Plant Archives Vol. 26, No. 2, 2026 pp. 2203-2212 e-ISSN:2581-6063 (online), ISSN:0972-5210

Plant Archives

Journal homepage: http://www.plantarchives.org

DOI Url : https://doi.org/10.51470/PLANTARCHIVES.2026.v26.no.2.302

HYDROLOGICAL MODELLING AND RUNOFF ESTIMATION USING HEC-HMS IN THE RAPTI RIVER BASIN IN BALRAMPUR DISTRICT, UTTAR PRADESH INDIA

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(Date of Receiving-06-08-2026; Date of Revision-27-09-2026; Date of Acceptance-07-10-2026)

ABSTRACT

This study estimates runoff from the Rapti River Basin in Balrampur District, Uttar Pradesh, India, using the Hydrologic Engineering Centre–Hydrologic Modeling System (HEC-HMS), which is a model designed to simulate the rainfall–runoff process based on basin characteristics, meteorological inputs, and hydrological parameters of the study area. The model was developed using historical rainfall and observed streamflow data; the simulation period was divided into a calibration period (1990–2009) and a validation period (2010–2019). Suitable loss, transform, baseflow, and routing methods were applied to represent the hydrological behaviour of the basin. Performance was evaluated using the coefficient of determination (R^2), Nash–Sutcliffe efficiency (NSE), root mean square error (RMSE), percent bias (PBIAS), and Kling–Gupta efficiency (KGE). The model produced R^2 = 0.6500, NSE = 0.6376, RMSE = 165.88 m^3/s, PBIAS = -1.04%, and KGE = 0.7892 during calibration, and R^2 = 0.7500, NSE = 0.7321, RMSE = 137.88 m^3/s, PBIAS = 0.00%, and KGE = 0.8660. The results of the validation demonstrated that the predicted streamflow was satisfactory to good, and there was a high link between the two. The HEC-HMS model that had been calibrated proved that it was able to mimic the rainfall–runoff response of the Rapti River Basin. Additionally, the model exhibited an adequate agreement between the simulated runoff and the observed. The validation results also confirmed the reliability and applicability of the model for independent streamflow simulation. The results suggest that HEC-HMS can be successfully used for runoff estimation and hydrological assessment of the Rapti River Basin, and the developed model can assist in flood forecasting, watershed management, irrigation planning, water-resource development, and sustainable surface-water resource management in Balrampur District and nearby areas.

***Key words*:** HEC-HMS, Rapti River Basin, Rainfall–Runoff, Hydrological Modelling, Balrampur, Uttar Pradesh, Watershed Management.

Introduction

On Earth, precipitation is the primary source of water that supports humanity. Understanding rainfall variability is essential for managing and budgeting available water resources. Because rainfall varies in time and space, severe scarcity or excess can have dire implications (Swain *et al*., 2021b). Current climatic trends contribute significantly to the unpredictability of rainfall. Number one culprit: human-caused climate change. As per Chang *et al*., (2019), global climate change impacts the distribution, intensity, and volatility of the rainfall. Accurate estimation of water balance components such as runoff, evapotranspiration, infiltration, and groundwater flow is the basis of water resource management and operational

