Rainfall-runoff modelling using HEC-HMS model, Remote Sensing and GIS in Middle Gujarat, India

Abstract

Hydrological modeling is a widely used approach for estimating the hydrological response of a basin to precipitation. Floods are among the most catastrophic natural disasters in small urban watersheds, inflicting loss of life, massive property destruction, and a severe danger to the economy. As a result, appropriate modeling can be a useful tool in preventing and mitigating such flood hazards. Despite this, flash flood prediction remains one of the challenges of hydrological modeling in ungauged basins due to a lack of runoff observations. This study aims to calibrate and validate the rainfall-runoff transformation model for Hathmati river sub watershed in the Sabarmati River basin using HEC-HMS (Hydrologic Engineering Centre Hydrology Modeling System). For the loss rate, SCS Curve Number method was selected while Clark Unit Hydrograph and SCS unit hydrograph was used for the transform method. The model is calibrated and verified using two rainfall-runoff events from 2006 and 2007 year The model calibration and validation efficiency were verified for both methods using the Nash-Sutcliffe efficiency (NSE), The coefficient of determination (R^2), and the Percent Bias (PBIAS) As a result, the model calibration and validation were found to be satisfactory with the acceptable value of NSE between 0.869 to 0.914, with R^2 0.901 to 0.947 and PBIAS from 9.76 to 14.8. it is observed that the model shows a very good correlation between simulated flow and observed flow. As a result, the model can be used to forecast river flow and aid in flood mitigation efforts to lessen their effects and associated costs. Additionally, the findings of this study can serve as guidelines for future assessments of the flood risk in the study area.

Keywords: SCS unit hydrograph, Clark unit hydrograph, Rainfall-Runoff simulation, rainfall Events, Hathmati watershed

INTRODUCTION

"Adequate knowledge of runoff within a watershed is vital to planning and designing water resources and related projects" (Zelelew and Melesse, 2018). "Soil and water are the two essential natural resources for agricultural development" (Lampurlanés et al., 2016). "The actual estimation of runoff volume and peaks are also important for planning different interventions in integrated watershed management and flood protection projects" (Romali et al., 2018). "However, detailed hydrological studies are challenged due to the scarcity of data and complexity of hydrological systems. The runoff simulation model is one of the hydrological models that can drive the watershed rainfall response and forecast flood for water resources management" (Teng et al., 2017). "So, flood simulation is simplified through employing model and understanding factors triggering runoff" (Tassew et al., 2019). "Nevertheless, hydrological modelling is among the recently developed tools feasible to reproduce the behaviour of a watershed during any rainfall event and could be a promising approach for the design of stormwater drainage systems". (Natarajan and Radhakrishnan

2021) “The detailed hydrological studies are challenged due to the scarcity of data and complexity of hydrological systems” (Guduru et al., 2023). “Effective management of these resources is crucial for crop production. However, rapid urbanization, industrial growth, deforestation, and climate change have limited the availability of water for agriculture” (Shi et al., 2016). “To address water scarcity, careful utilization and management of water resources are necessary” (Xiubin et al., 2003). “Insufficient land use planning and management strategies have negatively impacted surface runoff and agricultural production. Accurate measurement and quantification of river or channel flow are essential for designing soil and water infrastructure in development plans” (David, 1988). “However, the Hydrologic Modeling System (HEC-HMS) from the Hydrologic Engineering Centre is proven to be user-friendly and suitable for usage in areas with data scarcity” (Halwatura and Najim, 2013; Chu and Steinman, 2009). “Numerous research have demonstrated the HEC-HMS to be effective for hydrological modelling” (Knebl et al., 2005; Abushandi and Merkel, 2013; Gebre, S. L. 2015; Mandal and Chakrabarty, 2016; Gao et al., 2018; Darji et al., 2019; Natarajan and Yuan et al., 2019).

