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Assessment of Large River Basin Approaching GIS and Computation of Simulation Techniques Using Latest Software

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ABSTRACT

Advancements in computer techniques with a geographic information system (GIS) interface have greatly contributed to simulating river basins with a reasonable level of accuracy. It becomes possible to analyze and model various aspects of a river basin, such as water flow, land use, and hydrological processes. Water is essential for sustaining life. Previous studies revealed that effective watershed management requires an understanding of the impact of rainfall in the catchment area, but due to poorly gauged river basin, it becomes difficult to predict the hydrological response. In this context, hydrologic engineering centre – hydrologic modeling system (HEC-HMS) model is used to simulate surface runoff in different watersheds. The study simulated the Wainganga river basin, geographically located between longitude 78°0'–80°45' E and latitudes 19°41'–22°50' N. The model utilizes eighteen year data for rainfall extracted from Indian Meteorological Department with 0.25×0.25 grid. Similarly, evapotranspiration and observed discharge were extracted from India water resource information system. Shuttle radar topography mission dataset with digital elevation model of 30×30 m spatial resolution, extracted from United States of Geological Survey was an input to HEC-HMS 4.10. Different approaches with changing parameters were implemented for suitable simulation. SCS curve number method with Muskingum routing was implemented for study. The purpose of study was to compare the calculated and observed discharge as well as test model performance. Nash efficiency coefficients (NSE) were used for testing performance. The results show a satisfactory performance with NSE above 0.7 for basin. The description outlines, model can be used for assessing the behavior of large river basin.

Keywords: Wainganga river basin, HEC-HMS, rainfall, runoff, GIS**.**

INTRODUCTION

Water, while crucial for life, can also pose risks and dangers, particularly during natural calamities like heavy rainfall and floods, which was assessed by Al-Mukhtar et al. (2019). Excessive rainfall leads to flooding, resulting in damage to infrastructure, displacement of communities, and loss of life, as studied by Patil et al. (2022). Chevuturi et al. (2023), and Bhattacharya et al. (2013) put forward that the water scarcity and population growth are major issues that can be addressed by using available water to its optimum. It is time-consuming to address this issue by focusing on hydrological parameters using conventional methods and hence there is the urge of gaining understanding using new model setups. By understanding and addressing the potential dangers associated with water, one can work towards minimizing the impact of natural calamities and ensuring the safety and well-being of communities, as summarized by Alsubeai et al. (2021).

Overall, hydrological modeling plays a crucial role in understanding the hydrologic behavior of watersheds and can help in predicting future conditions, supporting watershed management practices was stated by Karna et al. (2021), Koneti (2018), Wang et al. (2019). Furthermore, Halwatura et al. (2013), Nair et al. (2022) added – by accurately estimating runoff – that watershed managers can make informed decisions and implement appropriate strategies to address various water-related challenges. Hydrological model demands parameters in terms of physical features of basin as well as meteorological data (Shan et al., 2017). The real world phenomenon of rainfall runoff influences watershed parameters. It is a challenge to generalize all basin characteristics, as discussed by Dimri et al. (2022), Masika et al. (2018). Paudel et al. (2019) and Balkrishna et al. (2019) expressed that Geographic Information System (GIS) plays a crucial role in providing spatial information and supporting various aspects of hydrological modeling, analysis, management, and decision-making. Devi et al. (2015) and Sahu et al. (2020) briefly discuss variable infiltration capacity model (VIC), TOPMODEL, HBV, MIKESHE and soil and water assessment tool (SWAT) model, Hydrologic Engineering Centre - Hydrologic Modeling System (HEC-HMS) model. The present study focused on HEC-HMS (USACE, 2006). HEC-HMS offers several features and capabilities that make it a popular choice among hydrologists and water resource professionals. It is featured by various extensions like HEC–GeoHMS. The model was successfully used for the Segamat river for assessment of flood risk. A single stream flow event was simulated on an hourly basis in Wadi Dhuliel revealing that simulated peak discharge was very close to the observed value. In the present study, the HEC-HMS model was used to model the Rainfall-Runoff process in the Wainganga basin.

