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Integration of GIS Data Based SWAT and SWMM Models for Urban Catchment Flood Simulation and Management

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ABSTRACT

The rapid growth of urban areas has made urban flooding a severe concern because cities contain more paved surfaces and aging drainage systems combined with rising rainfall intensity. A GIS-driven hybrid modeling combination of Soil and Water Assessment Tool (SWAT) and Storm Water Management Model (SWMM) was used by researchers to evaluate flood behaviors in Wakad Watershed of Mula River within Pimpri Chinchwad Municipal Corporation (PCMC) Pune District Maharashtra India. The SWAT model utilized historical rainfall data from 1993 to 2023 to conduct both calibration and validation of hydrological simulations at the catchment level. Simulation of urban drainage behavior during 2007 and 2019's major flood events was achieved by linking SWMM with the model outputs. The model received its performance assessment through statistical measurement of Nash-Sutcliffe Efficiency (NSE) along with Root Mean Square Error (RMSE). The hybrid SWAT–SWMM model demonstrated superior predictive capability, as reflected by NSE values exceeding 0.85 and peak flow estimation errors below 3%. More importantly, the combined optimization technique led to a 41% reduction in RMSE, offering a significant advancement over the standalone modeling frameworks and reinforcing the model's applicability in research driven urban flood assessments. The integration of SWAT–SWMM modeling via GIS offers a powerful decision-support tool for urban planners, water managers, and policymakers. By delivering more accurate and spatially explicit flood forecasts, this approach enables proactive drainage system planning, climate-resilient infrastructure development, and sustainable resource management in growing cities.

INTRODUCTION

Modern cities experience urban flooding which represents their main environmental challenge because of quick urban development and increased impervious surfaces alongside climate changes. Unplanned urban development has transformed watershed hydrological systems by creating excessive surface runoff leading to heightened flood peaks that result in surcharges of storm water (Ahiablame & Shakya, 2016). Traditional modeling methods fail to clarify the natural relationship between the hydrological system and drainage engineering structures in Wakad's Pune region of India. Geographic Information Systems (GIS) and hydrologic and hydraulic models enable scientists to enhance urban flood simulation spatial accuracy according to Abdul-Aziz and Al-Amin (2016) and Berhanu (2018).

As a basic hydrologic modeling system, the Soil and Water Assessment Tool (SWAT) supports nationwide applications by performing semi-distributed operations between sub-basins and hydrologic response units (HRUs) (Arnold et al., 1998). Each watershed undergoes transformation by SWAT through creation of sub-basins which form hydrologic response units (HRUs) to reflect different land types and soil types present within the watershed. SWAT does not possess the features needed to model urban drainage systems and to simulate surface flooding conditions in engineered systems while running its operations. A SWAT model adds value by linking EPA SWMM software to overcome its restriction because SWMM performs piped stormwater routing with pipe overpressure control and floodplain management (Rossman, 2010).

Through SWAT and SWMM integration users can obtain whole hydrologic process analysis together with city drainage system response observation (Babaei et al., 2018). SWAT provides extensive capabilities for long-term land use and climate change simulations of hydrological processes but SWMM demonstrates maximum benefits during swift stormwater system reactions under exceptional precipitation conditions (Gao et al., 2020; Akhter & Hewa, 2016).

The modeling process for urban floods becomes more complex due to climate change activities. The increasing rainfall intensification and modifications in rain patterns have rendered previous historical datasets useless for making predictive forecasts (DeGaetano & Castellano, 2017). According to Ahmad et al. (2016) and Gado et al. (2021) short-duration heavy rainfall occurs increasingly frequently across South Asian regions and the Indian territory. The integration of real-time models requires dynamic approaches through which climate-adjusted rainfall patterns merge with urban system reactions because climate conditions continue to change. Scientists can comprehend watershed behavior using SWAT models (Dudula & Randhir, 2016) while SWMM demonstrates its strength in evaluating drainage systems during modified climate storm events (Berggren et al., 2014). The integration of GIS-based systems through unified tools occurs infrequently during the entire developmental cycle of urban centers across India.

Watershed definition and land use visualization as well as drainage integration with output displays result from spatial processing enabled by GIS according to Ghimire et al. (2019). SWAT sub-basin data is paired with SWMM sub catchment hydraulic system using GIS tools integration. Research by Birhanu et al (2016) and

Chen et al (2012) established that hybrid GIS models deliver reliable framework for simulation and models and data testing which integrates active satellite mapping data with soil databases and precipitation records. Several researchers show that correct topographic and land use data play a crucial role for flood predictions because imprecise inputs lead to substantial variations in the predicted outcomes (Del Giudice & Padulano, 2016; Dotto et al., 2010).

Although integrated hydrologic–hydraulic modeling has gained global attention, its application under Indian urban monsoon conditions remains limited. Rapid urbanization, extreme seasonal rainfall, and inadequate drainage systems create complex flood dynamics that are not well captured by single-model approaches. This study addresses this gap by applying a GIS-based hybrid SWAT–SWMM modeling framework in the Wakad Watershed, demonstrating its effectiveness for multi-event flood forecasting and sustainable water resource planning in monsoon-prone urban areas. Recurrent floods have affected Mumbai and Chennai along with Pune throughout recent years because drainage breakdowns combined with uncontrolled urbanization and deficient warning systems (Bisht et al., 2016). Wakad area in Pune endured two severe rainfall events in 2007 and 2019 which revealed the importance of developing advanced simulation and planning tools. Researchers have addressed this study gap through SWAT-SWMM modeling framework by achieving better catchment runoff processes and higher resolution urban flood propagation modeling. Every model output must be analyzed sensitively because model calibration requires techniques that reduce output uncertainty. According to research from Behrouz et al. (2020) and Brun et al. (2001) automatic calibration tools in coupled SWMM and SWAT models enhance the models' reliability. The generated flow volumes and peak discharge values by SWAT and SWMM models depend extensively on curve number (CN2) parameters alongside conduit roughness parameters. The study integrates a robust verification approach using historical flood and storm data to check the precision of the developed models.