hydrology. Hydrologic models are used for water resources planning, flood forecasting, water quality monitoring, management of aquifer recharge, and hydrology with land use and climate changes (Flores *et al*., 2021). This system's regulation of water flow and rational use of natural resources, particularly water bodies, distinguish it. This system is characterized by the regulation of water flow and the rational use of natural resources, especially water bodies. According to Tariq *et al*., (2023), Bryndal (2023), and Bouramtane *et al*., (2020), the main factors controlling the water drainage routes are climate, topography, and geological and morphological structure. According to Venkatesh and Anshumali (2019) and Ghosh and Gope (2021), morphometric analysis can be used in a more effective way by the planners to enhance the efficiency of industrial, agricultural, and urbanization operations in a watershed. Studies based on the geoprocessing capabilities of ArcGIS have reported that the viability and sustainability of alternative drainage networks are controlled by the geometry of the basin, drainage texture, and morphometric features (Bharath *et al*.,; Bahiru *et al*., 2021). DEMs and LULC data are also an important part of remote sensing that is heavily depended upon for watershed characterization and hydrological modeling (Al-Taei *et al*., 2023; Ahmad *et al*., 2023; Ghaffari *et al*., 2023). The hydraulic and hydrological modeling frameworks can be applied to geographic information systems and remote sensing-generated data sets to study drainage systems, surface conditions, and watershed topography (Bilasco *et al*., 2021). Furthermore, GIS is a base for the simulation of hydrological models (Gambolati *et al*., 2002; Kn.) Rainfall-runoff modeling is an important topic of study in hydrology. It describes how precipitation creates runoff in a river basin. Watershed features, as well as the temporal and spatial variability of precipitation and other factors, affect the relationship between rainfall and runoff. Precipitation and watershed attributes change with space and time. These factors influence the relationship between rainfall and runoff. Runoff estimation is crucial for the planning of water resources, flood management, reservoir operation, and other hydrological applications (Nayak *et al*., 2007). The Rapti River Basin in eastern Uttar Pradesh is a significant river system with strong seasonality and extreme variability in rainfall. Frequent floods are happening in the basin. So it is important to know the hydrological response and rainfall pattern of the basin (Malani & Yadav, 2024). The river system of Rapti occupies a large region of Balrampur District. The district is generally flat and gently sloping and therefore prone to flooding and prolonged waterlogging during the monsoon (National Green Tribunal, 2026). Basin floods are mainly caused by heavy rainfall in the Terai region of Uttar Pradesh and the Rapti catchment (Uttar Pradesh State Disaster Management Authority, 2024). According to modern official statistics (Ministry of Jal Shakti, 2025), Rapti River floods in Balrampur also had major social and agricultural impacts. An accurate rainfall-runoff model of the basin is necessary to understand the basin's hydrological response and to promote optimal water resources and flood management. Hydrological data is limited, and hydrological systems are complex; hence, hydrological studies are difficult to carry out (Guduru J.U. *et al*., 2023). This is a problem since the water accessible for agriculture has declined due to rapid urbanization, industrial expansion, deforestation, and climate change, which are significant in agricultural production (Shi D., Wang W., Jiang G., Peng X., Yu Y., Li Y., Ding W. 2016). Therefore, careful use and management of water resources are needed to alleviate water scarcity (Xiubin H., Zhanbin L., Mingde H., Keli T., Fengli 2003). Inadequate land use planning and management have contributed to reduced surface runoff and agricultural output. Soil and water infrastructure design is dependent upon accurate measurement and quantification of river or channel flow (David WP1998). However, the Hydrologic Modeling System (HEC-HMS) from the Hydrologic Engineering Centre is easy to use and applicable for a wide range of applications. Conversely, the Hydrologic Engineering Center's Hydrologic Modeling System (HEC-HMS) has been found to be user-friendly and acceptable for application in data-scarce regions (Halwatura D., 2013; Chu X., Steinman A., 2009). The HEC-HMS method is useful for hydrological modeling in several study domains (Knebl M.R. *et al*., 2005; Natarajan S., 2019). The Rapti River is the main river system of Balrampur District and is an important feature of the drainage and agricultural landscape of the district. Where a big percentage of the geographical region is under agriculture (National Green Tribunal, 2026). However, the hydrometeorological observations in the basin are sparse in space and the rainfall has substantial geographical and temporal variability in the Rapti Basin (Central Water Commission, 2025; Malani & Yadav, 2024). Such features hinder the assessment of the hydrological response of the basin and emphasize the need of accurate hydrological modeling and regionally spread data. However, the discharge is very much reliant on seasonal variations due of unpredictable monsoon rainfall and hence, long-term prediction of runoff is a matter of worry (Shekar and Vinay, 2021). The Hydrologic Engineering Center-Hydrologic Modeling System, an

established open-source model, is utilized in this study (Hamdan *et al*., Pulipati *et al*., 2021, 2023). to model the conversion of basin rainfall to runoff. This will study the excess precipitation loss and flow routing in an effort to improve the accuracy of flood forecasts using the geographic data with the observed hydrometeorological factors. Spatial information of land use/land cover and soil parameters can be used as major inputs for rainfall–runoff simulation in hydrological modeling systems (Cacal *et al*., 2023; Mehta *et al*., 2023) for analyzing watershed responses to extreme hydro-meteorological events. Rather than relying on the time-consuming and error-prone manual calculation method, the discharge hydrographs were generated using the powerful and feature-rich HEC-HMS model (Goodarzi *et al*.,; Kencanawati *et al*., 2024). (2023). The platform offers the mathematical basis for describing hydrological processes at the basin scale and has received international recognition for its successes in both event-based and continuous simulations (Bhusal *et al*., 2022; Pramada and Reddy, 2022). The present work is an attempt to analyse the geographical and temporal variability of rainfall over Rapti River Basin using gridded precipitation data at daily, monthly and annual time scale (Malani and Yadav, 2024). The semi-distributed physical-based approach has been shown to be able to capture the dynamics of the medium flow and basin-specific responses, especially in complex watershed configurations, and allows the characterization of basin-wide hydrological responses even in data-scarce environments where traditional empirical approaches may fail (Chathuranika *et al*., 2022; Masood, *et al*., 2023).

Materials and Methods

Study area

The Rapti River is a major tributary of the Ghaghara River, rising in the Siwalik Hills of the sub-Himalaya in Rukum Kot, Nepal and debouching on the left side of the river in Deoria district of Uttar Pradesh, India.