METHODOLOGY

Study area

Figure 1a highlights the river basin of India. The Wainganga basin (51550.60 km^2) is the subcatchment of the Godavari river basin (312,800 km^2) located in the Deccan plateau, India as shown in Figure 1b. The basin resembles shape of top as shown in Figure 1c, lies between longitude 78°0'–80°45' E and latitudes 19°41'–22°50' N (Kudnar *et al.* 2020). Wainganga originates in Mahadeo hill in Seoni, Madhya Pradesh. The river is a key tributary of the Godavari passing through Madhya Pradesh (23109 km^2) and Maharashtra (27350 km^2).

Data collection

The Wainganga basin is delineated by using the shuttle radar topography mission (SRTM) dataset with digital elevation model (DEM) of 30×30 m spatial resolution from USGS Earth Explorer. EarthExplorer (usgs.gov), as shown in Figure 2.

Curve numbers for basin is extracted from GCN250 for an average condition. Arc GIS 10.8 is used for spatial data creation of basin. The area covered by basin, Sub basin area, stream length and slope was calculated through digitized map. Meteorological input data was obtained from Meteorological Department (IMD) for a resolution of 0.25×0.25° (imd.gov.in). Total 93 stations rainfall data was collected for a period of 2001–2018. Evapotranspiration data was also collected for same year. The observed stream flows at Ashti runoff gauging station were collected from India Water Resources Information System (India-WRIS) for a period of 2001–2018 India-WRIS (indiawris.gov.in). The observed discharge was collected from HDUG Nasik H.D.U.G. (mahahp.gov.in).

Model setup

HMS is designed to simulate the precipitation-runoff processes within dendrite watershed systems and is versatile enough to be applied to various geographic areas and a wide range of hydrological problems .The fourth and last program launch was called Version 4.0 with advanced GIS component]. The HEC-HMS 4.10 model incorporates stimulation based on daily stream flow. HEC-HMS encompass four main components, namely Basin model manager, Terrain data manager, Meteorological model manager, Control specification manager and time-series data manage. Table 1 below refers to the components of HEC-HMS and their application in model building. DEM Tiles downloaded from USGS were merged in Arc GIS. A basin model was created using basin manager The Digital Elevation Model was imported from Arc GIS through terrain data manager. The coordinate system was set for model. The model was preprocessed for sink followed by stream identification. "Sinks" refer to depressions or low points in the terrain, where water can accumulate and potentially disrupt the flow of water within the basin. These are important to address, as they can impact the accuracy of hydrological modeling. Preprocess Sinks stimulate pit removal algorithm on the terrain data and produce a new, hydrological-corrected DEM. The overall goal of this process is to enhance the accuracy of hydrological modeling by eliminating artificial sinks that can lead to incorrect water flow patterns. Preprocessing drainage leads to flow direction and flow accumulation. Stream is

