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Geospatial Analysis of Hydrological Responses and Surface Runoff Patterns in the Saroor Nagar Urban Watershed

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Abstract

A useful technique for forecasting a watershed's hydrological response and creating effective management plans for its water resources is hydrological modelling. Due to the ongoing rapid urbanization since the formation of the Telangana State, the primary goal of this investigation is to use geospatial techniques to simulate rainfall-runoff processes in the Saroor Nagar urban watershed, Telangana, for the years 2008, 2014, and 2020. The rainfall-runoff process is simulated using the Hydrologic Engineering Centre's Hydrologic Modeling System (HEC-HMS) model. Three distinct techniques are utilized to simulate the infiltration loss, the transformation of surplus rainfall into surface runoff, and the flow routing of the channel reach: the Soil Conservation Service-Curve Number (SCS-CN) approach, the SCS unit hydrograph technique, and the Muskingum routing approach. The discharge data from the Hussain Sagar catchment is taken into consideration during the calibration and validation of the proposed model using the regionalization method due to the lack of gauging in the watershed. The model's performance is evaluated by employing the coefficient of determination (R^2) as well as the Nash-Sutcliffe Efficiency (NSE). The HEC-HMS model analysis indicates that between 2008 and 2020, the simulated peak discharge increases from $44.4 m^3/s$ to $57.1 m^3/s$. During calibration, R^2 and NSE are 0.88 and 0.75, correspondingly; during validation, they are 0.83 & 0.89. The study's conclusions unequivocally show that the suggested model can faithfully replicate basin stream flow and that it can be used as a guide for wise water resource management in the watershed.

Key Words	Runoff, Regionalization, Saroor Nagar Watershed, HEC-HMS, Urbanization
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Introduction

Hydrological investigations are essential for effectively managing the water resources that are currently available. It is expected that the concerns with water resources will intensify in the future. Hydrological models can enhance our understanding of the availability of water resources and the processes that occur within river basins worldwide

(Gebre, 2015). Govidaraju et al. (2024) used SCS-CN method to estimate surface runoff of Kurumballi watershed. Hydrological models must be developed in order to assess the water availability in basins and prepare for future environmental changes. The primary obstacle to meeting the fundamental needs of all individuals lies in the sustainable governance of the finite reservoir of freshwater resources on our planet. Failure to effectively manage water resources could have detrimental consequences for society, potentially leading to droughts or floods. The rainfall-runoff model is a significant hydrological model that analyzes the correlation amongprecipitation and the resulting surface runoff, considering the impact of different physical characteristics of the watershed (Choudhari et al. 2014; Ramly and Tahir, 2015). Water resource experts have spent decades examining the relationship between structure complexity and streamflow prediction from rainfall events (James and Zhijia, 2010). HEC-HMS is essential for estimating runoff across diverse hydrological contexts. Its adaptability makes it suitable for applications in flood forecasting and water resource management (Basu et al., 2021). The HEC-HMS model allows for both lumped and distributed parameter modeling (Paudel et al. 2019). The model incorporates various input data, such as rainfall and land use, enabling detailed runoff simulations (Paredes et al., 2020). HEC-HMS uses multiple mathematical models to evaluate dendritic watershed hydrological functions. The control specifications, the meteorological model, and the basin model are the 3 inputs that constitute the HEC-HMS model. To accurately forecast the behavior of each of these components within a hydrological system, it is imperative to utilize a specific set of parameters. Each basin element supplies the element with its downstream counterpart to enhance river water flow and construct a dendritic network (Aggarwal, 2005). Throughout the simulation run, the boundary conditions of the river basin are taken into account by the metrological model. It includes data on the amount of precipitation and evapotranspiration that fall within the watershed. In essence, control specifications provide the time step, start and end dates, and duration of the simulation (Scharffenberg, 2006). All input data has been stored in time-series and paired-value formats in the HEC Data Storage System. The HEC-HMS model calculates gross water volume and peak flow for each basin component. (Agarwal, 2005). Namara et al. (2020) used HEC-HMS to simulate rainfall-runoff processes in the Awash Bello watershed. The model performed well, with $R^2 = 0.867$ and NSE = 0.855 during calibration and $R^2 = 0.863$ and NSE = 0.739 during validation. Paudel et al. (2019) showed how simple it is to analyze as well as comprehend the hydrological response along with the prediction of the upper Marshyangdi River basin, thereby demonstrating the suitability of the HEC-HMS model as a hydrological model. Patil et al. (2019) utilized the HEC-HMS model to forecast the rainfall-runoff relationship in the upper basin of the Godavari River. Their findings demonstrated that urbanization was the cause of the increased runoff volumes. Sarminingsih and Rezagama (2019) employed the HEC-HMS model to study the relationship between rainfall and runoff in the Garang watershed. Tassew et al. (2019) successfully simulated streamflow in the Lake Tana Basin, Ethiopia, employing the HEC-HMS model. Mokhtari et al. (2016) simulated rainfall-runoff in the Algerian Wadi Cheliff-Ghrib watershed using the HEC-HMS model. Their simulation demonstrated how the HEC-HMS model might be employed in hydrological modeling. The continuous rainfall-runoff model yielded very satisfactory results when compared to field discharge measurements in Kaffas and Hrissanthou's (2014) study of a watershed in the Greek Kosynthos River. Vivekanand Singh and Shishir Ranjan (2022) revealed that the Punpun basin achieved better results from monsoonal rainfall-runoff models. The monthly model was found to be more effective than the daily and monsoonal models. Nadeem et al. (2022) utilized the HEC-HMS model to replicate floods in the Hazara watershed in Pakistan. The model generated an increasing alert for flood prediction. Hamdan et al. (2021) employed the HEC-HMS to replicate the A-Adhaim River's discharge between 2015 and 2018 and determined that the model performed satisfactorily. Verma, R. et al. (2022) successfully simulated the rainfall-runoff processes in the Upper Sabarmati River using the HEC-HMS model. HEC-HMS is particularly effective in urban watersheds, where rapid runoff presents unique challenges (Verma et al., 2023). Its integration with Geographic Information Systems (GIS) enhances spatial analysis and visualization capabilities (Brahman et al., 2022). Recent advancements in parameter optimization have improved model calibration and reliability (Yadav et al., 2022). Hyderabad, the capital of Telangana state, is in close proximity to the study area of Saroor Nagar. Over the past few years, there has been significant growth in both the infrastructure and technological landscape of Hyderabad. The main cause of this issue is insensitive urbanization practices that disregard the improvement of drainage systems, insufficient maintenance, as well as improper disposal of solid waste into drainage systems. Nevertheless, modifications to the initial terrain have also reduced the linkages between soil and water, consequently amplifying the challenge of controlling and assimilating the erratic rainfall that results in urban flooding. Table 1 displays the actual and normal rainfall details of the study area during the last two decades. The investigation area encountered abnormally high precipitation during the specified time periods, in contrast to the average monthly rainfall established by historical data. The aim of our research is to utilize the HEC-HMS model to analyze the impact of changes in Land Use and Land Cover (LULC) on the amount of surface runoff in the Saroor Nagar area during 2008 and 2020.

