 2005, 2006,2007,2013,2016 and 2017 years because that year's peak flow is maximum. Thematic map such as LULC and soil map were prepared from https://daac.ornl.gov/ and www.FAO.org which is show in Figs. 2 and 3 respectively. While DEM was extracted with the help of the tiles which is downloaded from Bhuvan portal.

MATERIAL AND METHODS

Runoff of Purna river basin was estimated using Green Ampt parameter in HES-HMS model. Methodology adopted in this study is summarized as below (Fig. 4).

The first phase in the model development process is the creation of the basic model. The Study area is created by using Arc-Gis (10.3). In the present study, HEC-GeoHMS and Arc-Hydro tool were used in ArcGIS for developing basin model. The study area basin was delineated and divided into two sub basins. After that, basin model has been imported in to the HEC-HMS (4.6.1), which is shown in Fig. 5.

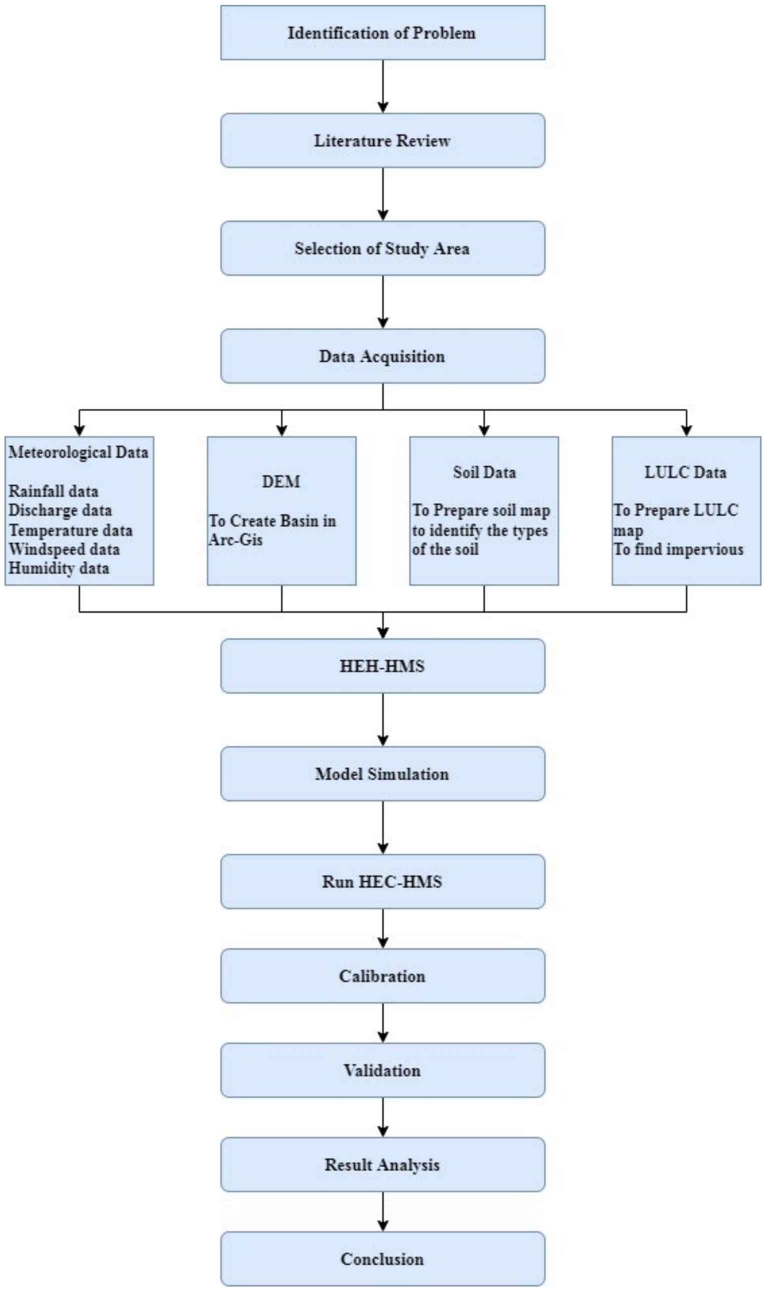

Figure 4: Flow Chart of methodology

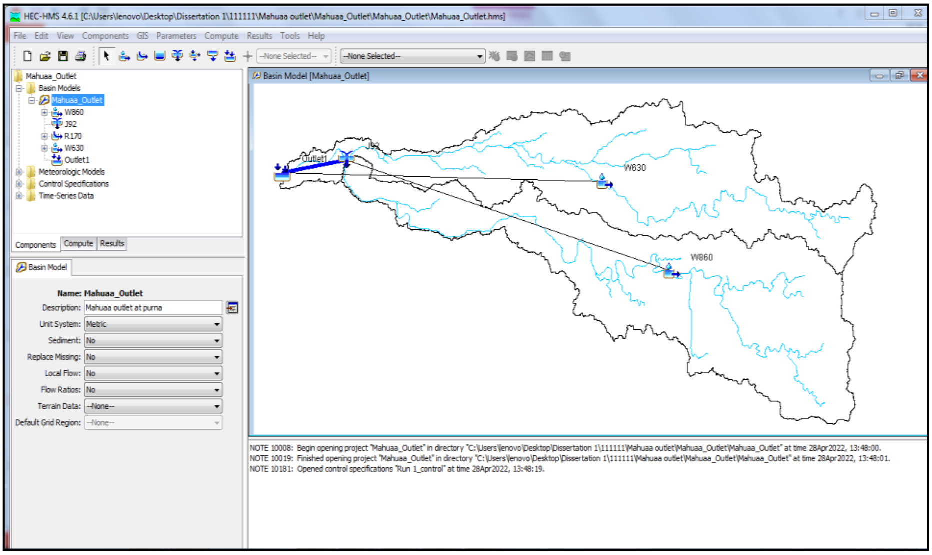

Figure 5: HEC-HMS model Setup

HEC – HMS uses a separate model to represent each component of the runoff process. For input the data for each sub basin all the hydrological parameters have been initially calculated and simulated the model for observed boundary conditions to compute the basin runoff. Then computed hydrograph is compared with the simulated hydrograph in ordered to determine how well the model fit with real hydrograph. The model parameters were adjusted until the results were satisfactory.

There are many methods to calculate loss parameters of these initial and constant rate method, SCS curve number method, Green and Ampt method.

Loss method

In most HEC-HMS loss models, the volume of runoff is calculated by subtracting the amount of water caught, invaded, deposited, evaporated, or happened from the precipitation. To estimate direct runoff from a design rainfall, the method of loss of the Green Ampt method was used.