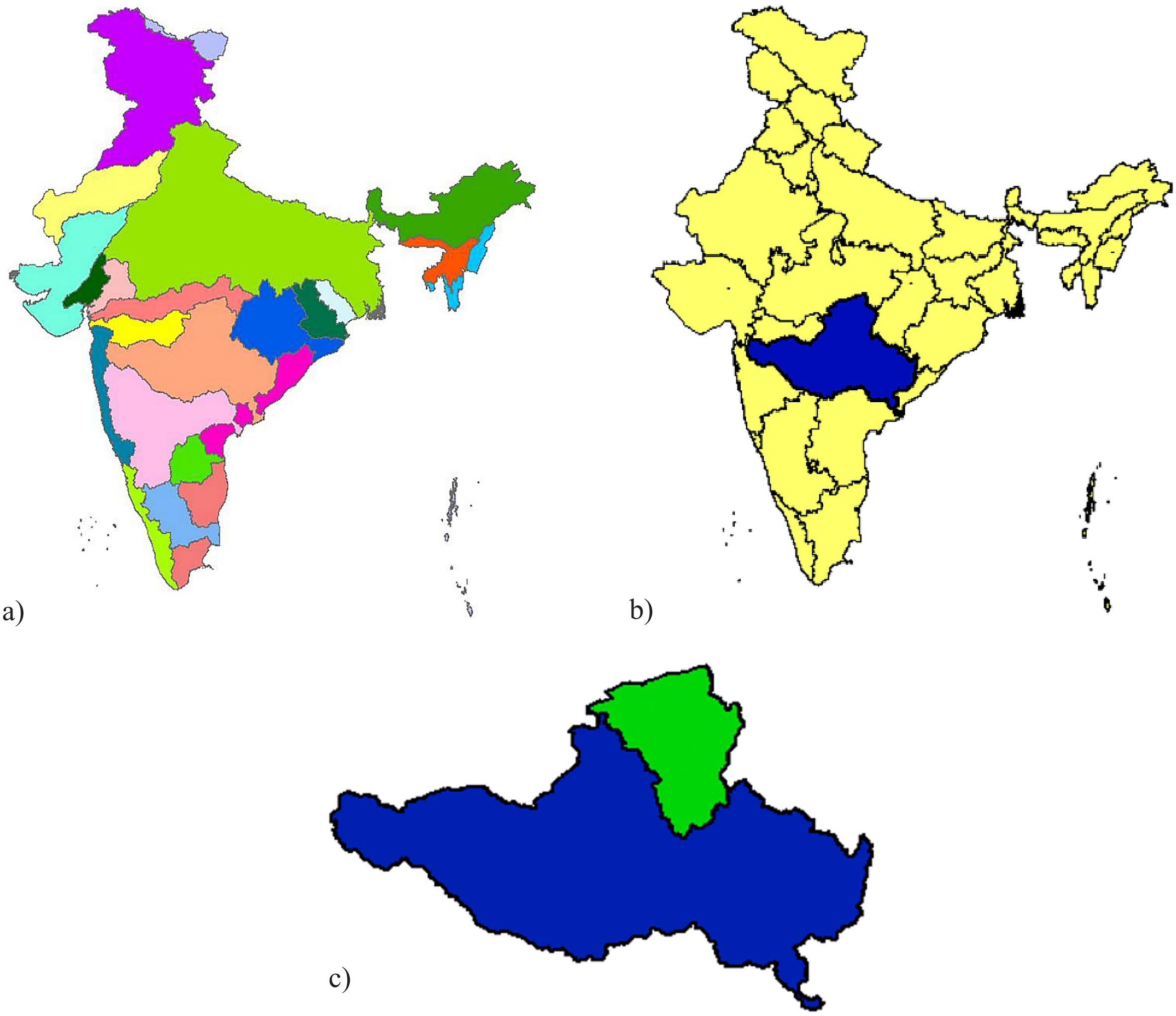

Fig. 1. (a) basin map of India, (b) location map of the Godavari River basin, (c) Wainganga basin

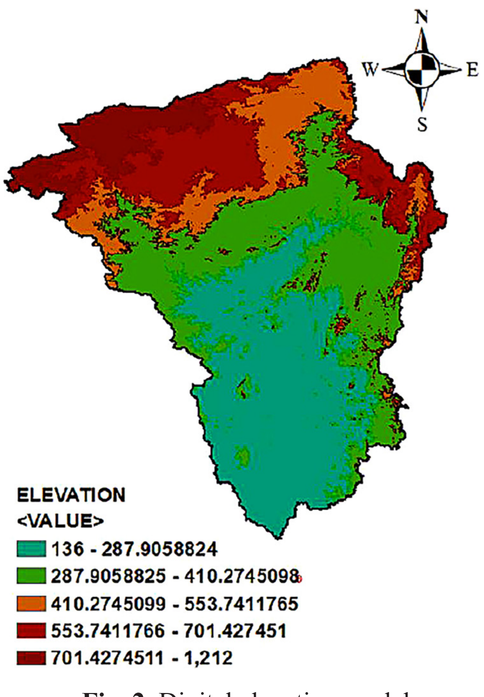

Fig. 2. Digital elevation model

identified by selecting sub-basin areas. Break point manager represents a break point of a basin. In the present study, the Ashti station was taken as a break point and it was considered that whole basin drains towards this point. The model was delineated to obtain a basin model with sub basin and reaches.