STUDY AREA AND DATA USED

The Hathmati River is located in the Sabarkantha district of Gujarat, India, and the current study is being conducted there in its sub watershed. One of the principal tributaries of the Sabarmati River is the Hathmati River (left) (Western India). Geographically, the watershed is situated between the latitude of 23°30'49"N and the longitude of 72°49'29"E.. It lies in Bhiloda (Sabarkantha district) and rises from Gujarat Malwa Hills. After travelling a course of 98km it meets Sabarmati near village Ged. It covers a total geographical area of sub-watershed around 289.75 sq. km, with an elevation range of 197 to 585 m above mean sea level. The average annual rainfall is 864 mm. The soils of the watershed are clayey and loamy. The location of the study area is shown in **Figure 1.**

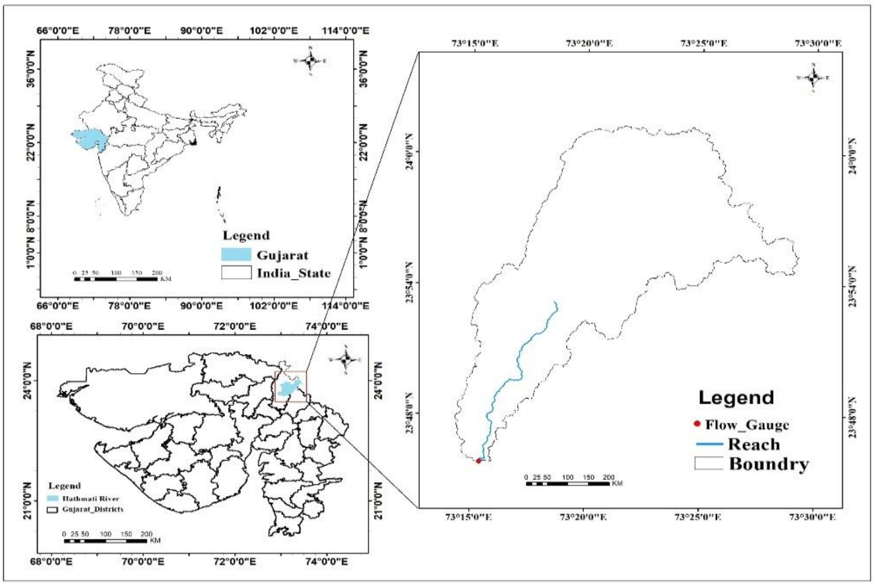

Figure 1. The location of the study area

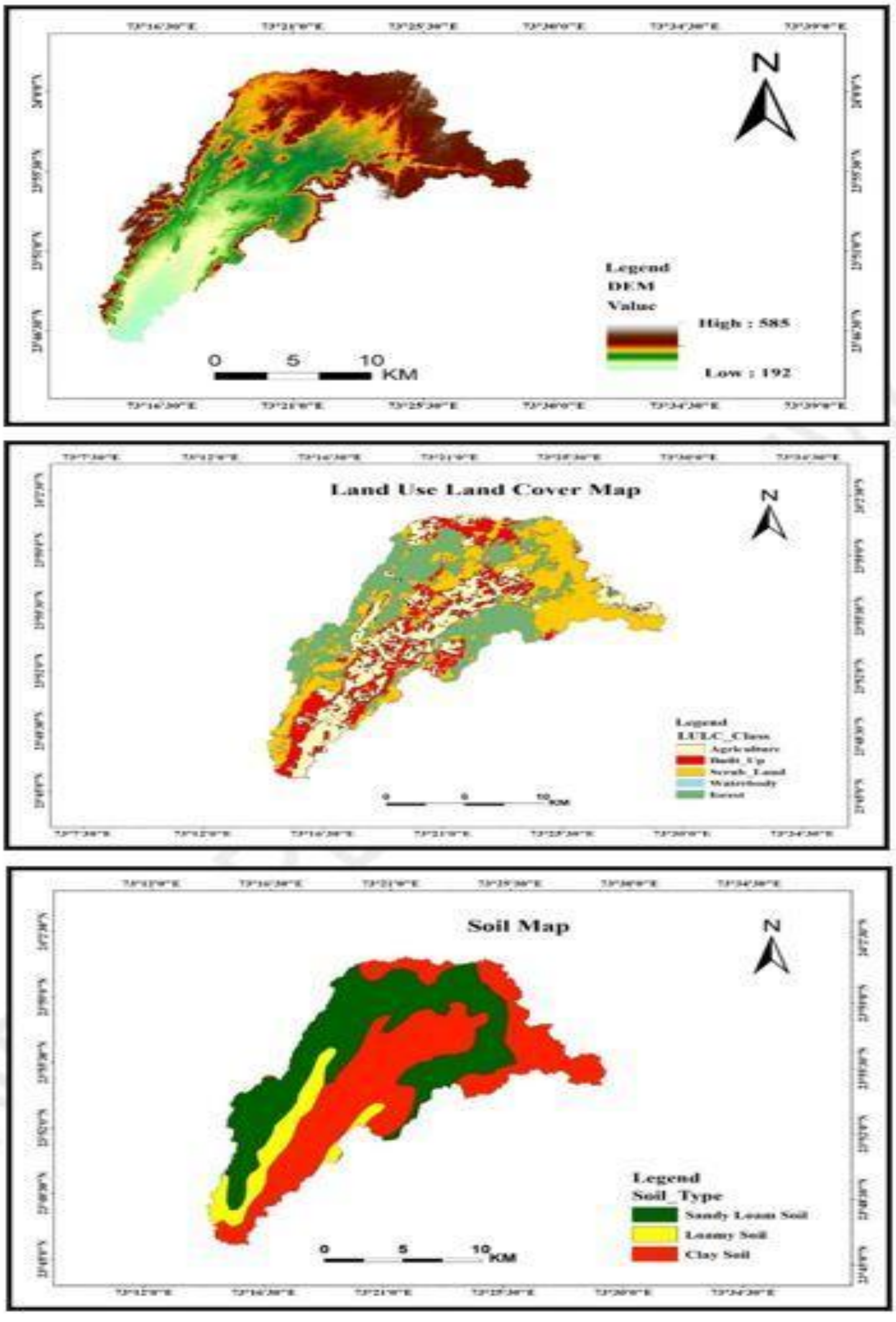

Figure 2. shows the Digital **Elevation Model (DEM), LULC Map and Soil Map of Study area**

Terrain Data

Digital Elevation Model (DEM) is a digital representation of a topography surface. The SrtmDEM (Shuttle Radar Topography Mission) with 30meter resolution of the study area is obtained from Earth Explorer U.S. Geological Survey (https://earthexplorer.usgs.gov/).

Rainfall Data

The daily rainfall data is obtained from India Meteorological Department (IMD) website (http://imdpune.gov.in/ with the spatial resolution of data was 0.250x0.250. In the current study, rainfall data are extracted for the study area. Using ArcGIS 10 software and the weighted rainfall from the years 2005 to 2020 prepared using the Thiessen polygon method.