Table 1: Historical rainfall data for the study area

Month/Year	Actual rainfall during that month (mm)	Normal rainfall during that month (mm)	Source
August 2000	413.7	176.9	Chief Planning Officer, Ranga Reddy District
August 2008	508.4	176.9	
September 2016	456.4	121.5	
September 2019	232.9	121.5	
October 2020	465.6	86.5	
July 2021	371.3	141	

Study Area

The investigation is conducted in the Saroor Nagar watershed, which is located in the state of Telangana. The study area is 42 km2 and lies between latitudes 17°16'59" N and longitude 78°29'25" E, and between latitudes 17°21'47" N and longitude 78°33'50" E. There is a range of 411 to 556 meters in altitude. The study area is basically residential. The usual temperature range is between 34 and 36 degrees Celsius. 725.8 mm of normal annual rainfall is expected. The study area experienced a rise in annual precipitation from 1054.8 mm in 2008 to 1478.6 mm in 2020. Given the process of urbanization and the impact of climate change, it is important to determine the possibility of surface runoff in the study area, and Figure 1 depicts the study area map.

Methodology

The LULC map, the Digital Elevation Model (DEM), the Soil map, along with meteorological data are needed for the modeling. Rainfall data is collected from the chief planning officer, district collectorate of Ranga Reddy, LULC maps were taken from previous research (Shiva Chandra and Reshma, 2022; Vaddiraju et al. 2023). Discharge data is collected from The Greater Hyderabad Municipal Corporation. Cartosat 1 DEM is collected from The National Remote Sensing Agency, and FAO soil database is used to extract the soil map.