The combination of evidence-based principles through hybrid SWAT-SWMM models produces outstanding results in urban flood simulation applications since they offer operational feasibility as well as evidence-based foundations according to scientific reviews. The model effectively captures complex urban flood dynamics, offering a scalable solution for data-informed flood forecasting and sustainable infrastructure planning in monsoon-prone cities. End-users can easily utilize GIS technology implementations which produce accurate models in operational environments. Integrated modeling frameworks enable better decisions by providing solutions for structural development planning alongside policy formation activities that address flood risks in expanding urban areas under rising environmental uncertainties and growing land requirements.

To address the limitations of conventional flood models in monsoon-affected urban catchments, this study develops a GIS-integrated SWAT–SWMM hybrid framework that combines catchment-scale hydrological modeling with urban hydraulic simulation. Using Python-scripted GIS tools, temporally disaggregated hydrographs from SWAT sub-basins are dynamically routed into SWMM sub catchments. The objective is to evaluate model performance under multi-event flood scenarios in the Wakad Watershed (PCMC, India), using 30 years of rainfall data (1993–2023) and flood records from 2007 and 2019. Model accuracy is assessed via NSE and RMSE, benchmarking the hybrid model against standalone configurations for improved flood prediction and drainage response analysis.

2. METHODOLOGY

Runoff hydrographs generated from QSWAT were spatially linked to SWMM sub catchments using GIS shape files and temporally disaggregated using a Python-assisted data transformation workflow to produce hourly inflow series. SWAT runoff outputs were simulated at a daily time step and subsequently disaggregated to hourly resolution to match the temporal requirements of the SWMM model. This disaggregation was performed using rainfall distribution curves derived from observed monsoon events, preserving flow volume while better capturing peak runoff behavior for storm water drainage analysis.

To facilitate hydrologic–hydraulic coupling, a semi-automated integration workflow was implemented between the QSWAT and SWMM modeling environments. The process involved three key steps:

1. Hydrograph Extraction from QSWAT: The SWAT model was calibrated at the sub-basin scale to simulate daily runoff, which was exported from the QSWAT output database (.dbf and .txt formats). These outputs were used as inflow data for urban drainage modeling.
2. GIS-Based Spatial Mapping: The SWAT sub-basins were spatially overlaid with SWMM subcatchments using GIS tools (QGIS). This ensured consistent spatial referencing between the hydrologic and hydraulic domains. Each SWAT sub-basin was matched to the nearest or contributing SWMM subcatchment based on watershed flow direction and drainage boundaries.
3. Python-Assisted Temporal Disaggregation and Formatting: A Python-supported routine (partially scripted) was employed to disaggregate daily SWAT runoff values into hourly time series, using rainfall intensity profiles and adjustment factors derived from observed storm events. The disaggregated data was formatted into SWMM-compatible INFLOW. INP or .txt files for direct import into the model.
4. Model Execution and Validation:
   The coupled SWAT–SWMM model was executed for flood simulation scenarios corresponding to 2007 and 2019 events. Model performance was evaluated using standard metrics such as the Nash–Sutcliffe Efficiency (NSE) and Root Mean Square Error (RMSE) to validate the accuracy of predicted hydrographs against observed flow records at key outfall locations.

This coupling approach allowed event-based flood simulations to incorporate accurate upstream hydrology into downstream urban drainage analysis. While not fully automated, the workflow is reproducible and adaptable to other urban watersheds using standard GIS and hydrologic-hydraulic modeling platforms.

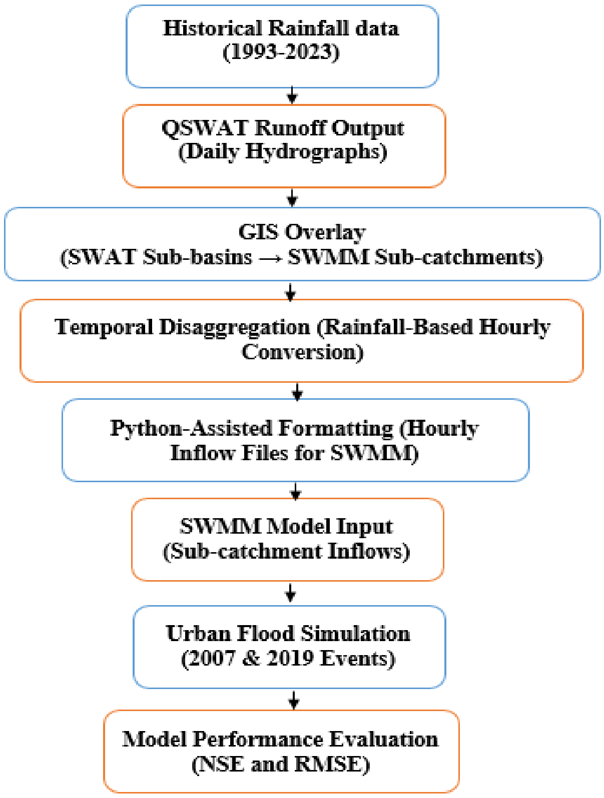

Figure 1: Workflow for SWAT–SWMM Integration via Python-GIS-Based Data Conversion

This schematic of Figure 1 represents the stepwise integration of SWAT and SWMM models through a GIS-assisted data conversion process. SWAT outputs (daily runoff hydrographs) are extracted from QSWAT and spatially matched to urban subcatchments defined in SWMM. Using a Python-assisted workflow, runoff values are temporally disaggregated to hourly resolution and formatted into SWMM-compatible inflow files. The processed data is then imported into SWMM for urban drainage simulations under different flood scenarios.

2.1 Study Area

Wakad Watershed serves as the main focus of the present research located in the Pimpri Chinchwad Municipal Corporation (PCMC) area within the Pune District of Maharashtra state in India. The Mula River basin contains this watershed as one of its significant tributaries that leads to the Bhima River. Wakad experiences fast urban development because farmers transformed their farmland into residential properties combined with industrial buildings and shopping centers. The expanding human-made structures have created more waterproof surfaces that cause elevated storm runoff and recurring flooding events in the area. The landscape features both flat plains alongside medium-level elevated positions for which hydrological modeling can be performed effectively. The study region contains both natural streams and human-built storm drains before water flows into

Mula River. The repetitive flood situations from 2007 and 2019 make Wakad an essential area for conducting integrated flood modeling that utilizes GIS-based systems.