Figure 3 indicates catchment of the river Wainganga with 44 sub-basins, indicating the reach and icons of the catchment area. The catchment can be further processed by merging and splitting basin and can also exported to Arc GIS for further calculation of parameters. The data collected from various agencies was analyzed and organized in a suitable manner. A model was set up with different methods and input values. Figure 4 indicates the methodology adopted for hydrological modeling. Objective functions were set and Model was calibrated for a specific time followed by validation if performance criteria were satisfied. In the present study, the soil conservation service (SCS) unit

Table 1. Components of HEC-HMS

Component	Application
1. Basin model manager	Creates basin model
2. Terrain data manager	Delineation process
3. Meteorological model	Preparing boundary conditions
4. Control specification	Control simulation runs
5. Time-series data	Estimate basin-average rainfall

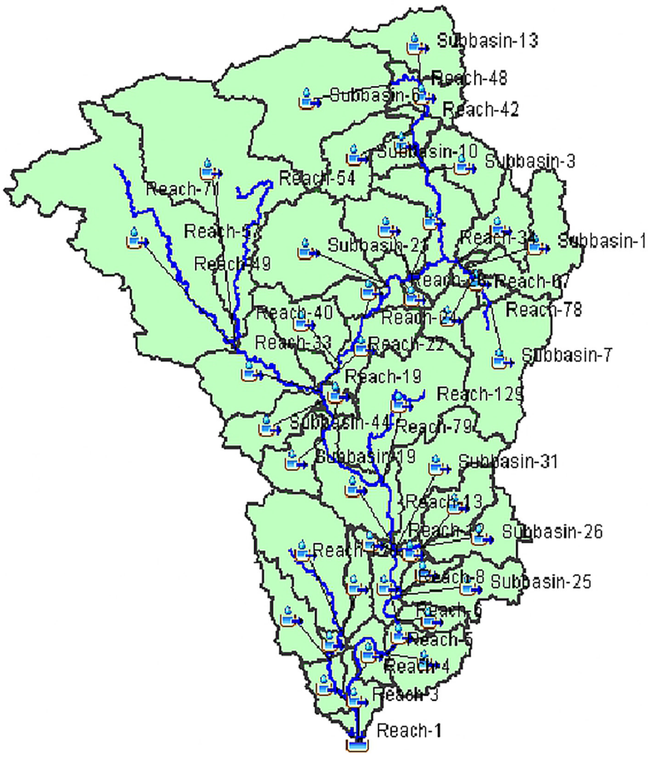

Fig. 3. Delineation of the basin in HEC-HMS

hydrograph model was used to transform excess precipitation into direct runoff hydrograph. Lag time is the time lag between peak rainfall amount and the peak runoff. The Muskingum routing model was used to model the reaches. Time of concentration is travel time of water from its place to outlet of watershed. On the basis of the longest path flow and slope time of concentration and vice a versa, lag time is calculated for each sub basin.

$$T_{lag} = 0.6\ T_c \quad (1)$$

where: T_{lag} – lag time (min); T_c – Time of concentration (min).

$$T_c = l0.8*(S+1)0.7/1140*Y\ 0.5 \quad (2)$$

$$S = (1000/CN)-10 \quad (3)$$

where: l = flow length,ft; Y – land slope,%; S – maximum potential retention; CN – curve number.

Determination of flood hydrograph at the downstream of the river by utilizing the inflow data of upstream is called routing. The Muskingum method was used to route outlet of sub basin to outlet of whole basin. The Muskingum K parameter reflects the travel time through the reach.