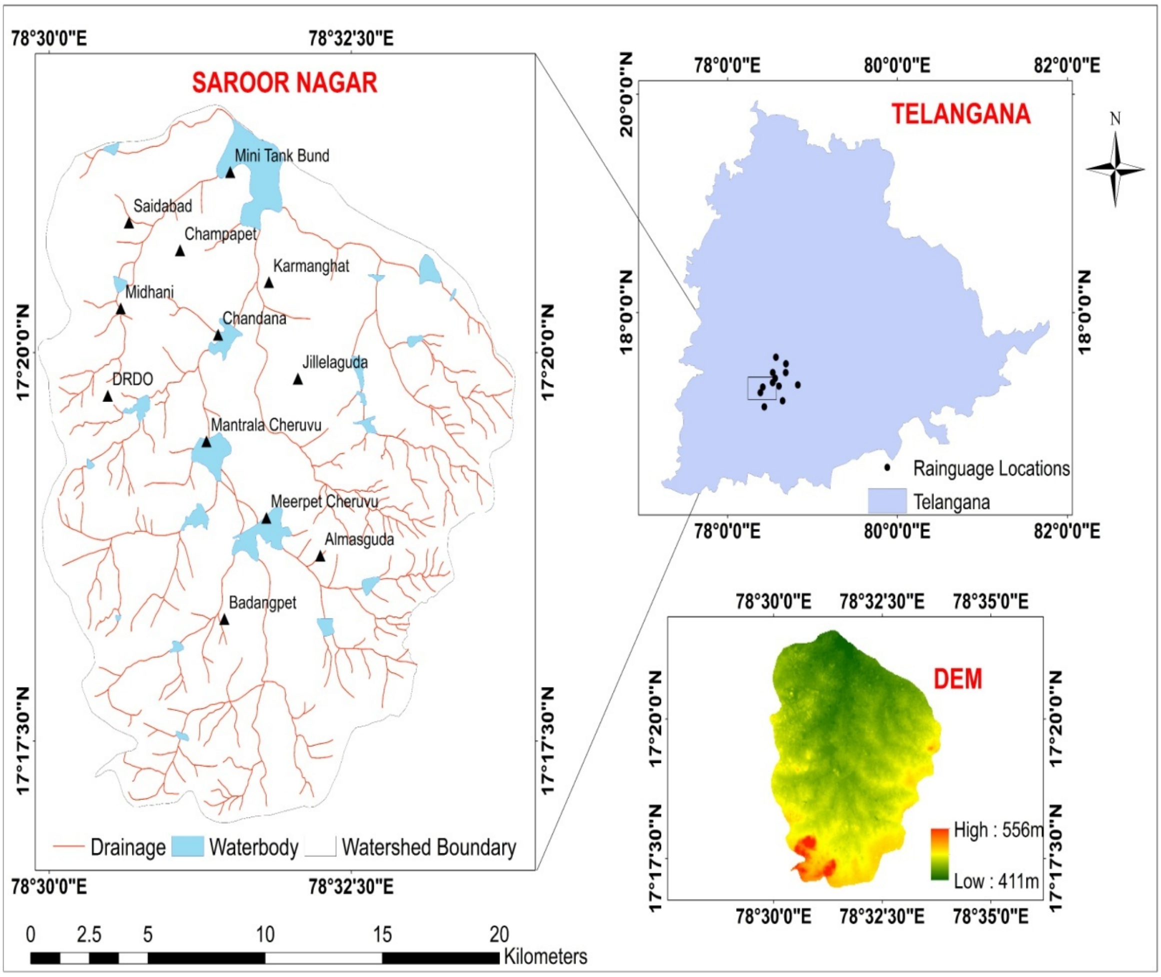


Figure1: Study Area Map

Preparation of LULC and Soil map

The LULC maps prepared by Shiva Chandra and Reshma, (2022) has been used in the present study. Hydrologic soil groups (HSGs) have been divided into A, B, C, & D on the basis of factors such as rainfall, runoff, and infiltration (Derdour et al. 2018). Group A is distinguished by a significant rate of infiltration and a limited capacity for runoff. Group B is composed of silt loam soil that has a coarse texture and moderate infiltration capacity. Group C soils, characterized by moderately fine textures, exhibit slow rates of infiltration as well as a moderate level of water transmission. These soils are typically classified as clay loam. In contrast, Group D soils have a high tendency for runoff and show limited infiltration. The study area is comprised exclusively of Group C soil.

Creation of curve number map

The curve number (CN) of the study region is influenced by soil type and land use. Its value spans from 30-100. A lower CN value signifies a diminished runoff coefficient, while a higher value signifies an elevated runoff coefficient. CN values are assigned to different combinations of HSG and LULC using NRCS tables. Then using the spatial join tool in ArcGIS, the CN maps are prepared for respective years. To calculate the mean CN for each sub-basin, employ Equation 1:

$$\mathrm{CN_{Avg}} = \sum_{i=1}^{n} \frac{\mathrm{CN_i} * \mathrm{A_i}}{\mathrm{A_{Total}}} \qquad (1)$$

Where i denotes the number of subbasin

A_i denotes the area of the specific subbasin

and A_{Total} denotes the total area of the basin.

Hydrological modelling using the HEC-HMS model

The hydrological parameters of the basin were assessed by simulating the physical characteristics of each sub-basin. The SCS-CN method was utilized to quantify precipitation losses, chosen for its relevance and the availability of local data (Yu et al. 2017; Tassew et al. 2019). Curve Numbers (CN) for each sub-basin were calculated to facilitate accurate estimates of infiltration.

SCS unit hydrograph transformation

The SCS-UH approach" was utilized to compute the discharge at the specified outlet. This approach requires two things: lag time as well as the percentage of impervious area in the basin (Barman & Bhattacharya, 2020; Tassew et al. 2019). Subramanya (2013) states that the basin lag time is equal to 0.6 times the concentration time. For each sub basin, calculations are performed to determine the proportion of imperviousness, lag time, concentration time, composite CN, potential soil storage, and initial abstraction.

Stream flow routing

The stream flow at the basin's outlet is determined using the straightforward and low-input Muskingum method (Song et al. 2011; Tassew et al. 2019). The input parameters K and x in the Muskingum method are essential for effective flood routing. The parameter x, which ranges from 0 to 0.5, represents the proportion of the reach's length affecting the flow. K can be calculated by dividing the reach length (x) by the average flow velocity. Notably, when x equals 0.5, the channel exhibits both minimum and maximum attenuation.