The Wakad watershed, located in the northwestern part of Pune District, is characterized predominantly by urban residential development (90.52%), followed by agricultural land (6.06%) and open spaces or fallow land (2.46%), as derived from 2020 land use/land cover data. The rapid urbanization in this region, especially post-2000, has significantly altered the hydrological response of the catchment, increased impervious surfaces and reduced natural infiltration zones.

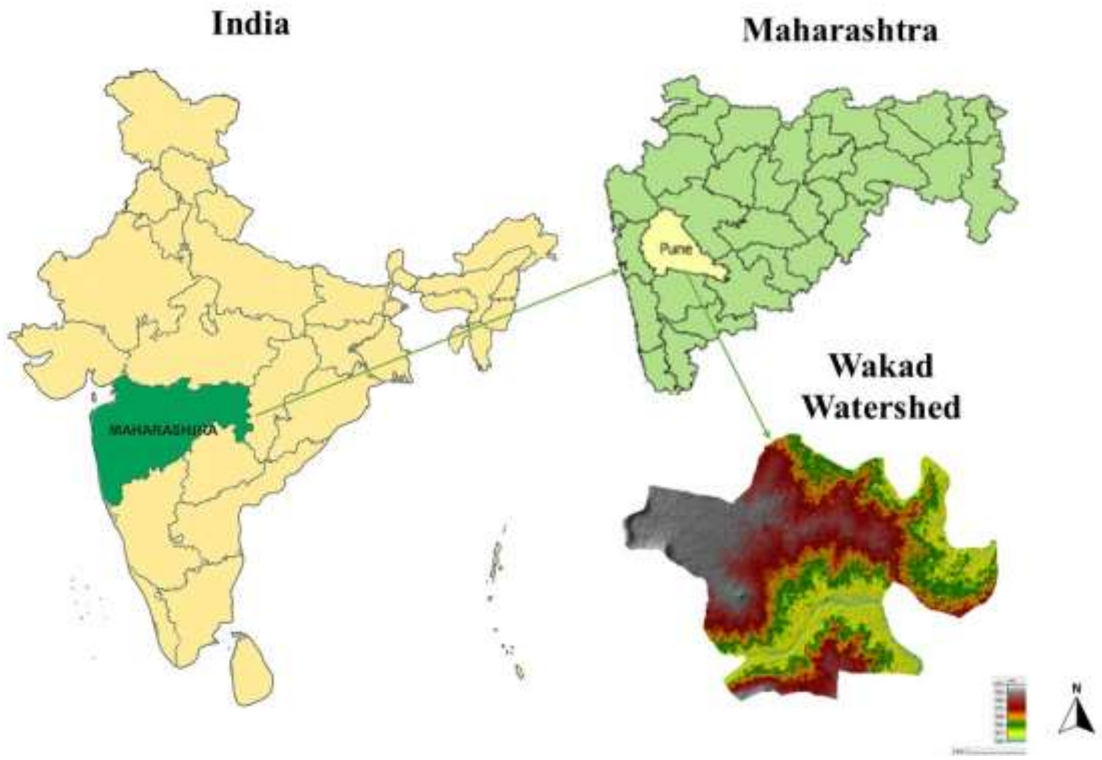

Figure 2: Study Area Map

Historically, the watershed has been vulnerable to urban flooding due to inadequate drainage and high runoff coefficients. Flood events have been documented in the years 2007, 2010, 2013, 2015, and 2016, with major flooding recorded in 2019, caused by intense monsoonal precipitation events and infrastructure bottle-necks along the Pavana and Mula rivers. Most recently, 2023 witnessed local inundations, confirming the on-going stress on the drainage network in high-density zones in Pimpri-Chinchwad such as Wakad. The study area is shown in Figure 2 and geographically defined by the following coordinates:

- **Northern latitude**: 18.610° N (18°36′35″)
- **Southern latitude**: 18.580° N (18°34′52″)
- **Eastern longitude**: 73.780° E (73°46′51″)

- **Western longitude**: 73.750° E (73°45′00″)

2.2 Data Used

Table 1: Data Used in This Research

Sr. No.	Spatial Data	Source
1	Digital elevation model (DEM) (30 m × 30 m)	Shuttle Radar Topography Mission (SRTM) of USGS
2	Land use/land cover (LULC) (10 m LULC map)	National Remote Sensing Centre, ISRO
3	Soil Data	National Bureau of Soil Survey and Landuse Planning (NBSS-LUP)
4	Meteorological Data (From the year 1993 to 2023)	Indian Meteorological Department (IMD), Pune, India
5	Flow and gauge data	PCMC Drainage & Town Planning Department and India-WRIS

The research implements a combined hydrologic-hydraulic modeling protocol which connects SWAT with SWMM and uses GIS to predict urban flooding within the Wakad Watershed situated in Pimpri Chinchwad, fast-developing Pune region. The project seeks to replicate runoff generation in the catchment area together with urban drainage system responses for intensifying rainfall events that occurred during 2007 and 2019.

The India Meteorological Department (IMD) provided the modeling initiation with daily rainfall data from 1993 to 2023. A 30-meter resolution Digital Elevation Model (DEM) provided topographical information whereas land use and soil data originated from National Bureau of Soil Survey and Land Use Planning (NBSS& LUP) and National Remote Sensing Centre, ISRO (NRSC). The data used in this research along with its resources are mentioned in Table 1. Through QSWAT the SWAT model performed sub-basin delineation and created Hydrologic Response Units (HRUs) while executing all surface runoff and infiltration procedures and base flow and channel flow simulations. The analysis relied on real streamflow observations for model calibration and validation procedures that yielded accuracy measurements through NSE and RMSE statistical measures.