Discharge Data

Daily discharge data of stream gauging station at outlet Bhiloda of the watershed from 2005 to 2020 year is collected from State Water Data Center, Gandhinagar.

Soil Data

"The soil map was prepared in GIS environment as a vector layer using sheet no. 3 of the soil map produced by the National Bureau of Soil Survey and Land Use Planning (NBSSLUP) at a scale of 1:500,000. And as per infiltration rate based on" (Usda, 1986). Soil group with HSG of B and D are available that have the properties of low infiltration rate and more runoff. **Figure 2** shows the soil map of the research area. The majority of the study area's soil is clay at the surface (hydrological group D), sandy loam at the subsurface (hydrological group A), and silt/loam sandy soil at the bottom (i.e. hydrological group B)

Land Use/Land Cover (LULC)

The LULC map was prepared using a Landsat 8 satellite image with a spatial resolution of 30 m. Unsupervised classification was used to classify the pictures. High imagery from Google Earth is used for the validation. **Figure 2** shows the LULC map of the study area.

Methodology

The overall Methodology presented in **Figure 3**. In order to extract the sub-watersheds and channel characteristics, The curve number is generated using based on the LULC and the HSG provided by the Natural Resources Conservation Service (Usda, 1986). The curve number grid is shown in **Figure 4.** In the present study, two methods were used such as the Soil Conservation Service Curve Number (SCS-CN) and deficit and constant loss as loss method and Soil Conservation Service Unit Hydrograph method and Clark unit hydrograph as the transform method