Calibration and Validation of the model

The watershed must be gauged for validation and calibration purposes. Because the Saroor Nagar watershed is not monitored by hydrometric stations, different approaches must be used to calibrate and validate the models. The regionalization method can be used to forecast hydrological model parameters for ungauged basins (Bardossy, 2007). Watersheds with comparable hydrological treatments typically have similar basin characteristics, allowing hydrological parameters from various watersheds to be transferred. The Hussain Sagar Lake catchment, which is at 14 km, is considered a donor catchment, and its discharge values are transferred to the Saroor Nagar watershed based on the simple area ratio method for validation purposes. This method uses the ratio of the areas of the two watersheds to adjust the reference parameters, assuming that hydrological responses are proportional to watershed size. Trial-and-error calibration was used to obtain the correct values for each parameter that produced the best fit between the observed and predicted hydrographs. The calibration period in this study was from June 2014-October 2014, and the validation period was from June 2020-October 2020. The proposed HEC-HMS model's performance was assessed using the coefficient of determination and Nash-Sutcliffe Efficiency. Equation 3 depicts the NSE coefficient, which measures the predictive capability of the hydrological model.

$$\mathrm{NSE} = 1 - \frac{\sum_{t=1}^{T}\left(Q_{m,t}-Q_{o,t}\right)^2}{\sum_{t=1}^{T}\left(Q_{o,t}-\overline{Q}_o\right)^2} \quad (3)$$

where, $Q_{o,t}$ = Observed flow at t time ,

$\overline{Q_o}$ is the mean of observed flow

$$and\ Q_{m,t} = \text{Simulated flow at t time},$$

In a linear regression setting, a metric called the coefficient of determination (R^2) is used to assess a model's ability to predict an outcome. Equation 4 illustrates how to express R^2:

$$R^2 = \frac{\sum_{i=1}^{n}(O_i - O)\,(S_i - S)}{\sum_{i=1}^{n}(O_i - \overline{O}\,)2 \quad \sum_{i=1}^{n}(S_i - \overline{S}\,)2} \quad (4)$$

$$\text{where } O_i = \text{Observed flow at i time,}$$

$$\overline{S}\ \text{Mean of simulated flow at i time}$$

$$S_i = \text{Simulated flow at i time,}$$

$$\text{and } \overline{O} = \text{Mean of observed flow at i time,}$$

Results and Discussions

LULC Maps

The LULC maps for the years 2008, 2014, and 2020 prepared by (Shiva Chandra and Reshma, 2022) were used in the present study. The LULC of Saroor Nagar watershed consists of built-up, waterbody, vegetation, and barren classes. The LULC maps show that there is a continuous increase in the built-up area from 2008 to 2020, which means there is a situation that increases the runoff due to more impervious areas. Table 2 displays the statistics for LULC. Figure 2 shows LULC maps for different years.

Soil and curve number maps

The hydrological soil group map and the LULC maps from 2008, 2014, and 2020 are employed to create the CN map of the basin for the respective years. Figure 3 displays the corresponding year's CN maps, and Table 3 shows HSG, CN, and Weighted CN values of the watershed.

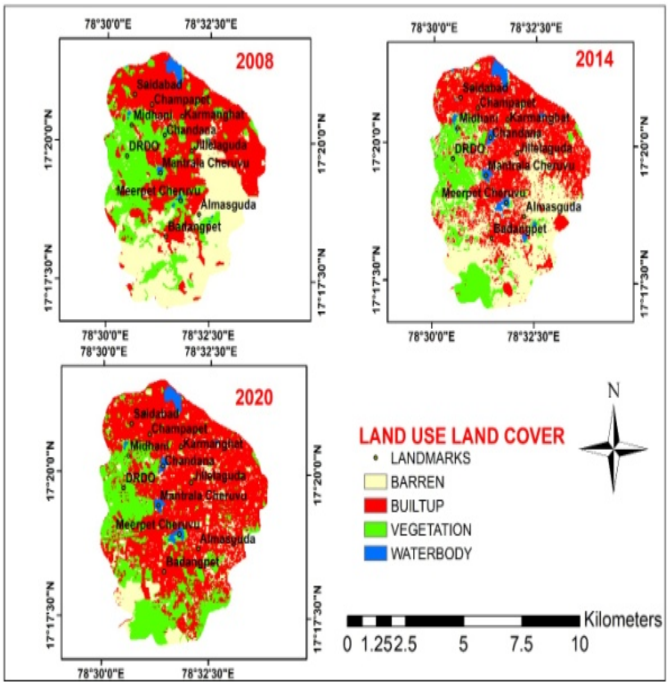
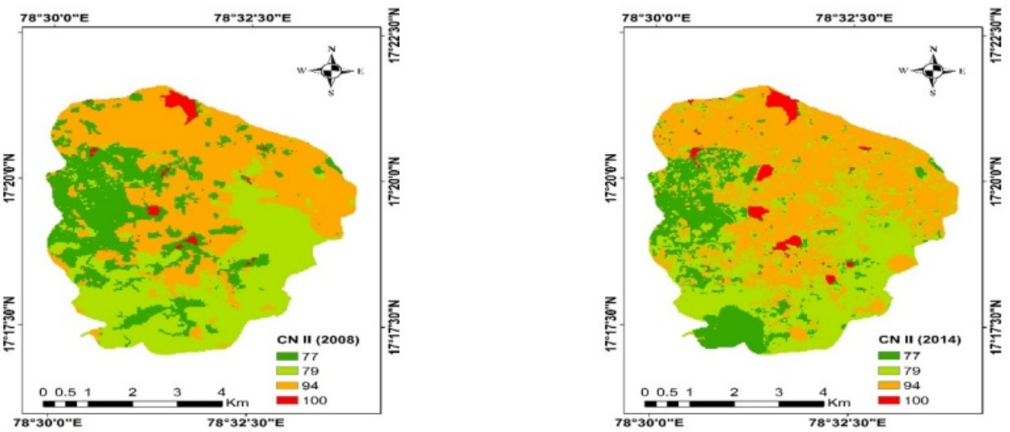