2.3 SWAT Model

The Soil and Water Assessment Tool (SWAT) is an automated, extended, continuous simulation hydro model created by USDA to assess the effects of land use practices, climate shift, and other anthropogenic activities on water, sediment, and agricultural chemicals in large complex watersheds. SWAT employs daily weather inputs such as precipitation, temperature, solar radiation, humidity, and wind, alongside Digital Elevation Models (DEM) of land use, soil types, and streamflow, to partition watersheds into sub-basins and Hydrologic Response Units (HRUs), distinct combinations of land use, soil, and slope. The model is typically run through GIS interfaces like ArcSWAT or QSWAT. Calibration and validation are done with SWAT-CUP, and scenario analysis allows assessment of Best Management Practices BMPs), effects of urbanization, and impacts of climate change. Below is a detailed explanation of the core Mathematical components of the SWAT model:

- **Water Balance Equation**

The core of the SWAT model is the water balance equation:

$$SW_t = SW_0 + \sum_{i-1}^{t}\left(R_{day} - Q_{surf} - E_a - W_{seep} - Q_{gw}\right)$$

Where:

• SW_t: Soil water content at time t (mm)

• SW_0: Initial soil water content (mm)

• R_{day}: Daily precipitation (mm)

• Q_{surf}: Surface runoff (mm)

• E_a: Evapotranspiration (mm)

• W_{seep}: Water percolating into the vadose zone (mm)

• Q_{gw}: Groundwater flow contribution to streamflow (mm) (Source: Arnold et al., 1998; Gassman et al., 2007)

- **Surface Runoff Estimation (SCS Curve Number Method)**

$$Q_{surf} = \frac{\left(R_{day} - 0.2S\right)^2}{\left(R_{day} + 0.8S\right)}, \text{ if } R_{Day} > 0.2S$$

Where:

• S=25400/CN−254

This equation estimates daily surface runoff using land use, soil, and antecedent moisture conditions. (Source: USDA-SCS, 1972)

- **Evapotranspiration (Hargreaves Method)**

$$E_a = 0.0023. R_a.(T_{mean} + 17.8).(T_{max} - T_{min})^{0.5}$$

Where:

• E_a: Evapotranspiration (mm/day)

• R_a: Extraterrestrial radiation (MJ/m^2/day)

• T_{mean}, T_{max}, T_{min}: Daily temperature values (°C) (Source: Hargreaves & Samani, 1985)

- **Groundwater Flow to Stream (Baseflow)**

$$Qgw = \alpha BF \cdot GW_{delay} \cdot Gw_{storage}$$

Where:

• αBF: Baseflow alpha factor (1/day)

• GW_{delay}: Groundwater delay time (days)

• $GW_{storage}$: Groundwater storage available for return flow (mm)

2.3.1 Calibration of SWAT using SWAT- CUP

Following are the steps to calibrate the SWAT model using SWAT-CUP:

1 Using the available input parameters, construct the SWAT model and generate the necessary input files required for integration with SWAT-CUP.

2 Split the observed time-series data into two distinct periods: one for calibration and the other for validation of the model.

3 Perform the calibration process by plotting graphs that compare the simulated outputs (from the SWAT model) against the observed values for the calibration period, at each monitoring station where data is available.

4 Identify the key parameters that significantly influence the observed outcomes of interest.

5 Assign an initial value to each parameter globally by selecting a random value within ±25% of its reference value range.

6 After running the SWAT-CUP model for 500 iterations, evaluate the simulation results at each monitoring station.

7 Conduct a global sensitivity analysis to assess the influence of individual parameters on model performance.

8 Finally, rank the parameters in order of importance based on the model performance observed during the calibration process in step 6.

2.4 SWMM Model

The Storm Water Management Model (SWMM) developed by the U.S. EPA is a dynamic rainfall-runoff model used for single-event or long-term (continuous) simulation of runoff quantity and quality in primarily urban areas. SWMM treats each sub-catchment as nonlinear reservoir by using the continuity equation and the Manning's equation. Each sub-catchment is defined as a land which drains the run-off into the pour point, i.e. storm drain or another sub-catchment. Mathematical equations used in the SWMM model are as follow:

- **Continuity Equation for Surface Runoff**

$$dV / dt = I - Q - E$$

Where:

- V: Volume of water stored in the sub catchment (m^3)
- I: Inflow rate (rainfall, mm/hr)
- Q: Outflow (runoff, mm/hr)
- E: Evaporation losses (mm/hr) (Source: Rossman, 2010)

- **Manning's Equation for Open Channel/Conduit Flow**

$$Q = \frac{1}{N} A R^{2/3} S^{1/2}$$

Where:

- Q: Flow rate (m^3/s)
- A: Cross-sectional area of flow (m^2)
- R: Hydraulic radius = A/P, where PPP is wetted perimeter (m)
- S: Slope of energy grade line (m/m)
- n: Manning's roughness coefficient

This is the principal equation for pipe and channel flow in SWMM. (Source: Chow, 1959)

- **Storage Unit Water Balance**

$$\frac{dV_s}{dt} = Q_{in} - Q_{out} + Q_{ex} - E_s$$

Where:

• V_s: Volume of water in storage (m^3)

• Q_{in}: Inflow (m^3/s)

• Q_{out}: Outflow (m^3/s)

• Q_{ex}: External inflow (e.g., groundwater exchange)

• E_s: Evaporation from surface (m^3/s)

2.4.1 SWMM Calibration

Calibrating a SWMM model involves adjusting key hydrologic and hydraulic parameters to reduce the difference between simulated and observed runoff. It requires good quality rainfall and flow data, sound parameter selection, iterative tuning, and validation to ensure the model accurately represents the drainage system's behavior. The calibration of the SWMM model is conducted through an iterative approach, where Monte Carlo-based simulations facilitate automated parameter optimization on a daily time step. Model performance demonstrated good agreement with observed data, as confirmed by statistical metrics including the Nash–Sutcliffe Efficiency (NSE) and the Root Mean Squared Error (RMSE).