It is a simple method for estimation of the direct runoff amount from empirical rainfall data. It depends only on the types of the soil. Green-Ampt model is a conceptual model to calculate rain-fall loss in permeable surfaces in a specific period (Sahour and Mahana, n.d.).

There are five parameters to be defined in HEC-HMS to run the Green-Ampt method:

Initial content-initial saturation as a volume ratio-θ_i

$$\theta_i = \theta_e (1 - S_e) \tag{1}$$

Where, θ_e is the Effective Porosity and S_e is the relative saturation of the soil when the rainfall begins. It is worth noting that S_e varies within the following range, $0 \le S_e \le 1$.

Brooks and Corey (1964) studied variations of the suction head ψ, with moisture content θ. They constructed a graphical and then an empirical link between soil suction head and effective saturation S_e by doing laboratory tests on a variety of soils, which is known as the Brooks-Corey equation (1964):

$$S_e = \left(\frac{\psi_b}{\psi} \right)^{\lambda} \tag{2}$$

Where ψ_b is the Bubbling pressure or air entry pressure, ψ is the Suction head, and λ is the Pore-size distribution index. Brooks-Corey equation (1964) is solved with the help of the slopes of the resultant curves are:

1. 1 / λ and intersections with the S_e-axis are $\ln \psi_b$. Which is given in the (Brakensiek 1981)
2. Saturated content- total porosity as a volume ratio-n.
3. Suction (mm)-wetting front soil suction head—ψ.
4. Conductivity (mm/hr)-hydraulic conductivity-k.
5. Impervious (%)-percentage of the basin with impervious cover.

Above all the parameters have been calculated from the different types of the soil present in the basin. For known soil type suction head, conductivity can be taken from the Green-Ampt parameter table given by V.T Chow (1988).

Transform model

The HEC-HMS transform prediction models replicate the cycle of direct runoff of surplus precipitation on the watershed and convert excess precipitation into runoff. In this investigation, the Soil Conservation Service Unit Hydrograph model and Synder unit hydrograph model were employed to determine surplus precipitation into runoff.