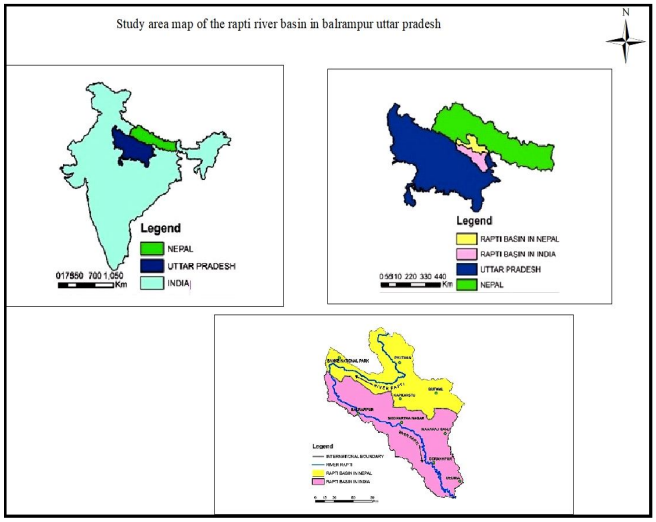


Fig. 1: The location of study area map of the Rapti river basin Balrampur Uttar Pradesh India.

The whole basin is bounded by longitudes 81°03’00"E and 83°28’45"E and latitudes 26°18’00"N and 05°00’N. The upper Rapti basin is dominated by the mountain ranges of Himalayas. The northern half consists of the Lesser Himalaya (Mahabharat Range), sub-Himalaya (Siwalik Range) to the north and south and the center Dun Valley. On the other hand, the Tarai and Indo-Gangetic plains are located in the lower basin. The Rapti basin has a total area of 26499 km^2, of which 43 % (11,352 km^2) are in Nepal Uttar Pradesh accounts for 57% of the total area, which is 15,147 km^2. 8219 km^2 of this 15,147 km^2 make up the Balaram district, which is where I will be studying.

Terrain Data

A digital elevation model (DEM) is a digital depiction of a topography surface. Earth Explorer U.S. Geological Survey (https://earthexplorer.usgs.gov/) provides the Srtm DEM (Shuttle Radar Topography Mission) of the research region at a resolution of 30 meters.

Rainfall

The India Meteorological Department (IMD) website (http://imdpune . gov . in/) supplied daily rainfall data for the research region using ArcGIS 10.2 at a spatial level of 0.250 × 0.250. 2 programs and the Thiessen polygon method-prepared weighted rainfall from 1990 to 2019. The humid subtropical climate of Uttar Pradesh’s Balrampur district results in an average rainfall of roughly (Balrampur Braucher CGWB). The majority of the yearly rainfall occurs in July and August, when the region experiences intense monsoon showers after dry, hot springs (Balrampur Braucher CGWB). The annual average rainfall is between 902.3 and 1000 mm.

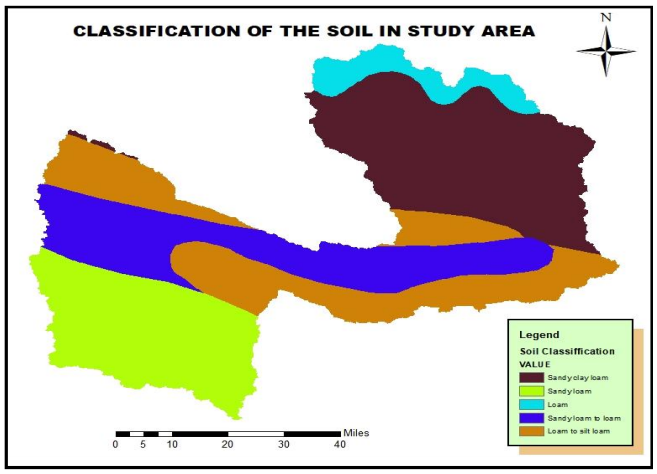


Fig. 2: Classification of the soil of the study area Balrampur district Uttar Pradesh.

Table 1: Performance Rating for Different Evaluation Criteria.

Performance Rating	PBIAS (%)	R^2	NSE
Very Good	PBIAS < ±10	0.75 to 1.00	0.75 to 1.00
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

Type of soil

Fertile alluvial soils created by river deposition predominate in the Balrampur district, which is situated in the eastern Indo-Gangetic plain and Rapti River basin. Himalayan sediments carried by the Rapti and its tributaries are the primary source of the soils.

General Features of Soil The texture of the soil is mostly sandy loam to silty clay loam. The pH of the soil is typically neutral to slightly alkaline (6.8–8.0). Low to medium levels of organic carbon. Upland locations have high drainage, while low-lying floodplain areas have poor drainage. Due to yearly sediment deposition, soil fertility is moderate to high.

Soil Distribution Pattern: The Rapti River's recent alluvium deposits dominate the northern and floodplain areas. High moisture content and vulnerability to flooding.