Figure 2: LULC Maps



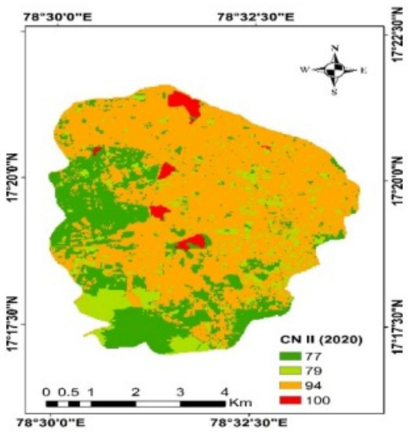


Figure 3: CN Maps

2 Table 2: Watershed LULC class distribution

Class Name	2008 Area (%)	2014 Area (%)	2020 Area (%)
Built-up	41.8	54.4	64.9
Waterbody	1.3	1.5	1.9
Vegetation	23.9	23.5	25.3
Barren	32.8	20.8	7.9

3

HEC-HMS Model Development

The Saroor Nagar Watershed's seasonal flow is simulated by the model, which was created using HEC-HMS software. Seven sub-basins have been identified within the study area, along with the basin's outlet. The basin model is depicted in Figure 4 and Figures 5–11 display each sub-basin attributes regarding CN, lagtime, initial abstractions, and impervious area, respectively. The analysis of sub-basin characteristics reveals a decline in initial abstractions and lagtime between 2008 and 2020. Simultaneously, there is a consistent rise in curve number and imperviousness, indicating possibility of increased runoff.

Simulation of Runoff in the Saroor Nagar Urban Watershed Using HEC-HMS

After the basin characteristics are calculated, the CN, initial abstractions, imperviousness and lagtime are fed into the HEC-HMS module for each sub-basin, and the model is executed to simulate the runoff of 2008, 2014, and 2020. Due to the absence of observed discharge data for the Saroor Nagar tank, the model is calibrated using the observed discharge data of the Hussain Sagar catchment using the regionalization method. The discharge values recorded in the Hussain Sagar catchment are transferred to the Saroor Nagar watershed using the simple area ratio technique. The discharge values from the donor catchment are scaled based on the area ratio of donor and receiving catchment. The daily observed data from June 1, 2014, to October 31, 2014, is used to calibrate the model, and the daily noted data from June 1, 2020, to October 31, 2020, is used to validate the model. The calibration is done by considering SCS Curve Number (Curve Number Scale Factor), SCS Curve Number (Initial Abstraction Scale

Factor), Muskingum – K, and Muskingum x as the calibration parameters. Initially, the model is simulated by taking values of 1, 1, 0.5, and 0.2 for SCS Curve Number (Curve Number Scale Factor), SCS Curve Number (Initial Abstraction Scale Factor), Muskingum – K, and Muskingum x, respectively. Later, based on trial-and-error methods, optimised values are found, and simulations are run to estimate the surface runoff. The initial and optimised values of calibrating parameters are presented in Table 4. The simulated discharge data for 2020 is validated using the optimized values that were acquired during the calibration process. The NSE as well as $R^2$are employed to determine the performance of the proposed HEC-HMS model. The model demonstrates strong performance, as indicated by the R^2& NSE values obtained during the calibration as well as validation phases, which are 0.88 & 0.83, and 0.75 & 0.89, accordingly. The analysis shows that between 2008 and 2020, the simulated peak discharge improved from 44.4m^3/s to 57.1m^3/s and the discharge volume increased from 36.57MM^3 to 52.26MM^3. The simulated and observed discharge were lower in 2014, as the study area witnessed less rainfall of only 523 mm as opposed to 725 mm of normal annual rainfall. During the validation period of 2020, the simulated peak discharge is 57.1 m^3/s, whereas the observed discharge is 51.4 m^3/s. Table 5 presents specifics of observed and simulated discharges as well as model performance. Figure 12 displays the details of the simulation for different years. Figure 13 shows the linear regression of the observed as well as simulated discharge during the calibration and validation years. Figure 14 shows the details of some sub-basins simulations.

Table 3: Saroor Nagar Watershed LULC, HSG, and CN Distribution

Year	LULC	HSG	Curve Number (CN)	% of Area	(% of Area) X (CN)	Weighted Curve Number
2020	Built-up	C	94	65	6110	89 (CN II)
	Waterbody	C	100	2	200	
	Vegetation	C	77	25	1925	
	Barren	C	79	8	632	
2014	Built-up	C	94	54.5	5123	87 (CN II)
	Waterbody	C	100	1.3	130	
	Vegetation	C	77	23.5	1809	
	Barren	C	79	20.7	1635	
2008	Built-up	C	94	41.8	3929	85 (CN II)
	Waterbody	C	100	1.4	140	
	Vegetation	C	77	24	1848	
	Barren	C	79	32.8	2591	