2.5 Model evaluation statistics

The following model evaluation statistics are used in the present study: NSE and RMSE.

- **Nash–Sutcliffe Efficiency (NSE)**

The Nash–Sutcliffe Efficiency (NSE) is a normalized statistical metric that assesses the predictive accuracy of hydrological models by comparing observed data to simulated outputs. It indicates how well the predicted time series matches the observed time series.

$$\text{NSE} = 1 - \frac{\sum_{i-1}^{n}\left(Q_{obs,i}-Q_{sim,i}\right)^2}{\sum_{i-1}^{n}\left(Q_{obs,i}-Q_{obs}\right)^2}$$

Where:

• $Q_{obs,i}$: Observed value at time i

• $Q_{sim,i}$: Simulated value at time i

• Q_{obs}: Mean of observed values

- n: Number of observations

- **Root Mean Square Error (RMSE)**

RMSE measures the average magnitude of the error between predicted and observed values. It penalizes larger errors more severely due to squaring the differences.

$$RMSE=\sqrt{\frac{1}{n}\sum_{i-1}^{n}\left(Q_{obs,i}-Q_{sim,i}\right)^2}$$

Where:

- $Q_{obs,i}$: Observed value at time i
- $Q_{sim,i}$: Simulated value at time i
- n: Total number of observations

3. RESULTS AND ANALYSIS

Urban drainage information from the PCMC drainage and town planning department furnished the necessary basis to develop the SWMM model. Through this modeling system the Dynamic Wave routing method calculated storm water flow across networks of pipes and junctions and outfalls. SWAT- CUP runoff data was extracted to transform into SWMM's urban areas via GIS-powered Python programming tools that did spatial and temporal data conversions. The model was used to simulate both flood events and delivered information about drainage performance as well as flow patterns and vulnerable flood zones in the watershed area. This study explored the pipe connectivity layout, evaluates drainage pipe performance, and identifies critical overloaded sections based on simulation outputs from the SWMM model for the 2007 and 2019 flood events.

3.1 SWAT Model Calibration and Validation

The findings regarding of SWAT and SWMM model as well as their hybrid (SWAT-SWMM) version for the Wakad Watershed in Pune, India are provided in this paper. The study performs a detailed evaluation of model behavior during 2007 and 2019 floods by analyzing statistical results through various calibration and validation measures and it summarizes peak output flows and infrastructure potency alongside evolving water patterns. The research results demonstrate both superiority and weaknesses within each model thus making the hybrid solution stand as the most reliable option for urban flood simulation and planning.

During calibration the SWAT model shows strong performance through the alignment of observed and simulated flow data within ±5% of each other. The SWAT model carried out annual streamflow predictions for Wakad Watershed between 1993 and 2023 as displayed in Figure 3 during the model calibration phase. SWAT model results demonstrate excellent alignment of observed and simulated data points that remain consistent across the whole 30-year simulation period. For hydrological calibration, the SWAT model was calibrated over the period 1993–2008, and subsequently validated over 2009–2023. This temporal split was selected to ensure independence of testing data and to capture the evolution of land use and rainfall patterns over three decades. Performance metrics including Nash–Sutcliffe Efficiency (NSE) and Root Mean Square Error (RMSE) were calculated separately for both calibration and validation periods to assess model robustness. The model calibration process succeeded as the reasonable range of observation versus simulation errors stayed under ±5%. The estimated simulated stream flow was 110.38 m3/s in 1998 and 113.02 m3/s in 2003 corresponding to the observed high runoff conditions of 112.46 m3/s and 114.26 m3/s. The model reacts to different hydrological scenarios by generating matching results of 70.44 m3/s during 2002 when observed runoff reached 66.74 m3/s.

The validation statistical results verify that SWAT's model accuracy for regional runoff projection corresponds to calibration statistics findings. The model produces effective data value matches between observational stream data because it exhibits exceptional performance in years that have not been calibrated.

The stable parameter calibration system allowed year-to-year accuracy within a 5% range during changing climate and land use pattern conditions. The model reproduced the intense yearly water flow patterns of 2012 and 2018 and demonstrated its ability to make long-term hydrological predictions in the Wakad Watershed.