Temperature

The Rapti River in Balrampur, Uttar Pradesh, experiences a humid subtropical climate with significant seasonal temperature Summer (March to June) During the intense summer months, when ambient air temperatures often exceed to the river water temperature typically ranges from to Monsoon (July to September) The water temperature generally moderates, settling between and Winter (October to February). Balrampur experiences a humid subtropical climate characterized by hot summers, a humid monsoon season, and cool winters. During 1990–2019, the district showed strong seasonal temperature variation typical of the eastern Indo-Gangetic Plain.

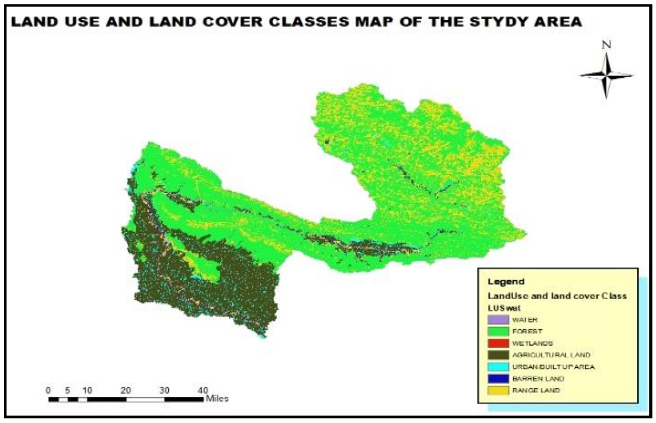


Fig. 3: Classification of the land use and land cover map of the study area Balrampur district Uttar Pradesh.

Topographic data

SRTM DEM (Shuttle Radar Topographic Mission Digital Elevation Model) with resolution 90 m were used. The DEM was georeferenced, but was re-projected to UTM co-ordinate system to enable their input into the model. All input data should be in the same projection system to enable their overlay and analysis.

Land Use and Land Cover (LULC): The LULC map of the study area illustrates the spatial distribution of major land-use categories, including water bodies, forest, wetlands, agricultural land, urban/built-up areas, barren land, and range land. The LULC pattern is important in regulating rainfall partitioning, infiltration, evapotranspiration, surface runoff, and soil erosion; agricultural and less-vegetated areas may produce relatively higher runoff and sediment under intense rainfall, whereas forested and well-vegetated areas typically enhance infiltration and reduce runoff and erosion. In contrast, urban, barren, wetland, and water-body classes are distributed in comparatively smaller and spatially dispersed patches.

Discharge data

The discharge data for the Upper Ganga Basin are mainly collected by the Central Water Commission through the Upper Ganga Basin Organisation.)

Topographic data

SRTM DEM (Shuttle Radar Topographic Mission Digital Elevation Model) with resolution 90 m were used. The DEM was georeferenced, but was re-projected to UTM co-ordinate system to enable their input into the model. All input data should be in the same projection

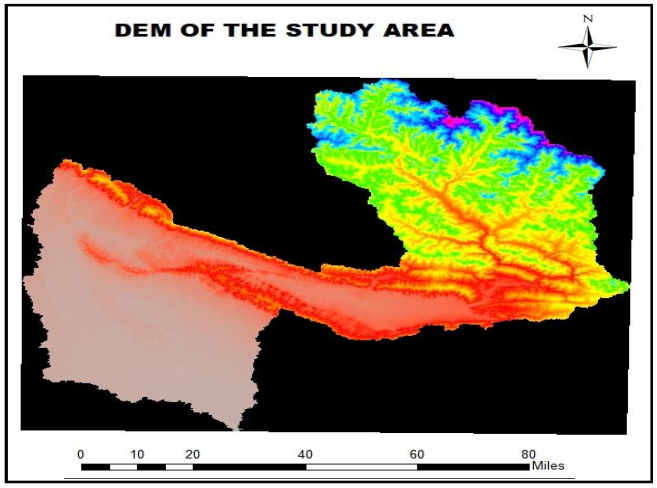


Fig. 4: Digital elevation model map of the study area Balrampur district Uttar Pradesh.

system to enable their overlay and analysis.

Spatial data

Spatial dataset which used for the prediction of stream flow and sediment yield using SWAT model were DEM, land use and cover and soil map.

Digital Elevation Model (DEM): Topography is defined by a Digital Elevation Model (DEM), which describes the elevation of any point in a given area at a specific spatial resolution as a digital file (Chekol., 2006). Digital elevation model is one of the essential inputs required for HEC HMS to delineate the watershed.

Methodology

Below is an outline of the operational workflow and structural framework used for the current hydrological evaluation. Digital Elevation Models (DEM), Soil Texture Maps, and Land Use/Land Cover (LULC) layers were among the spatiotemporal datasets that were linked into a Geographic Information System (GIS) environment to assess runoff volume and peak discharge. The four key components of the HEC-HMS model are input data, control simulations, basin models, and meteorological models. The meteorological model includes data on precipitation, evapotranspiration, and melting, while the basin model retains the physical datasets defining the characteristics of the catchment. Control requirements that include the start and finish times of a simulation.