Table 4: Saroor Nagar Watershed Calibration Parameters

Element	Parameter	Initial Value	Optimized Value
All Sub-basins	SCS Curve Number – Curve Number Scale Factor	1.00	0.9
All Sub-basins	SCS Curve Number - Initial Abstraction Scale Factor	1.00	0.9
All Reaches	Muskingum – K	0.5	0.1
All Reaches	Muskingum – x	0.2	0.1

Table 5: Model Output and Performance

	Simulated Discharge		**Observed Discharge**		**NSE**	**R²**
Year	Peak (m^3/s)	Volume (1000 m^3/s)	Peak (m^3/s)	Volume (1000 m^3/s)	-	-
2008	44.4	36570	Data Not Available	Data Not Available	Data Not Available	Data Not Available
2014	10.3	14428	13.9	8238	0.75	0.88
2020	57.1	54269	51.4	41490	0.89	0.83

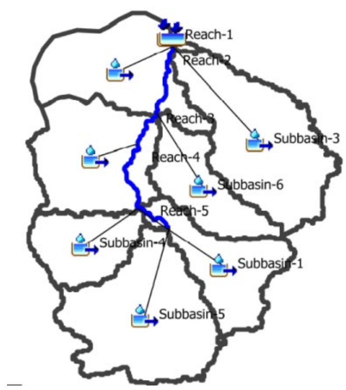


Figure 4: Basin Model of the study area

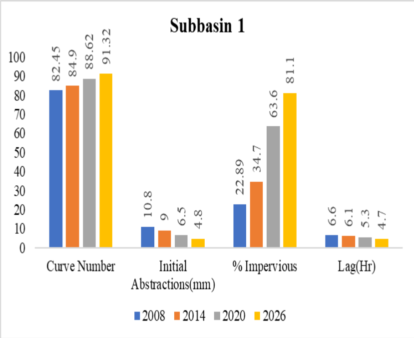


Figure 5: Basin Characteristics of Sub basin 1