RESULTS AND DISCUSSION

Model calibration

Model parameters were estimated based on calibrated manually using a trial and error method. Calibration is the process of adjusting the model parameters to improve the agreement between the simulated results and observed data. In the present research, the Wainganga river basin was calibrated

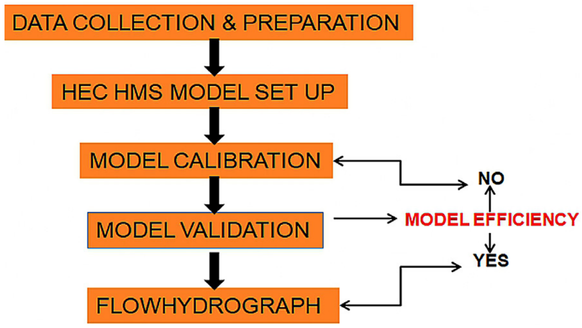

Figure 4. Methodology

for a period of 2010–2014 daily rainfall data. The basin is divided into 44 sub-basins. The sub-basins are assumed to be homogeneous. Root-mean-square error (RMSE) and percentage BIAS (PBIAS) are used for predicting performance of model as shown in Figure 5 (Kastali et al., 2021).

The Nash Sutcliff efficiency coefficients (NSEC)

This objective function indicates the degree of fitting simulated flow and measured flow. It reflects the consistency of the curve. The model indicates good performance when the NSEC value is near to 1.

$$\text{NSE} = 1 - \frac{\Sigma Qi,s-Qi,o)^2}{\Sigma(Qi,o-Qo)^2} \quad (4)$$

where: NSE – Nash Sutcliff efficiency, Qi,s – is the ith simulated discharge, Qi,o – is the ith observed discharge.

$$\text{RMSE}= \left(\frac{\sum_{i=1}^{n}(Qi,o\text{-}Qi,s)^2}{n}\right)^{1/2} \quad (5)$$

$$\text{PBIAS}= \left(\frac{\sum_{i=1}^{n}(Qi,o\text{-}Qi,s)*100}{\sum_{i=1}^{n}(Qi,o)}\right) \quad (6)$$

Figure 6 indicates the comparison of simulated runoff and observed runoff for Calibration for a period 2010–2014. It is observed that daily hydrograph of simulated runoff and observed discharge was good for a calibration period with NSE (0.79) and RMSE (0. 50).

Sensitivity analysis

Performing a sensitivity study on the lag time and other parameters of a hydrological model can help understand the impact of parameter changes on the model output. Parameters are deviated within a range of 0.2 to 0.8, while keeping other parameters constant. The study revealed that the lag time is more sensitive compared to the percentage imperviousness. Sensitivity analysis allows assessing the relative importance of different parameters in influencing the model's behavior and output was put forward by A Bhuyan *et al.* (2017). By systematically varying the parameter values while keeping others constant, Chathuranika *et al.* (2022) experimented to observe how changes in each parameter affect the model's response by The study indicated that the percentage imperviousness was the least sensitive parameter. The finding that percentage imperviousness is less sensitive implies that the changes in this parameter have a relatively smaller impact on the overall model response compared to other parameters.

Model validation

Model encompasses a wide range of parameters capable of predicting suitable results when experimented with a combination of parameters, as suggested by Rauf *et al.* (2018). Even though these results fit curve, it cannot be predicted that the parameter values are real time world. It is of utmost importance to check model for some different data apart from data used in calibration. Validation of model can reflect accuracy of different data with the same parameters. The Wainganga river basin is calibrated for a period of 2015–2020 daily rainfall data. Various criteria or performance measures can be used to evaluate the model's performance. After optimizing the model parameters, it was observed that the performance of the model improved. This indicates that the calibrated parameters resulted in a better match between the calculated discharge from the model and the observed discharge data. Improved