Loss Method:

SCS Curve Number (CN) Method:

It is a simple, predictable and stable method to estimate the excess precipitations as a function of the cumulative precipitation, soil cover, land use and the antecedent moisture. The equation is:

$$\mathbf{P_e = \frac{(P - Ia)^2}{(P - Ia) + S}}$$

Where,

P_e = Accumulated precipitation excess at time t;

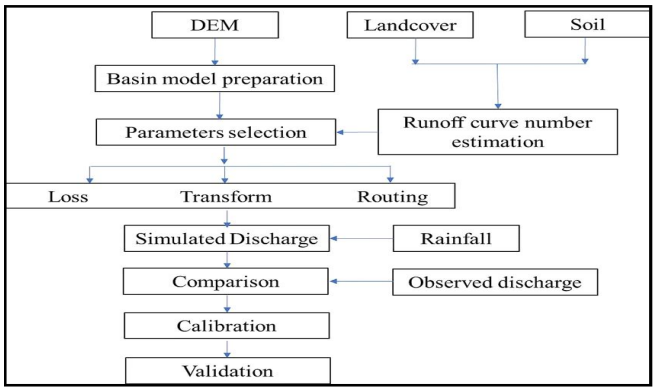


Fig. 5: Flow chart of the HEC HMS simulation of the runoff.

P = Accumulated rainfall depth at time t;

I_a = The initial abstraction (initial loss through interception, evaporation, detention, infiltration before runoff starts) and

S = Potential maximum retention (ability of a watershed to abstract and retain storm precipitation).

Using the results from many small experimental watersheds, the SCS developed an empirical relationship of Ia and S as:

$Ia = 0.2S$

$$\boldsymbol{P_e = \frac{(P-Ia)^2}{(P-Ia)+S}}$$ (Subject to $P \geq 0.2S$, otherwise $P_e = 0$)

Incremental excess for a time period is defined as the difference of accumulated excess at the start and end of the time period. Curve number (CN) is an intermediary parameter that correlates watershed characteristics with the maximum potential retention (S). It is an index which is a combination of hydrological soil group, land treatment classes and antecedent moisture conditions and expressed as:

$$S = \frac{25400}{CN} - 254$$

Value of CN is ranges from a minimum of zero to a maximum of hundred.

However, it can be zero for permeable impervious surface.

This is used in the Soil Conservation Service-curve number (SCS-CN) method to determine the potential maximum retention of water in the watershed once runoff begins.

In this study, the CN values are between 70 and 85 for various land uses, land treatments and hydrologic conditions. This range indicates moderate to relatively high runoff potential of the study area. The adopted values of Curve Number for different land-use, treatment and hydrologic conditions in the study area were ranging from

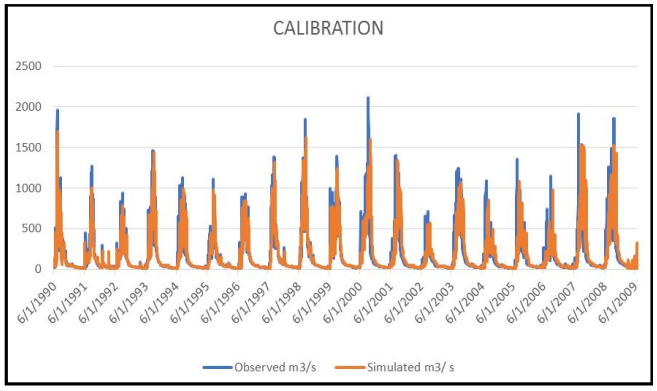


Fig. 6: Calibration of the model during 1990-2009 Rapti river basin Balrampur district Uttar Pradesh.

70 to 85. This range suggests moderate to relatively high potential for runoff in the watershed. Lower CN values around 70 correspond to sites of relatively improved infiltration capacity, sufficient vegetation cover or good conservation practices while higher CN values close to 85 refer to sites of relatively poor infiltration conditions, less vegetation, intensive cultivation, soil compaction or other conditions that favor surface runoff. The differences in the CN value represent the spatial heterogeneity of land use, soil properties, hydrological condition and management practices in the study area. The potential maximum retention is inversely proportional to CN. An increase of CN from 70 to 85 decreases from 108.86 mm to 44.24 mm, thereby increasing the potential for direct runoff generation.