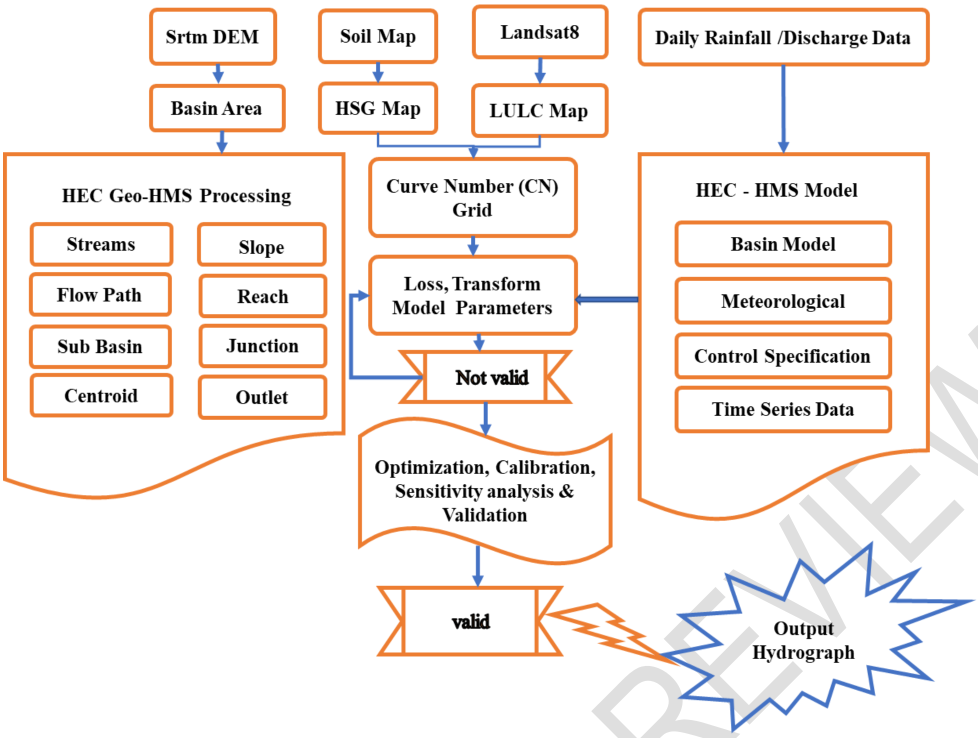

Figure 3 Shows the Flow Chart of Methodology

The basin models, meteorological models, control simulations, and input data are the four essential parts of the HEC-HMS model. Precipitation, evapotranspiration, and snowmelt data are included in the meteorological model, and the basin model maintains the physical datasets detailing the catchment features. Control specifications that include a simulation's beginning date and time, ending date and time,

Loss Method

The SCS-CN approach takes into account the majority of the runoff-producing watershed variables, including soil type, land use, hydrologic soil group, and antecedent moisture condition. (Mishra & Singh, 2004; Abushandi & Merkel, 2013; Yuan et al., 2019). The formula for calculating loss through the SCS-CN method is

$$Q = \frac{(P - I_a)^{2}}{(P - I_a + S)} \qquad (1)$$

Where Q is the runoff value (mm), P is the precipitation (mm), Ia is the initial abstraction (mm), S is the potential maximum retention. The potential maximum retention (S) is a measurement of the capacity of a catchment to abstract and retain storm precipitation. There will be no precipitation excess until the accumulated rainfall exceeds the initial abstraction. As shown in equation (2)

$$I_a = \ 0.2 \times S \qquad (2)$$

Therefore, the cumulative excess at time t is given as

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

Soil retention is calculated using CN values with the formula as

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

Where, CN = SCS curve number for the watershed. In this study the values of CN can be obtained for different land uses, treatment, and hydrologic conditions from the standard table are found in the Technical Release Number 55 (TR-55) (Soil conservation service engineering division, 1986). The CN values var from 98 to 32. The value of 98 is assumed for water bodies and 32 for permeable soils of moderate infiltration rates. The Curve number map of the study area as shown in **Figure 4.**