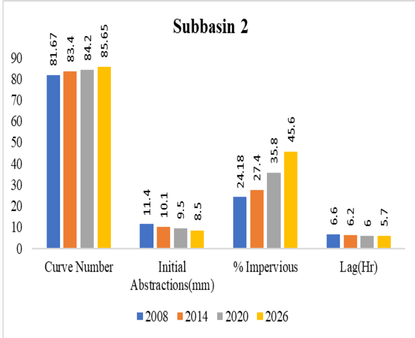


Figure 6:Basin Characteristics of Sub basin 2

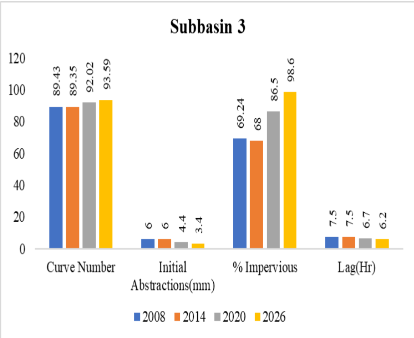


Figure 7: Basin Characteristics of Sub basin 3

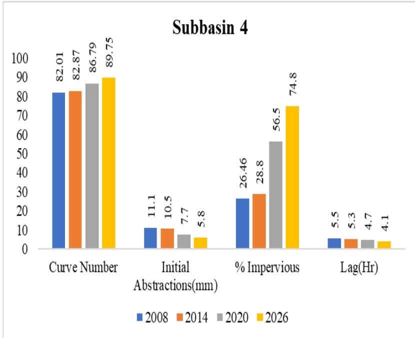


Figure 8: Basin Characteristics of Sub basin 4

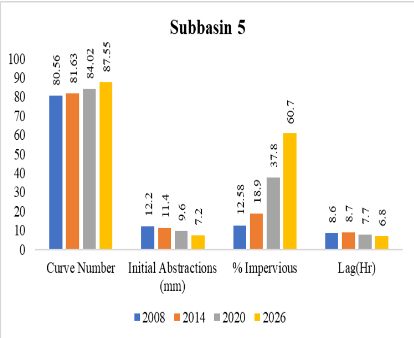


Figure 9: Basin Characteristics of Sub basin 5

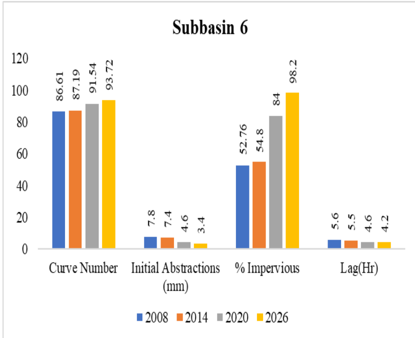


Figure 10: Basin Characteristics of Sub basin 6

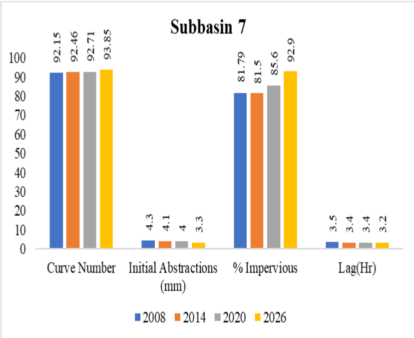


Figure 11: Basin Characteristics of Sub basin 7

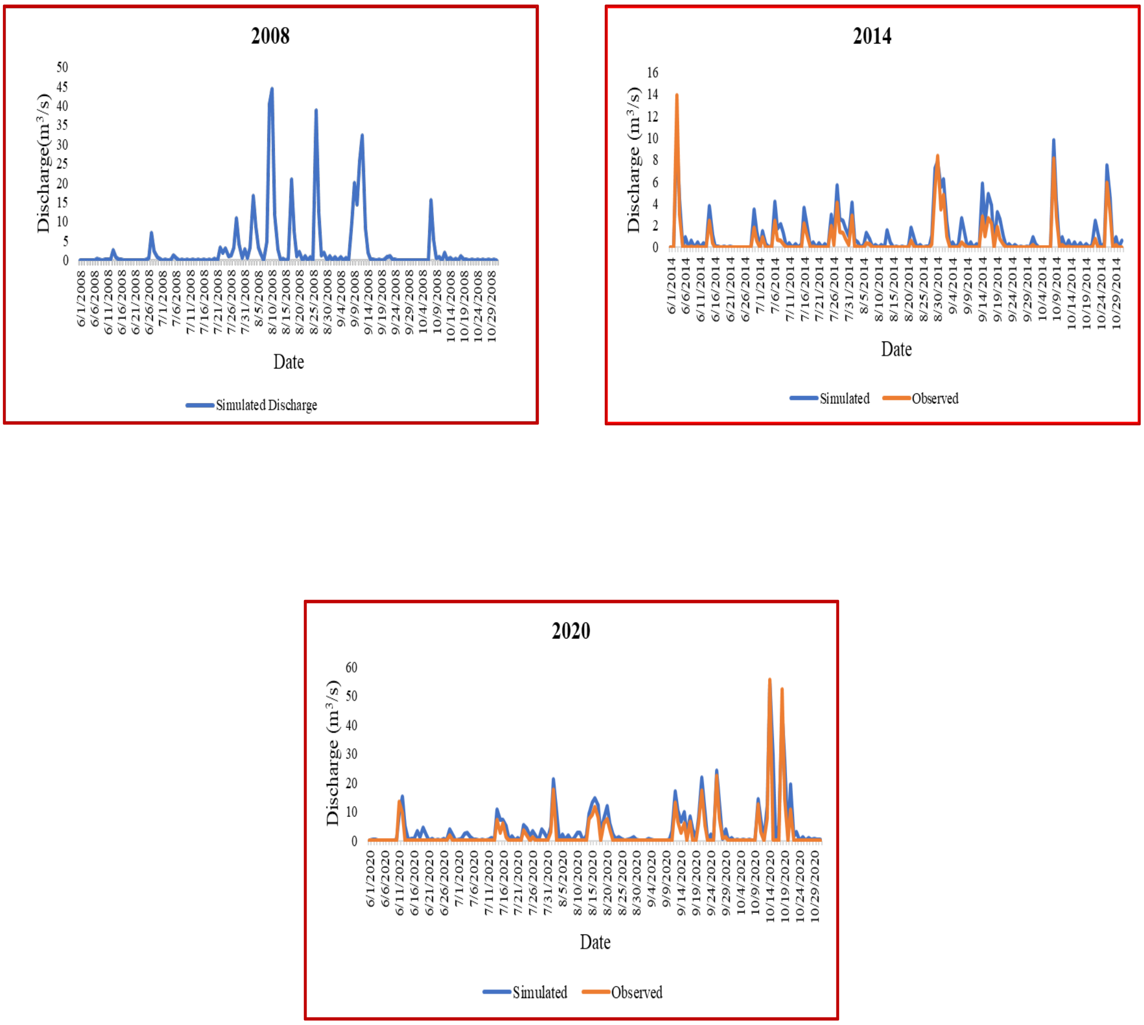


Figure 12: HEC-HMS Simulation results of 2008, 2014, and 2020

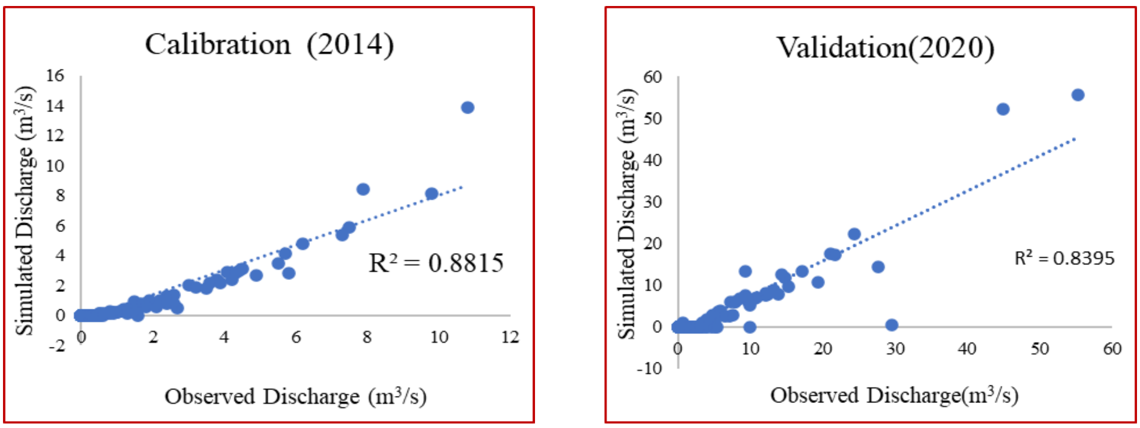


Figure 13: Linear Regression of Simulated and Observed Discharge During Calibration and Validation Period