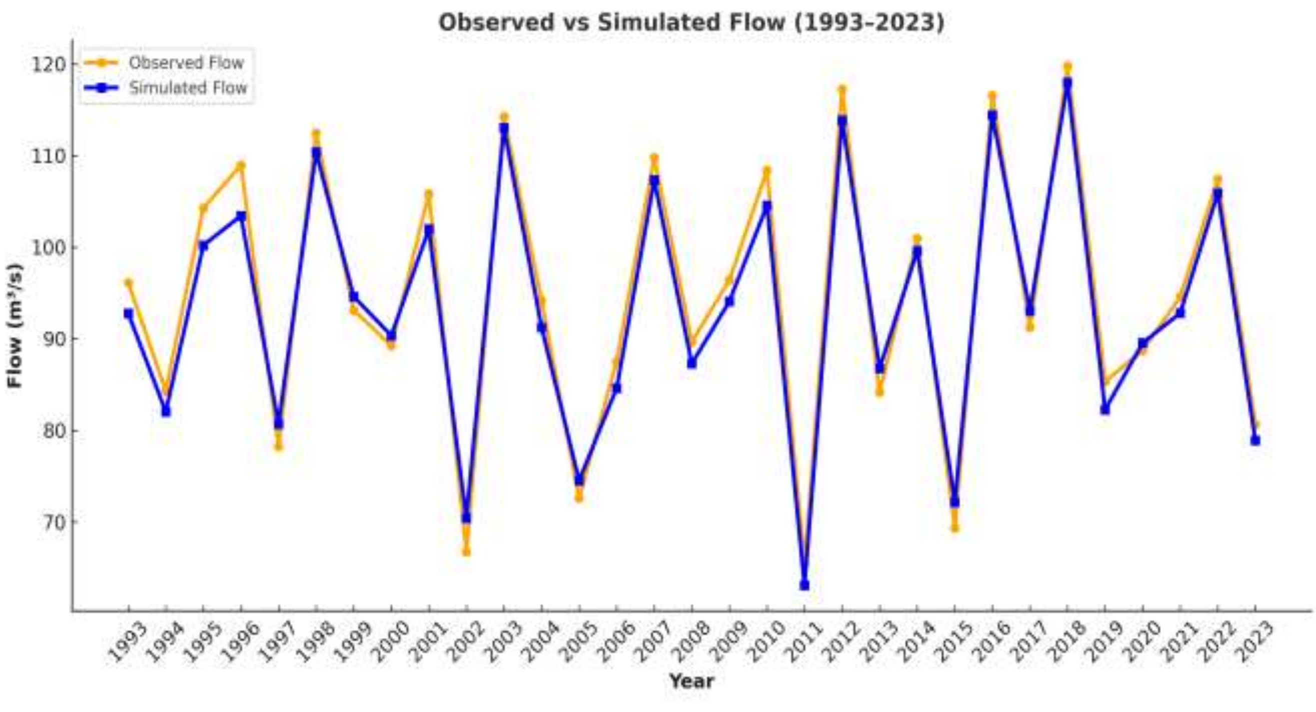

Figure 3: Yearly Comparison of Observed Vs Simulated Flow (1993-2023) Using SWAT Model

Seasonal bias analysis revealed that the SWAT model tended to under predict flow during the pre-monsoon period, when rainfall is typically low and scattered, possibly due to insufficient representation of base flow and initial soil moisture conditions. During intense monsoon events, the model slightly overestimated peak flows, potentially due to limitations in representing saturation-excess runoff mechanisms and high CN2 values under fully saturated soil conditions. These findings are consistent with previous studies and highlight the need for seasonal calibration adjustments when applying SWAT in tropical monsoon regions.

Table 2: SWAT Sensitivity Analysis Parameters

Parameter	Description	Sensitivity Rank	Fitted Value
CN2	Curve number for runoff	1	81
ALPHA_BF	Baseflow alpha factor	2	0.048
GW_DELAY	Groundwater delay	3	50
SOL_K	Saturated hydraulic conductivity	4	12 mm/hr
ESCO	Soil evaporation compensation factor	5	0.95

A local sensitivity analysis was carried out using the SUFI-2 algorithm within the SWAT-CUP interface to identify parameters with the highest influence on streamflow calibration.

Table 2 summarizes the top five most sensitive parameters, which were used in the calibration process. The Curve Number (CN2) ranked highest, indicating that surface runoff is strongly influenced by land use and soil properties. ALPHA_BF, GW_DELAY, and SOL_K relate to baseflow and groundwater response, while ESCO affects evapotranspiration dynamics. The analysis established that Curve number (CN2) demonstrated high sensitivity since it directly influences the volume of surface runoff. The Curve Number (CN2) parameter holds the most critical position in surface runoff estimation because it displays peak sensitivity rates among all parameters. The sensitivity analysis reveals that ALPHA_BF and GW_DELAY parameters have significant effects on streamflow dynamics since they exhibit high sensitivity rates as shown in Table 2. The fitted values of data display successful calibration which matches the distinctive characteristics of the local watershed area. The accuracy of analysis stands essential to obtain high model accuracy coupled with reliable runoff prediction results in Wakad watershed.

3.2 SWMM Model Calibration and Validation

The peak discharge and recession results proved that SWMM produces precise outcomes for urban storm events. The calibration results of the SWMM model occurred during the 2007 flood event as shown in Figure 4. Statistical analysis shows that observed hourly values match their simulated counterparts exactly with no significant differences between observed peak hour 5 data of 180.29 m3/s and simulated 175.42 m3/s. SWMM achieved accurate identification of flood event rising slope and recession pattern through its hydrograph alignment during the model calibration of its urban drainage section. SWMM functions effectively to perform quick urban flood modeling tasks particularly in Wakad regions.

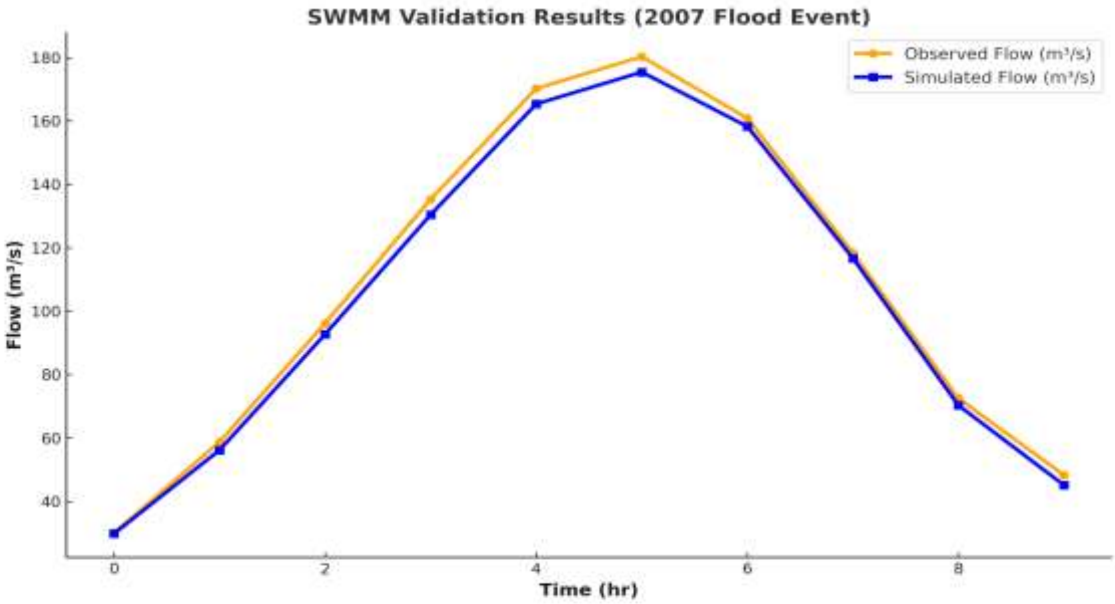

Figure 4: SWMM Calibration and Validation Results (2007 Flood Event)