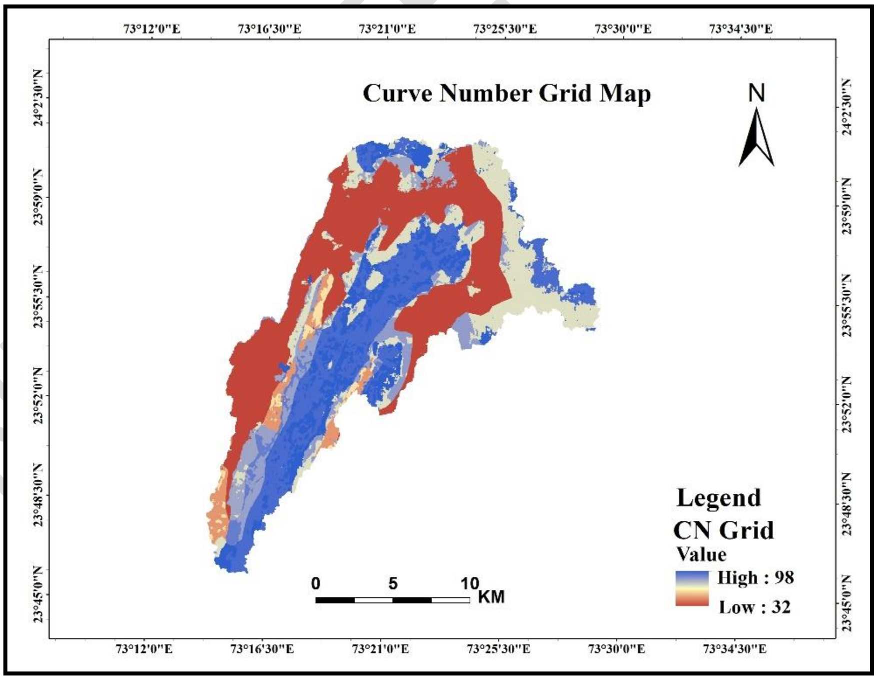

Figure 4. Curve Number Map

Model performance evaluations

"The performance evaluation of the HEC-HMS model was done by assessing the goodness of fit between the observed and simulated stream flow using through visual examination of the simulated and observed hydrograph, and through statistical indicators such as Nash and Sutcliffe efficiency (NSE), Coefficient of determination (R^2), the Percent Bias (PBIAS)". [31] The values of NSE, R^2, and PBIAS were calculated using the following equations

1. Percent Bias (PBIAS).

$$PBIAS = 1 - \frac{\sum_{i=1}^{n}(O_i - P_i)}{\sum_{i=1}^{n} O_i} \times 100$$

Where, O_i, P_i are the observed and simulated flows, respectively.

2. The Coefficient of correlation (R^2).

$$R^2 = \left(\frac{\sum \mathrm{Q_{obs}} - \bar{\mathrm{Q}}_{\mathrm{obs}})^2 - \sum \mathrm{Q_{sim}} - \bar{\mathrm{Q}}_{\mathrm{sim}})^2}{\sum Q_{obs} - \bar{Q}_{obs})^2}\right)$$

R^2 is indicates how the simulated data correlates to the observed values of data. The range of R^2 is extends from 0 (Unacceptable) to 1(best)

3. Nash-Sutcliffe efficiencies (NSE) (Nash & Sutcliffe, 1970)[23].

$$E = 1 - \frac{\sum_{i=1}^{n}(Oi - Pi)^2}{\sum_{i=1}^{n}(Oi - \overline{O})^2} \times 100$$

Nash-Sutcliffe efficiencies can range from -∞ to 1.

Where; O_i= observed discharge, P_i= simulated discharge, $\bar{O}$ = mean of observed discharge, $\bar{P_i}$ = mean of simulated discharge. The general performance ratings of interpretated results as shown in **Table 1** were used as a guide (Santhi et al., 2001; Moriasi et al., 2007, 2015; Gebre, 2015 and Ouédraogo et al., 2018)

Table 1 Performance indicator for various evaluation criteria

Performance Rating	**PBIAS (%)**	R^2	**NSE**
Very good	PBIAS < ±10	0.75 to 1	0.75 to 1
Good	±10 < PBIAS < ±15	0.65 to 0.75	0.65 to 0.75
Satisfactory	±15 < PBIAS < ±25	0.50 to 0.65	0.50 to 0.65
Unsatisfactory	PBIAS > ±25	<0.50	<0.50