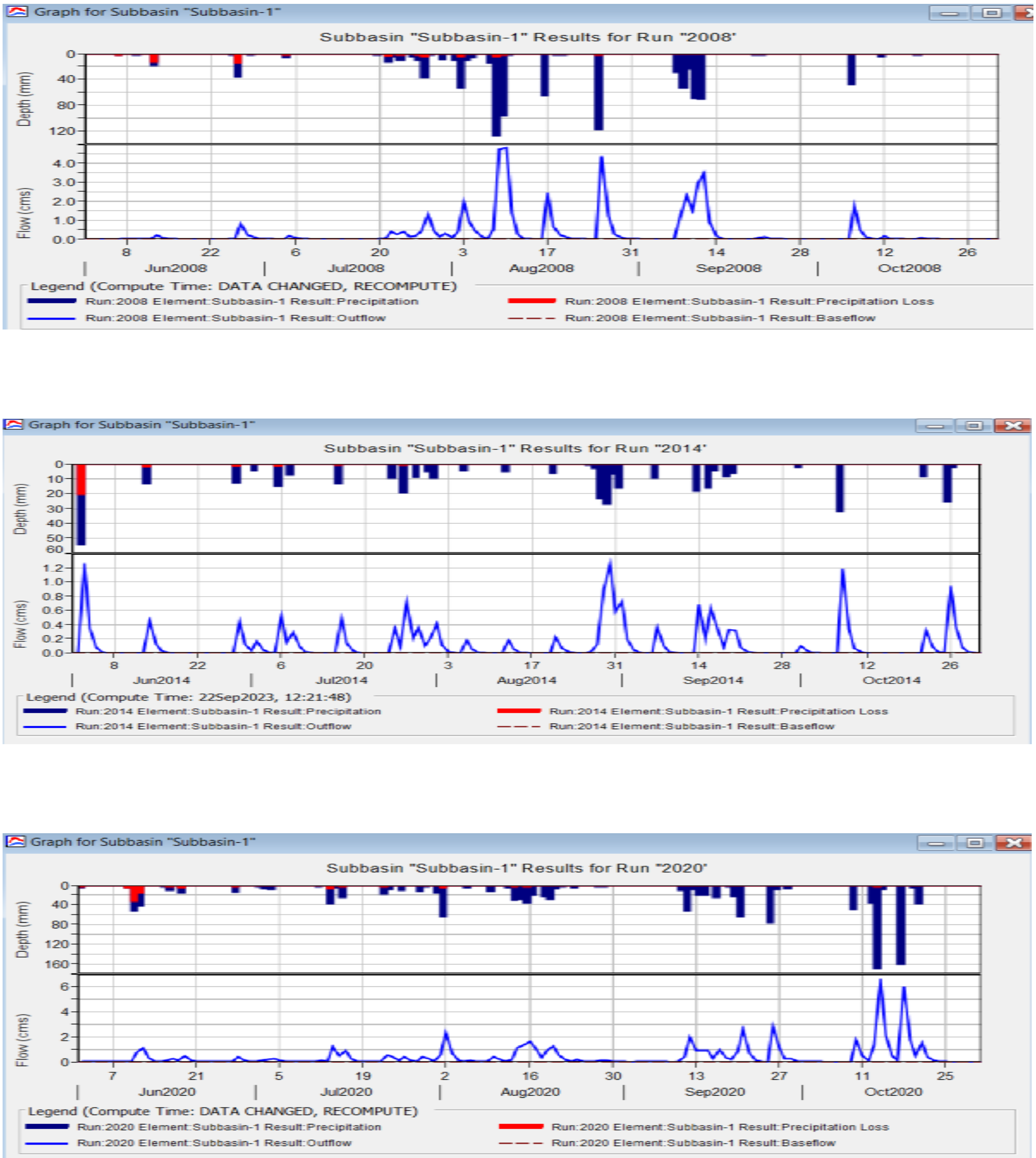


Figure 14: Simulation Details of Sub basin 1 for the Year 2008, 2014, and 2020

Conclusions

This study effectively utilized the HEC-HMS model to simulate the rainfall-runoff processes in the Saroor Nagar urban watershed of Telangana from 2008 to 2020, highlighting the impact of rapid urbanization on surface runoff. The model demonstrated strong performance with calibration R^2 and NSE values of 0.88 and 0.75, and validation values of 0.83 and 0.89, respectively. Analysis revealed an increase in peak discharge from 44.4 m³/s in 2008 to 57.1 m³/s in 2020, correlating with an increase in built-up areas and associated impervious surfaces. The LULC analysis showed a significant rise in urban land use, contributing to heightened runoff volumes. The study underscores the importance of integrating hydrological models in urban planning and water management strategies, especially in areas prone to flooding. It advocates for sustainable land management practices and infrastructure improvements to mitigate flooding risks. Additionally, the use of regionalization techniques for calibration in ungauged watershed proved effective. These findings provide crucial insights for local authorities to enhance flood preparedness and water resource management. Future studies should focus on continuous monitoring and adaptive management strategies to address ongoing changes in land use and climate.

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