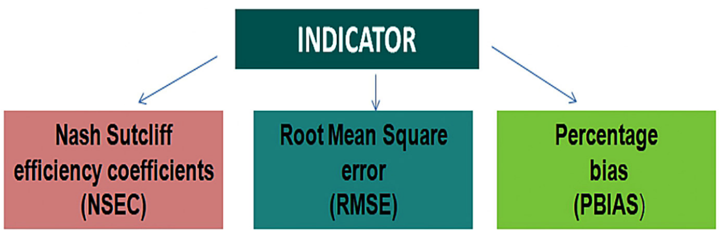

Figure 5. Objective function

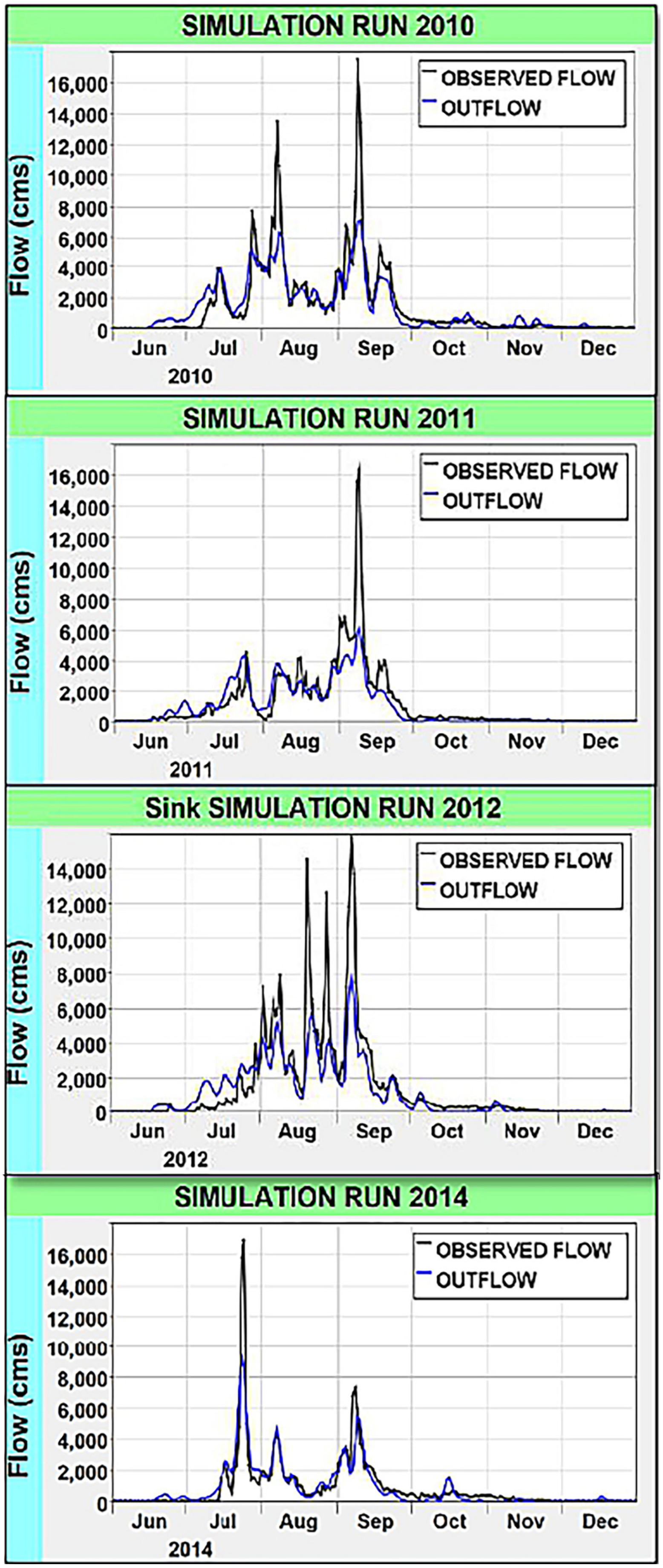

Fig. 6. Model calibration

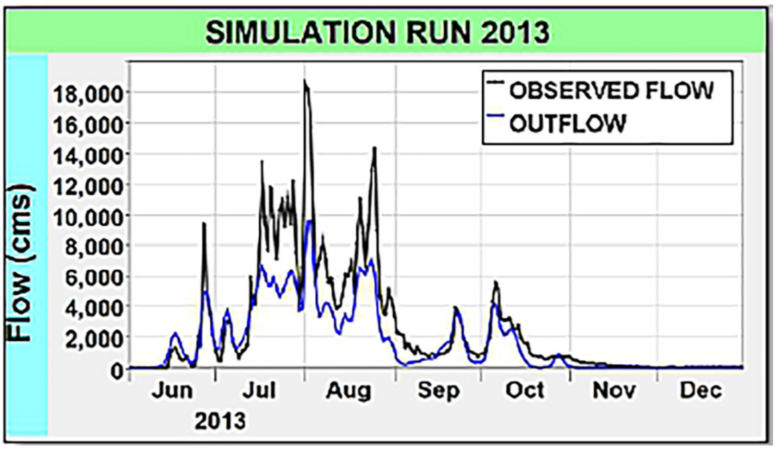

Fig. 6. Cont. Model calibration

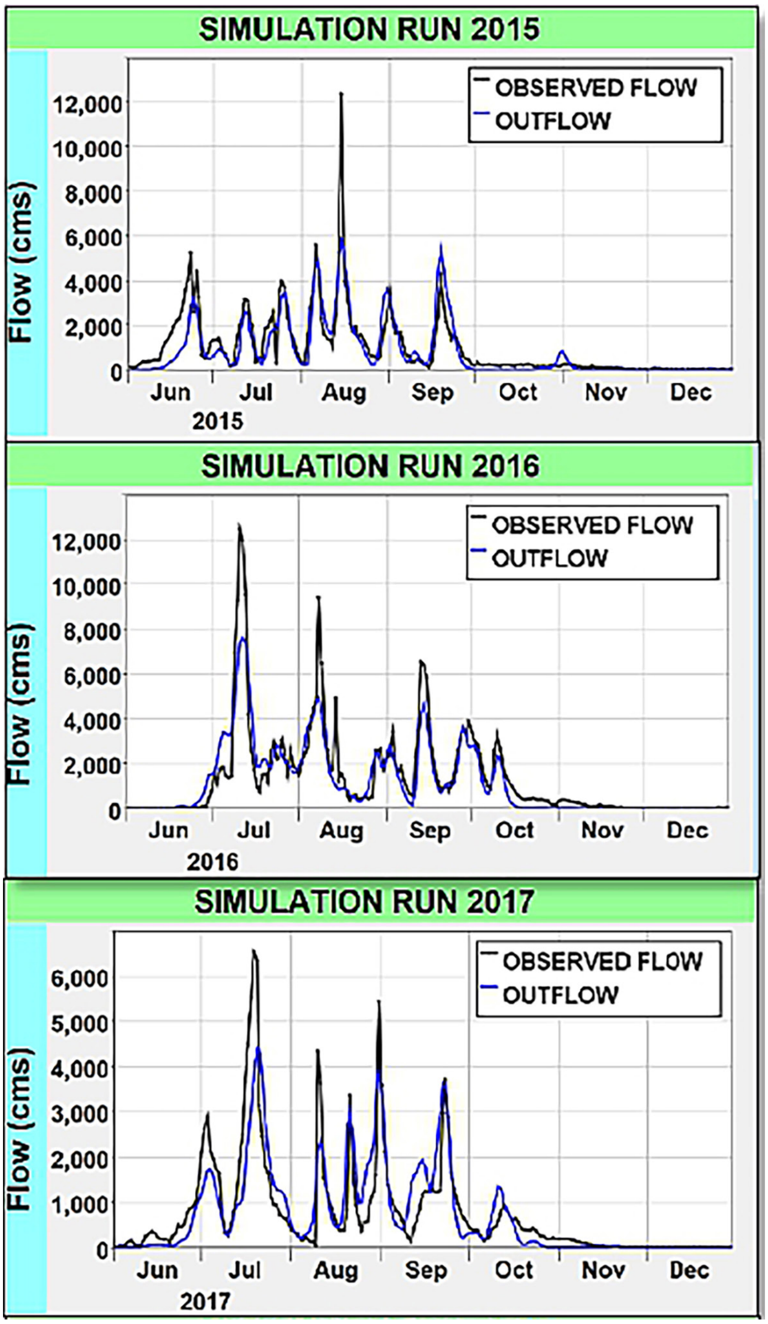

Fig. 7. Model validation

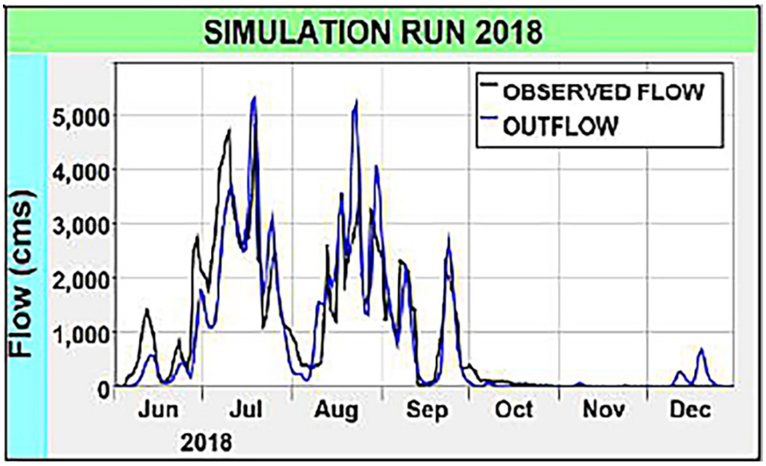

Fig. 7. Cont. Model validation

model performance after calibration suggests that the model is able to better simulate the hydrological processes within the watershed. Figure 7 indicates comparison of simulated runoff and measured runoff for validation 2015-2018. From the statistical analysis, it was found that the daily hydrograph of simulated runoff and observed discharge was good for a validation period with NSE (0.827) and RMSE (0.40).

CONCLUSIONS

Hydrological modeling of a catchment area is indeed a complex task that requires high-quality data and the application of various mathematical formulas. HEC-HMS is an effective tool for hydrological modeling of river basins. It provides a comprehensive framework for simulating rainfall-runoff processes, reservoir