Results and Discussion

Calibration and Validation of the HEC-HMS Model

“The model is calibrated in order to determine the best fit between the model and observation. HEC-HMS has a trail optimization function that can be used to match the simulated flow with observed flow”. [31] The HEC-HMS model is calibrated and validated using two different rainfall events of 2006 (August) and 2007 (August) in the Hathmati river watershed using SCS unit hydrograph and Clark unit hydrograph method respectively, as shown in **Figure 5.** From the results of the calibration run using event dated 16th August 2006 using the SCS unit hydrograph method the computed peak discharge was found to be 410.0 m^3/s higher than the observed peak discharge of 357.7 m^3/s, with acceptable values of the Percent Bias (PBIAS) 11.65%. In terms of model efficiency, the NSE was 0.869, which means there was an acceptable agreement produced by the rainfall-runoff model. Whereas, by using Clark unit hydrograph method the computed peak discharge was found to be 321.5 m^3/s lower than the observed peak discharge of 357.7 m^3/s. whereas, the computed peak discharge during the validation period for the event 2007 using both the method were found to be 31.8 m^3/s and 45.7 m^3/s respectively, with an acceptable value of the NSE and R^2 was found to be 0.69 and 0.7461 and 0.9794 respectively, during calibration period the optimized parameter such as curve number, lag time(min), initial abstraction (I_a) are found to be 89.92, 230 and 5.09 mm respectively. It is observed that the curve number value is found to be very high compare to the initial value, which indicate high runoff potential generated in the watershed it is due to the change in land use land cover and the most dominated land use type in the study area is found to be scrub/waste land and soil type is clay. It can be observed that the model is able to simulate the peak value satisfactorily, Since the parameters utilised here are those were optimised for event 1, it can be seen that the majority of the values are not very accurately simulated. It could be made clear that the first event was observed in the year 2006, whereas the second event was noticed in the year 2007 and the optimised parameters were used. It is possible that some of the geographical parameters are altered, making the larger discrepancy in the simulation of event