Statistical assessment of model performance:

The statistical assessment of the HEC-HMS model using PBIAS, R^2, and NSE demonstrated satisfactory agreement between observed and simulated discharge. The relatively high coefficient of determination confirmed a strong relationship between the observed and simulated flows, while the satisfactory NSE indicated good predictive efficiency of the model. Furthermore, the relatively low magnitude of PBIAS suggested limited systematic bias in the simulated runoff. Therefore, the calibrated HEC-HMS model was considered suitable for rainfall–runoff simulation and hydrological assessment of the Rapti River Basin, Balrampur, Uttar Pradesh.

$$\mathbf{PB\ IAS} = \left[1 - \frac{\sum_{i=1}^{n}(O_i - P_i)}{\sum_{i=1}^{n} O_i}\right] \times 100$$

Oi = Observed runoff/discharge at time i

Pi = Predicted or simulated runoff/discharge at time i

n = Number of observations

$$R^2 = \frac{\left[\sum_{i=1}^{n}(Q_{obs} - \overline{Q_{obs}})(Q_{sim,i} - \overline{Q_{sim}})\right]^2}{\sum_{i=1}^{n}(Q_{obs,i} - \overline{Q_{obs}})^2 \ \sum_{n=1}^{n}(Q_{sim,i} - \overline{Q_{sim}})^2}$$

Qobs = Observed discharge/runoff

Qsim = Simulated discharge/runoff

Q obs = Mean observed discharge

Q sim = Mean simulated discharge

n = Number of observations

$$NSE = \left[1 - \frac{\sum_{i=1}^{n}(Q_{obs,i} - Q_{sim,i})^2}{\sum_{i=1}^{n}(Q_{obs,i} - \overline{Q_{obs}})^2}\right] \times 100$$

The **Nash–Sutcliffe Efficiency (NSE)** equation

$$E = 1 - \frac{\sum_{i=1}^{n}(Q_{obs,i} - Q_{sim,i})^2}{\sum_{i=1}^{n}(Q_{obs,i} - \overline{Q_{obs}})^2}$$

A model was considered to have very good performance when the simulated values closely matched the observed values, resulting in a PBIAS within ±10% and R^2 and NSE values between 0.75 and 1.00. Good performance was assigned when PBIAS ranged between ±10% and ±15%, with R^2 and NSE values of 0.65–0.75. A satisfactory performance indicated a moderate agreement between observed and simulated values, with PBIAS between ±15% and ±25% and R^2 and NSE values ranging from 0.50 to 0.65. When PBIAS exceeded ±25% or the R^2 and NSE values were below 0.50, the model performance was considered unsatisfactory.

Results and Discussion

The observed and simulated daily discharge data for the years 1990–2009 were used to calibrate the HEC-HMS model. In order for the simulated runoff hydrograph to accurately replicate the observed streamflow characteristics of the Rapti River Basin, the key model parameters had to be adjusted. Further changes were implemented to the model parameters controlling precipitation losses, the baseflow contribution, channel routing, and the conversion of excess rainfall into direct runoff during calibration. Statistical performance indicators were used to assess the agreement between the simulated and observed discharges in order to determine the calibrated parameters.

Calibration of HEC-HMS Model (2010–2019)

The calibrated data collection for this study, which is contained in the provided HEC-HMS results workbook, comprises 6,970 daily observations from June 1, 1990, to June 30, 2009. Although the precise data period should be recorded as June 1990–June 2009, this period may be referred to in the thesis as the 1990–2009 calibration period.

The measured and simulated discharge have a rather strong relationship, as indicated by the R^2 value of 0.65.

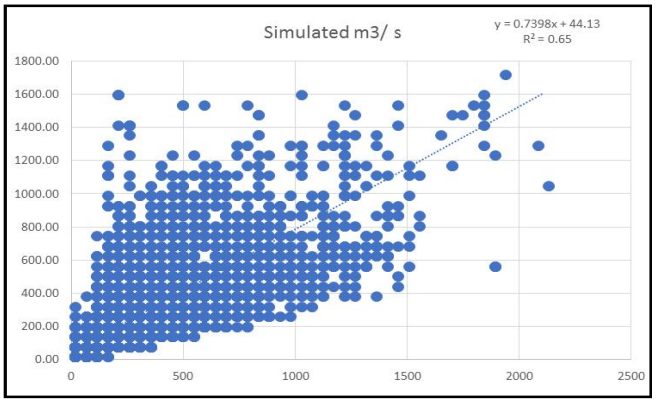


Fig. 7: Scatter graph showing the relationship between observed and simulated of HEC HMS model calibration (1990-2009).

The linear relationship between the simulated discharge and the observed discharge explains about 65% of the variation. This shows that the main temporal fluctuations in streamflow were replicated by the calibrated HEC-HMS model. The calibration of the simulation accurately represented the overall runoff response of the basin, as indicated by the NSE value of 0.6376, which shows satisfactory model efficiency. The positive NSE value confirms that the HEC-HMS model gave an improved representation of the observed flow than using the mean observed runoff as the prediction. A small amount of systematic bias is shown by the PBIAS result of +1.04%. The total observed and simulated runoff volumes differed only slightly because the value is near zero. The model has a modest tendency to underestimate the observed discharge, as indicated by the positive value, although this bias is negligible. More confirmation for the model's adequate calibration comes from the KGE value of 0.7892. This comparatively high value suggests that there is good correlation, variability, and bias between the simulated and measured discharge. The MAE of 75.16 m^3/s and the RMSE of 165.87 m^3/s show how much the simulated and measured discharge differed. The greater RMSE in comparison to MAE indicates that several comparatively big mistakes happened during specific flow occurrences, especially during times of high flow.