SCS unit hydrograph*:*

The SCS approach just requires a lag time between runoff and precipitation in each sub-basin. The computed direct runoff for the sub-basin is then utilized. Kirpich's equation is used to compute lag time. This is the popularly used formula relating the time of concentration of the length of travel and slope of the catchment as,

$$T_c = 0{,}01947.L^{0{,}77}.S^{-0{,}385} \quad (3)$$

$$T_{lag} = 0{,}6T_c \quad (4)$$

Synder unit hydrograph

The Synder unit hydrograph approach requires a lag time between runoff and precipitation in each sub-basin. And also peaking coefficient in each sub-basin. This metric is computed by combining the time of concentration, peaking coefficient and the peck flow. The computed direct runoff for the sub-basin is then utilized. Synder's equation is used to compute lag time.

$$T_{lag} = C_t(\mathrm{L} * L_c)^{0{,}3} \quad (5)$$

T_{lag} is the watershed lag time in hours, Lc is the distance along the main stream from the outlet to the point nearest the centroid of the watershed in kilometers, L is the total length of the main channel in kilometers, and Ct is the coefficient that varies geographically.

Snyder considered that the shape of the unit hydrograph is likely to be affected by the basin characteristics like area, topography, shape of the slope, drainage density and channel storage. He dealt with the size and shape of basin by measuring the length of the mainstream channel. The coefficient Ct reflects the size, shape and slope of the basin. But Synder did not specify any relationship between slope and basin area to identify Ct values.

Therefore, Linsley, Kohler and Paulhus gave an expression for the lag time in terms of the basin characteristics as:

$$T_p = C_t\left(\frac{L\,L_c}{\sqrt{S}}\right)^{0.38} \quad (6)$$

Where

T_p , = lag time (basin lag), hr

L = length of the longest water course (miles)

L_c = length along the mainstream from outlet to point closest to catchment Centroid (miles)

S = basin slope

C_t = empirical constant = 1.2 for mountainous region, 0.72 for foot hill areas, 0.35 for valley areas.

Snyder's formula for peak flow is as follows:

$$Q_p = \frac{2.78 \ x \ Cp \ x \ A}{Tp} \tag{7}$$

Where:

Q_p= Peak discharge (cumec)

C_p= empirical constant (inversely related to Ct)

A = catchment area (km^2)

T_p= lag time (basin lag), hr

Model calibration and validation

Model calibration is an important element that ensures simulation outputs are near to actual observations. After developing and simulating the model for initial parameter, it was calibrated against known runoff rates observed at the Mahuwa station during a rainfall event that occurred for 2004,2005,2007,2013 and 2016. The auto calibration tool was used for the parameter optimization which was performed by trial and error by periodically adjusting the parameters and analyzing the closeness of fit between the computed and observed hydrographs. To minimize the objective function value and establish ideal parameters, the automatic calibration was utilized to modify saturated content, suction head, and peaking coefficient and lag time.

For validation, the simulated data as synthesized by the model must be computed with the observed data and evaluation measures of error functions must be carried out. The model is validated if the values of the error functions are very small and within an acceptable range of accuracy. The validation was carried out for 2006 and 2017.

RESULTS AND DISCUSSION

Each component of HEC-HMS simulates a different aspect of the precipitation-runoff process within the basin. A component's representation demands a range of parameters that characterise the component's specific properties as well as mathematical relations that explain the physical processes. After calibration and validation, performance of model was evaluated by NSE and regression analysis. for SCS unit hydrograph the simulated and observed discharge, NSE, R 2 and RMSE values are shown in table 1. which indicate that performance of model is best suited for 2 July 2007. For this period NSE, R 2 and RMSE values are 0.928, 0.9680 and 0.3 respectively. Figure 6 and 7 shows comparison of the simulated and observed discharge for calibration of 2007 and validation of 2017 respectively. Whereas, for Synder unit hydrograph the simulated and observed discharge, NSE, R 2 and RMSE values are shown in table 2. For this, regression analysis varies between 0.7 and 0.9. Figure 8 and 9 shows comparison of the simulated and observed discharge for calibration of 2007 and validation of 2017 respectively.