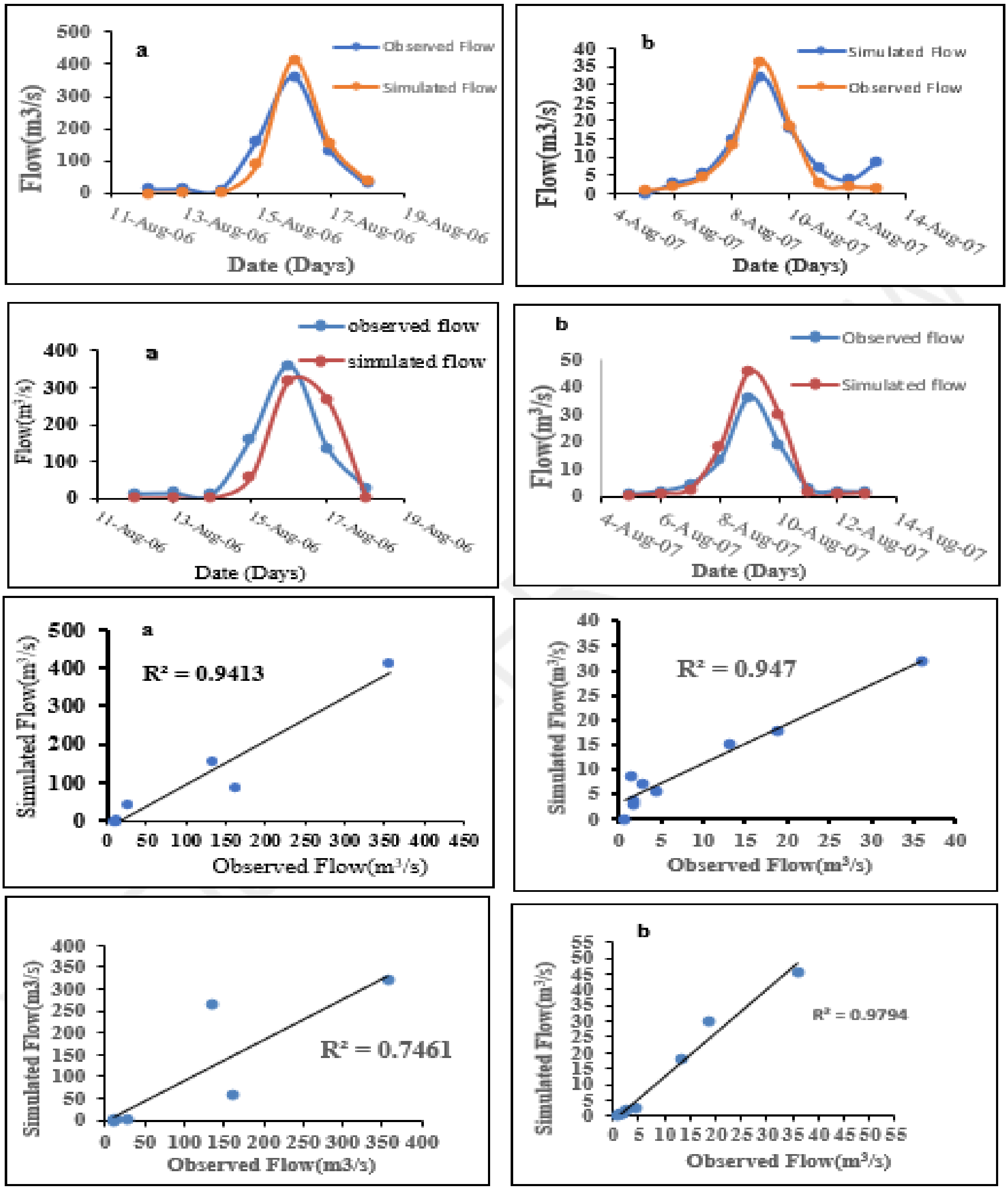

Figure 5 (a)&(b) shows the hydrograph and Scatter plots of observed discharge versus simulated discharge for the calibration and validation period. Using SCS unit hydrograph and Clark unit hydrograph method**.**

The Percent Bias (PBIAS), the coefficient of determination (R^2), and the Nash-Sutcliffe efficiency (NSE) for calibration events. It indicates a close relationship between the observed and simulated flow and the model performance is very good. Once the calibration was completed, then the calibrated final parameters were taken as input in the selected other events of August 2007 for the model validation. The validated results of 2007 events are as shown in **Figure 5.** The coefficient of determination (R^2), the Percent Bias (PBIAS) and Nash Sutcliffe efficiency (NSE) values are obtained as 14.8%, 0.947 and 0.914 respectively for 2007 event. This is resulted closely and good correlation between the observed and simulated flow. The Model performance statistics during calibration and validation period as shown **Table 2.** And Initial and optimized Parameters using HEC-HMS Model for Events 1 for SCS CN and Clark unit hydrograph transform method during Model calibration as shown in **Table3.** The calibrated and validated results of 2006 and 2007 events using Clark unit hydrograph method presented in **Figure 5.** The coefficient of determination (R^2) was found to be 0.7461 and 0.9794. from the statistical performance analysis of the model, it is observed that there is closely and good correlation the between observed and simulated flow.

Table 2. Model performance statistics during calibration and validation period

Period	**Objective function**		
	PBIAS (%)	**NSE**	**R^2**
Calibration	9.76	0.869	0.901
Validation	14.8	0.914	0.947

Table 3. Initial and optimized Parameters for Events 1 for SCS loss and transform method and Deficit and constant loss and Clark unit hydrograph transform method

Method	**Parametrs**	**Initial Parameter**	**Optimized Parameter**
Loss method	Initial abstraction (Ia), mm	10	5.09
	Curve number (CN)	62	89.92
Transform	Lag time(min), min	226.09	230

Method	**parameters**	**Initial parameter value**	**Optimized parameter value**
Deficit and constant loss method	**Loss Parameter**		
	Initial Deficit (MM)	5	2.8425
	Constant (MM/HR)	0.01	0.29059
	Impervious (%)	10	--
Clark unit hydrograph Transform	**Transform Parameter**		
	Time of Concentration (Tc)	3.76	--

method	Storage Coefficient (Sc	7.11	7.1046

CONCLUSIONS

In the present study, hydrological modelling of sub watershed Hathmati river is carried out using HEC-HMS. The loss method is represented by the SCS-CN, and the transform method is the Soil Conservation Service Unit Hydrograph method. The Nash-Sutcliffe efficiency, coefficient of determination, and Percent Bias are used to evaluate the model. Daily timescale calibration and validation results over the study area shown good performance with NSE, R^2 and Percent Bias PBIAS (%) 0.881, 0.913 and 9.76% respectively for calibration and 0.914, 0.947 and 14.8% respectively for validation. Whereas, The Nash-Sutcliffe efficiency, coefficient of determination, and statistical performance indicators for the Clark unit hydrograph transform method were found to be 0.69, 0.77, 0.7461, and 0.9794, respectively. the model's results indicate a strong correlation between simulated and observed peak flows, suggesting that the water resource practices in the study area or similar basins are effective. statistical indicators such as Nash and Sutcliffe efficiency (NSE), Coefficient of determination (R^2), the Percent Bias (PBIAS), demonstrate that the HEC-HMS model accurately reproduces daily stream flow, making it reliable for estimating desired peak values. Therefore, The simulation results can be utilized for various hydrological and environmental studies, flow forecasting, urbanization impact assessment, flood damage reduction, reservoir design, and overall system operation. The developed hydrologic model is well-suited for the Hathmati watershed and the calibrated model is very much useful for improved planning and management.

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