Validation of HEC-HMS Model (2010–2019)

After performing a successful calibration, the HEC-HMS model was independently validated using simulation and observed daily flow data for the years 2010–2019. The validation's goal was to determine whether the calibrated model parameters could replicate streamflow characteristics during an independent period without requiring additional model parameter adjustments.

Coefficient of Determination (R^2)

A high correlation between the simulated and observed discharge was demonstrated by the validation period's R2 value of 0.75. An R2 of 0.75 means that the linear relationship between observed and simulated discharge accounts for around 75% of the variation in observed discharge, according to the specified performance standards. This indicates that the temporal variability of streamflow during the independent validation period was effectively replicated by the calibrated HEC-HMS model.

The improvement in R^2 from 0.65 during calibration to 0.75 during validation indicates that the model performed well when applied to data that were not used for parameter optimization. This provides evidence of the model's ability to generalize beyond the calibration dataset.

Nash–Sutcliffe Efficiency (NSE)

When the HEC-HMS model was validated, its NSE was 0.73. This value is classified as good performance based on the evaluation standards that have been set. The simulated discharge far better replicated the real streamflow than a model based only on the mean observed discharge, as indicated by the positive and reasonably high NSE value. The calibrated model maintained strong predictive efficiency throughout the independent validation phase, according to the NSE result. Notable is also the rise in NSE from 0.63 during calibration to 0.73 during validation. It shows that the model was able to replicate the validation period's runoff dynamics more effectively.

Percent Bias (PBIAS)

The calculated PBIAS was -0.01%, which is extremely close to zero and denotes excellent performance. The negative sign indicates a very slight tendency toward overestimating observed discharge, but the bias is quite negligible. Consequently, there was very little systematic difference between the simulated and actual runoff volumes over the validation period. This practically negligible PBIAS indicates that the calibrated HEC-HMS model maintained a satisfactory water balance when applied to the independent validation period.

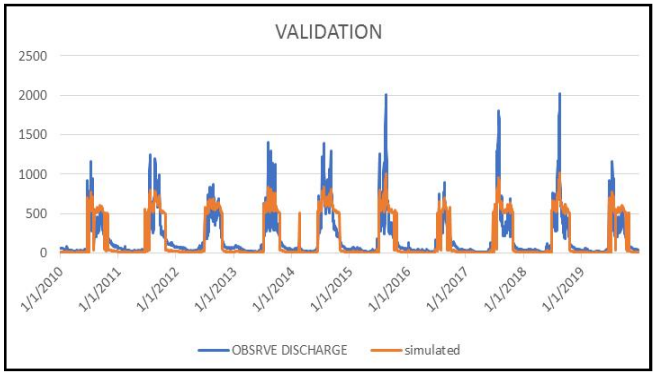


Fig. 8: Validation of the model during 2010-2019 Rapti river basin Balrampur district Uttar Pradesh.

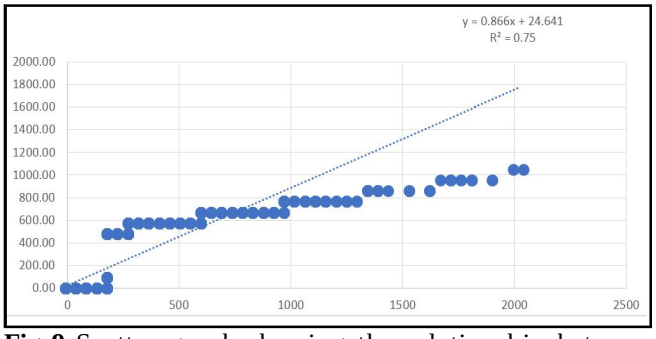


Fig. 9: Scatter graph showing the relationship between observed and simulated of HEC HMS model Validation (2010-2019).

Table 2: Comparative Performance of HEC-HMS Model during Calibration and Validation.

PI	CB	VD	OA
R^2	0.6500	**0.7500**	Improved
NSE	0.6376	**0.7321**	Improved
PBIAS (%)	+1.04	**≈ 0.00**	Improved
RMSE (m^3/s)	165.87	**137.88**	Decreased
MAE (m^3/s)	75.16	**87.88**	Slightly increased
KGE	0.7892	**0.8660**	Improved
Slope	0.7397	**0.8660**	Improved
Intercept	44.12	**24.64**	Reduced

PI: Performance Indicator; CB: Calibration (1990–2009); VD: Validation (2010–2019); OA: Overall Assessment

KGE, RMSE and MAE

Through a validation Kling-Gupta Efficiency (KGE) of 0.86, the observed and simulated discharge showed excellent general agreement. The model did well in terms of correlation, variability, and bias, according to the high KGE value. The average absolute difference between the simulated and actual discharge was 87.89 m^3/s, whereas the RMSE was 137.90 m^3/s, indicating the size of the bigger simulation errors. RMSE dropped from 165.87 to 137.90 m^3/s when compared to calibration, suggesting a decrease in the size of squared simulation errors during validation. Nonetheless, the MAE marginally increased from 75.16 to 87.89 m^3/s, suggesting that there were still moderate variations between the simulated and actual discharge in each individual observation.