operations, and water management strategies. HEC-HMS is integrated with geographic information system capabilities, allowing for the management and analysis of spatial data related to the basin. By utilizing hydrological models like HEC-HMS and integrating them with software technology and GIS, water resource managers and decision-makers can make informed decisions, develop effective water management strategies, and mitigate the impact of flood events in the studied river basin. Manual adjustment was adopted to make simulated flow closer to observed discharge. The findings reveal that the daily hydrograph of simulated runoff and observed discharge was good for a calibration period with NSE (0.79). Optimized parameters improve the performance of the model. The study found that lag time are more sensitive, whereas percentage imperviousness is least sensitive. Statistical analysis shows that the daily hydrograph of the simulated runoff and observed discharge was good for a validation period with NSE (0.827). The above result indicates that the HEC-HMS model can be used for hydrological simulation of river basin. The research will be beneficial to planners to implement water management in future. The research was conducted for a holistic approach towards the basin and can be applied to other catchment areas of interest. However, there are some limitations in such type of a large river basin, as there is large variation in geographic characteristics. The accuracy of the model depends largely on the basis of the discharge measured. Improved estimates of input data would enhance the results of import or export from the basin. At present, the model predicts the response of catchment area to rainfall. The calibration and validation of the model is based on the simulated and observed discharge at the outlet of basin; however, there is lack of comparisons at spatial points. For future research work, a model can be developed considering spatial patterns. Also, further improved techniques can be used to obtain more accurate data. In addition to this, high resolution space borne availability and map data is necessary.

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