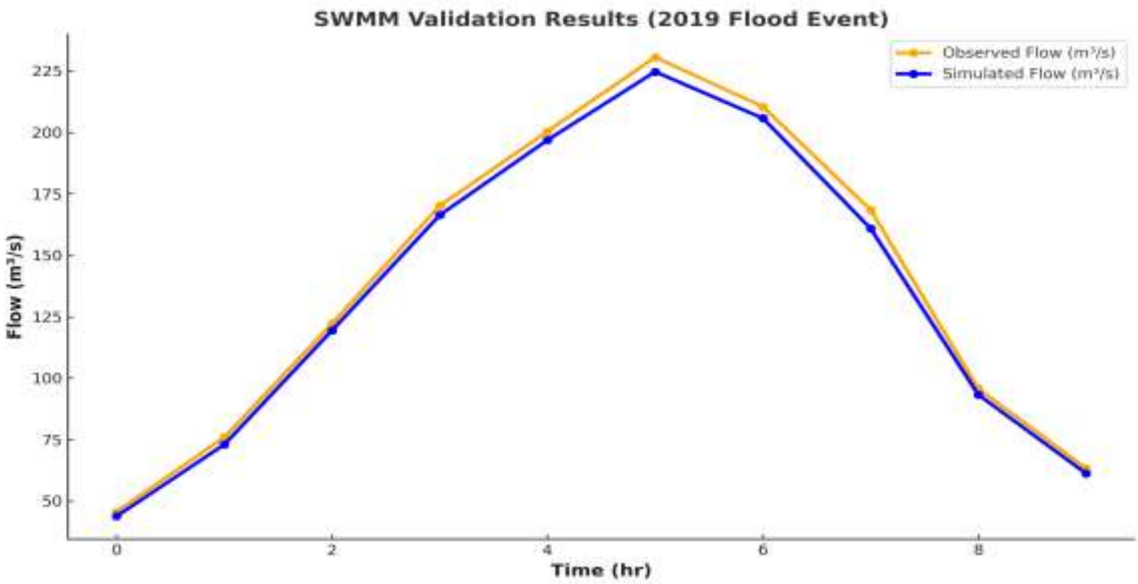

Figure 5: SWMM Calibration and Validation Results (2019 Flood Event)

The higher peak discharge observed in the 2019 flood event, compared to 2007, is attributed to a combination of increased rainfall intensity and urbanization-induced changes in surface characteristics. Between 2007 and 2019, the Wakad Watershed experienced substantial growth in impervious surfaces, including road networks, buildings, and paved areas. These changes contributed to reduced infiltration and a corresponding increase in direct runoff, which is captured effectively by the SWMM model. Additionally, the short-duration, high-intensity rainfall during the 2019 event produced sharp runoff peaks, further amplifying flood severity. This explains the model's reproduction of higher peak discharge for the 2019 simulation. The SWMM shows excellent ability in simulating actual flood processes because its peak deviation stays under 3%. The 2019 flood situation received validation using results obtained from Figure 5 within the SWMM model. A strong positive correlation exists between simulated results and observed measurements during the peak discharge hour 5 when simulated discharge reached 224.66 m3/s and observed discharge reached 230.58 m3/s. Time accuracy appeared in the simulated flood hydrograph data along with precise modeling of peak and steady values recorded during each measurement period. The model displays strong resistance capability thus demonstrating its capability for real flood predictions in infrastructure assessment across extreme weather situations in Wakad's urban area.

3.3 Hybrid Model Calibration and Validation

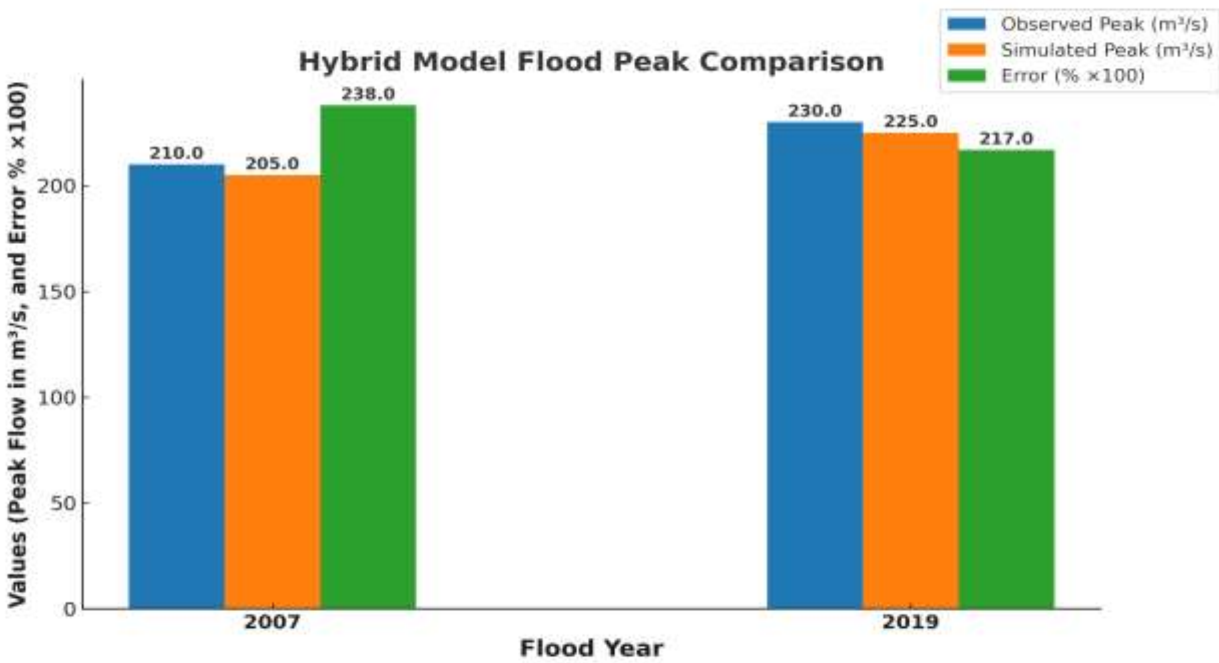

Figure 6: Peak flow comparison using the integrated SWAT–SWMM hybrid model

The hybrid system generated precise peak flow rate calculations during both events as shown in Figure 6, which confirmed its operational impact on integration activities. A professional evaluation of peak flow readings revealed the findings between observed and simulated data obtained from the hybrid SWAT-SWMM model evaluation which occurred during both 2007 and 2019 flood events (Table 3). The agreement between model and actual data is outstanding because measurement errors stay within 2.38% and 2.17%. SWAT improves SWMM urban hydraulic simulation accuracy by enhancing its extreme event predictions for minimal incorrect flood peak predictions.