Table 1: Result summary for Mahuwa Gauging site by using SCS method

Year	Date	Simulated discharge (Cumec)	Observed discharge (Cumec)	NSE	R^2	RMSE std dev	Remark
2004	4 Aug	8473.1	8835.5	0.926	0.9279	0.3	Calibration
2005	29 June	4899	5436.6	0.880	0.9599	0.3	Calibration
2006	5 July	4126.3	5113.6	0.867	0.9033	0.4	Validation
2007	2 July	3016.6	3058	0.928	0.9680	0.3	Calibration
2013	24 Sept	1458.8	1508.1	0.888	0.9037	0.3	Calibration
2016	9 Aug	1129.9	1048.1	0.928	0.9397	0.3	Calibration
2017	28 July	1104.0	1060.2	0.858	0.9098	0.4	Validation

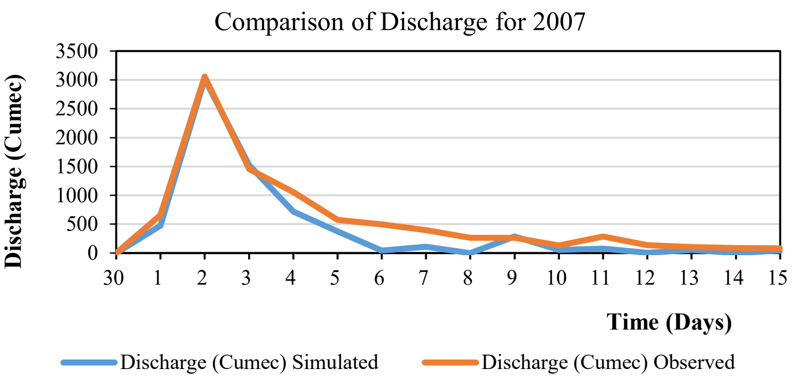

Figure 6: Comparison between simulated and observed discharge for 2007 (Calibrated) – SCS

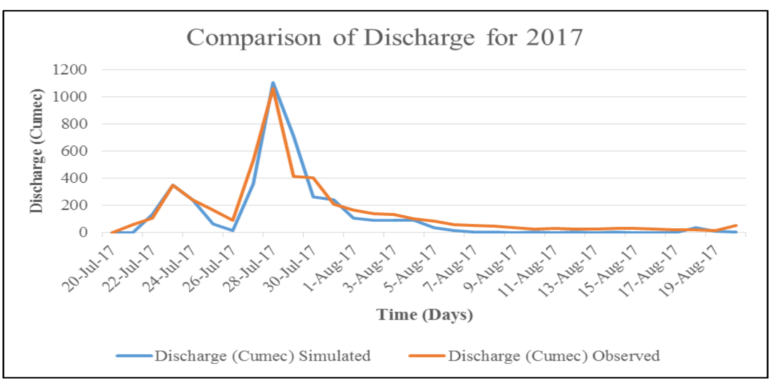

Figure 7: Comparison between simulated and observed discharge for 2017 (Validated) – SCS

Table 2: Result summary for Mahuwa Gauging site by using Synder method

Year	Date	Simulated discharge (Cumec)	Observed discharge (Cumec)	NSE	R^2	RMSE std dev	Remark
2004	4 Aug	7292	8835.5	0.833	0.8351	0.4	Calibration
2005	29 June	4323.9	5436.6	0.880	0.8837	0.3	Calibration
2006	5 July	4052.3	5113.6	0.729	0.7432	0.5	Validation
2007	2 July	2440.7	3058	0.890	0.8914	0.3	Calibration
2013	24 Sept	1418.8	1508.1	0.901	0.9042	0.3	Calibration
2016	9 Aug	866.8	1048.1	0.805	0.8577	0.4	Calibration
2017	28 July	916.7	1060.2	0.903	0.8799	0.3	Validation