Peak-Flow Simulation: The validation dataset shows a maximum observed discharge of approximately 2,022.89 m^3/s, whereas the maximum simulated discharge was approximately 1,013.77 m^3/s. Thus, the model underestimated the magnitude of the maximum observed peak by approximately 49.9%.

Although the model satisfactorily reproduced the general temporal behaviour and runoff volume, it

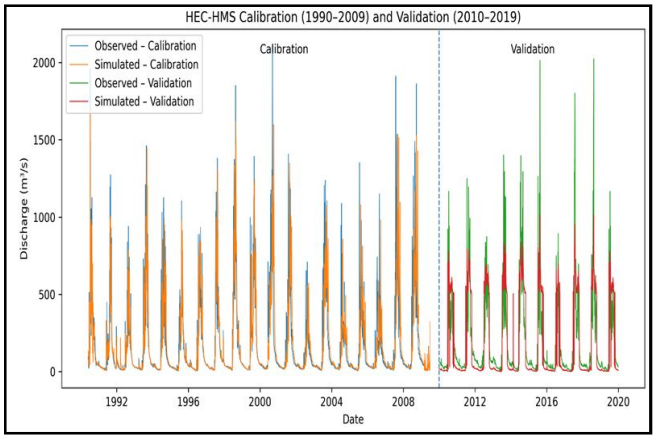


Fig. 10: Calibration and validation both in the same graph of the HEC HMS.

underestimated the magnitude of the maximum observed discharge by approximately 49.9%. This indicates that the model has good capability for general rainfall–runoff simulation, although further refinement may be required for accurate simulation of extreme peak-flow events. Overall, the validation results confirm the applicability and robustness of the HEC-HMS model for hydrological assessment of the Rapti River Basin.

The comparative assessment of the HEC-HMS

The HEC-HMS model performed well during validation and satisfactorily during calibration, according to the comparative evaluation. During validation, the model's R2 and NSE improved from 0.6500 to 0.7500 and 0.6376 to 0.7321, respectively, while PBIAS became closer to zero. In a similar vein, RMSE dropped from 165.87 to 137.88 m^3/s and KGE increased from 0.7892 to 0.8660. These findings show that when the calibrated model was applied to a different dataset, its predictive power remained strong. The overall statistical performance validates HEC-HMS's applicability and resilience for simulating rainfall and runoff in the Rapti River Basin. However, the observed underestimating of extreme peak flows suggests that flood-peak prediction may require more parameter tuning.

Summary and Conclusion:

- The current study used the Hydrologic Engineering Center–Hydrologic Modeling System (HEC-HMS) to assess the rainfall–runoff response of the Rapti River Basin in Balrampur District, Uttar Pradesh. The model was created utilizing hydrological parameters, basin characteristics, and historical rainfall and streamflow data. A calibration period (1990–2009) and an independent validation phase (2010–2019) comprised the simulation period.
- The coefficient of determination (R^2), Nash–Sutcliffe Efficiency (NSE), root mean square error (RMSE), percent bias (PBIAS), and Kling–Gupta Efficiency (KGE) were used to evaluate the model's performance. The model obtained R2 of 0.6500, NSE of 0.6376, RMSE of 165.88 m^3/s, PBIAS of about ±1.04%, and KGE of 0.7892 during calibration. These findings show that the calibrated model was able to replicate the main rainfall–runoff behavior of the basin and show a satisfactory agreement between the simulated and observed discharge.
- Peak flow analysis, however, showed that the model underestimated the maximum observed discharge. The maximum observed discharge

during validation was roughly 2,022.89 m³/s, while the corresponding maximum simulated discharge was roughly 1,013.77 m³/s, indicating an underestimation of roughly 49.9%. As a result, even though the model accurately replicated the overall temporal pattern and runoff volume, additional improvement might be necessary for accurate simulation of extreme flood peaks.

- The present study successfully developed and evaluated an HEC-HMS rainfall–runoff model for the Rapti River Basin in Balrampur District, Uttar Pradesh. The model incorporated basin characteristics and meteorological inputs to simulate streamflow and was calibrated using data from 1990–2009 and independently validated using data from 2010–2019.
- Thus, it can be said that the proposed HEC-HMS model is appropriate for general hydrological analysis, irrigation planning, runoff calculation, watershed management, and water-resource assessment in the Rapti River Basin. Future research should take into account more calibration of sensitive model parameters, better representation of basin and channel characteristics, and integration of higher-resolution hydro-meteorological data in order to improve flood-peak prediction. In Balrampur District and surrounding areas, the created modeling framework can offer important technical assistance for sustainable water resource management and flood risk reduction.

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