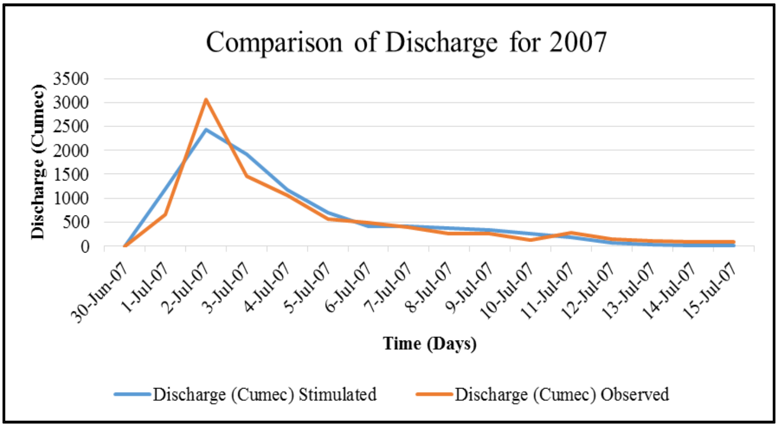

Figure 8: Comparison between simulated and observed discharge for 2007 (Calibrated) - Synder

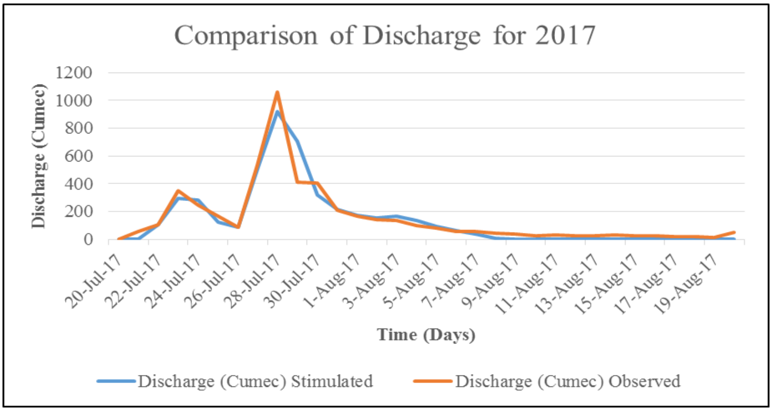

Figure 9: Comparison between simulated and observed discharge for 2017 (Validated) – Synder

Comparison between SCS and Synder unit hydrograph

In this study, the accuracy of the Snyder unit hydrograph and SCS unit hydrograph transform methods is examined. By holding all of the green ampt characteristics constant, the SCS and Snyder's methods are compared. The comparison graph between SCS and Synder shows that the SCS method creates better (higher side) peak discharges, and the correlation coefficient between observed and simulated discharges is more than 0.9 for all sub basins. While, Snyder's method gives the low peak discharges as well as the performance of the correlation coefficient varies between 0.7 and 0.9 which is lower than SCS method.

Peak discharges should be adequately anticipated to be on the safe side so, it is preferable to consider peak discharges on the higher side. Because it doesn't really matter how long the runoff lasts, what matters is the peak discharge. If the peak discharge is too high, it may leads to flooding of channel bank. As a result, the SCS unit hydrograph is being used for final simulation. Comparison between simulated discharge and of SCS and Synder method is shown in table 3. While, Figure 10 and 11 shows the comparison of SCS and Synder method's simulated discharge of year 2007 for calibration and 2017 for validation.

Table 3: Result summary table of simulated discharge of SCS and Synder

Year	Date	Q (Cumec)		R^2	
		SCS	Synder	SCS	Synder
2004	4 Aug	8473.1	7292	0.9279	0.9051
2005	29 June	4899	4323.9	0.9599	0.8837
2006	5 July	4146.2	4052.3	0.9033	0.8932
2007	2 July	3016.6	2440.7	0.9680	0.8914
2013	24 Sept	1450.8	1418.8	0.9037	0.9042
2016	9 Aug	994.7	866.8	0.9397	0.8577
2017	28 July	1035.9	916.7	0.9098	0.9085

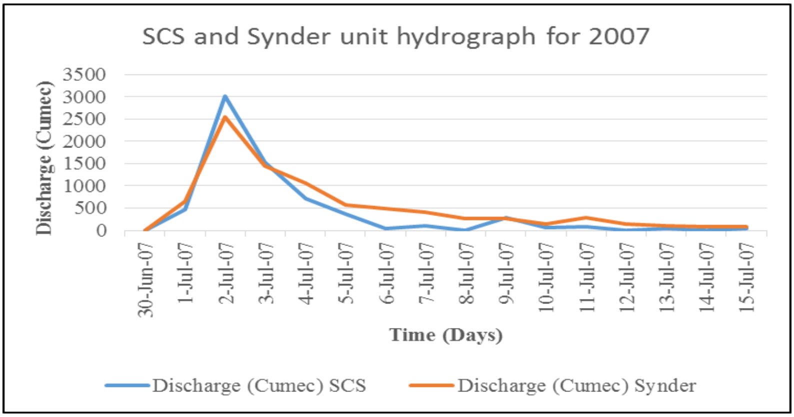

Figure 10: Comparison SCS and Synder for 2007 (Calibrated)

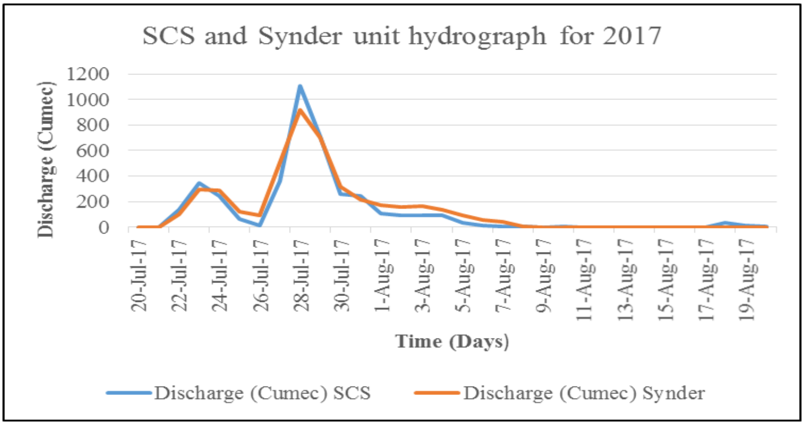

Figure 11: Comparison SCS and Synder for 2017 (Validated)

In SCS method, in the rainfall-runoff process the parameters and initial storage show a high variability and parameters of Green Ampt parameter and lag time are constant in the all events. The calculated RMSE values in peak flow between simulated and observed values in all pre-optimization simulations were very high. So that optimization is being used. In light of this finding, a sensitivity analysis was carried out to determine the most sensitive parameter for methods of loss and transformation. It was noticed that suction head, saturated content were more sensitive parameter whereas, lag time was less sensitive parameter. But after optimization, table 5.6 shows that the coefficient of determination (R-squared) was 0.9680, the NSE value was 0.928, and the RSME standard deviation was 0.3 for the year 2007 at mahuwa outlet.

The results of this study generally provide basic information on the extent of the total volume and peak flow generated in the catchment from the respective rainfall events, which in turn are useful for the planning, design and management of various water resources activities. So, this study would help in the proper management of Purna River Basin.

CONCLUSION

The rainfall runoff process was carried out in this study for Purna river sub-basin using HEC-HMS model and Green Ampt method. The rainfall-runoff simulation was carried out for seven event using rainfall data. The model was calibrated for five event and two event was used for validation. Thematic map shows that in Land use map most of the study area is covered with deciduous broadleaf forest and it would be also used to find out the impervious for Green Ampt parameter. Whereas, other parameter would be found with the help of the soil map. In addition, soil map indicate that Purna river basin has mainly two types of soil namely clay loam and clay. The regression analysis approach was used to forecast runoff, which also aided in the calculation of floods at the Purna River. In SCS unit hydrograph, the analysis results show that the coefficient of determination (R-squared) was 0.9680, the NSE value was 0.928, and the RMSE standard deviation was 0.3 for the year 2007 at Mahuwa outlet, which is indicating a good correlation between observed rainfall and estimated runoff value. This suggests that this model is best suited for the year 2007. While, the overall performance of the model was evaluated by Synder unit hydrograph which gave R-squared value varies between 0.7 and 0.9. By comparing both method SCS and Synder unit hydrograph show that SCS method gives better peak discharge in all year. Whereas, Snyder's method gives the low peak discharges as compared to SCS unit hydrograph. If the peak discharge is too high then it may lead to flooding of channel bank. For this reason, SCS unit hydrograph is considered for the better estimation of runoff in the Basin. Regression analysis of rainfall runoff data of the model's result indicated that both the model performs well but the prediction capability of SCS unit hydrograph is gave good result for all years as compared to Synder unit hydrograph. With these findings, it is possible to conclude that HEC-HMS can be used to develop rainfall runoff process for the particular basin.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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