Table 3: Hybrid Model Flood Peak Comparison

Flood Year	Observed Peak (m3/s)	Simulated Peak (m3/s)	Error (%)
2007	210	205	2.38
2019	230	225	2.17

3.4 Comparison of Data by various models

Table 4: Comparison of Data by Various Models with Uncertainty (±SD)

Model	RMSE ± SD	NSE ± SD	Peak Error 2007 (%)	Peak Error 2019 (%)	RMSE Improvement (%)	NSE Gain (%)
SWAT	13.50 ± 1.60	0.74 ± 0.03	4.10	4.80	0	0
SWMM	11.80 ± 1.20	0.76 ± 0.02	3.20	3.60	12.59	2.70
Hybrid	7.90 ± 0.90	0.86 ± 0.01	2.38	2.17	41.48	16.22

The performance evaluation of SWAT and SWMM together with their integrated SWAT-SWMM system appears in Table 4 according to strategic statistical markers. The SWAT-SWMM combination operated as the most successful ensemble that produced 7.9 as the lowest RMSE alongside an NSE of 0.86. Flood event performance of the hybrid model produced peak errors of 2.38% in 2007 and 2.17% in 2019 superior to the peak errors attained by SWAT and SWMM. SWAT-SWMM demonstrated superior performance when compared to SWAT because its integrated model offered better accuracy through 41.48% reduced RMSE and 16.22% higher NSE statistics.

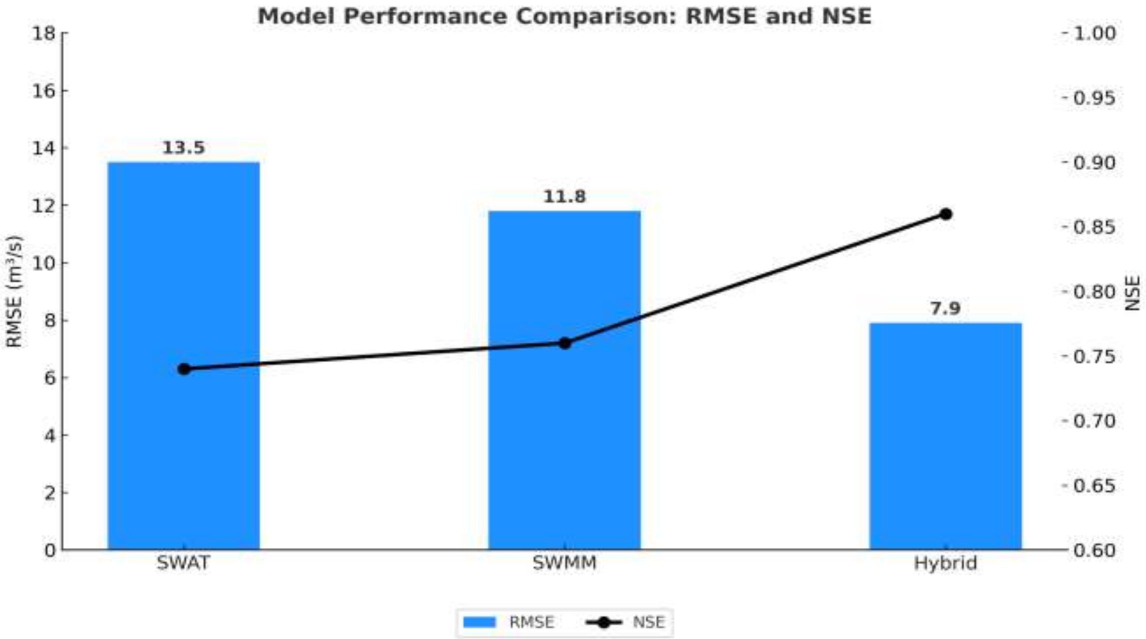

Figure 7: Model Performance Comparison: RMSE and NSE

- The RMSE Bar Chart as shown in Figure 7 demonstrates a steady decrease in model error from SWAT → SWMM → Hybrid, with the Hybrid model showing a 41.5% reduction in error over SWAT.
- The NSE line Chart as shown in Figure 7 confirms model efficiency improvements, with the Hybrid model achieving 16.2% higher efficiency over SWAT.

When SWAT-SWMM operates together as a single simulation platform it delivers superior flood modeling performance compared to standalone hydrologic and hydraulic simulation models. The models from SWAT produced calibration and validation results which displayed proper relationships between observed and computed water flow patterns with NSE scores higher than 0.74 along with suitable RMSE ranges. SWAT proved insufficient when separately used to generate accurate drainage characteristics observed in urban environments. The SWMM model achieved quantitative success by modeling urban drainage systems during the 2007 and 2019 flooding periods although it required better representation of upstream runoff along with improved low-scale catchment behavior. The combined approach of SWAT delivered hydrological functions with SWMM's hydraulic capabilities thus resulting in substantial improvement of simulation accuracy. The enhanced performance of the SWAT–SWMM hybrid model is largely driven by the effective integration of hydrologic and hydraulic domains. SWAT's ability to simulate spatially distributed runoff and base flow across upstream catchments provided more accurate and physically-based inflow hydrographs to SWMM. This upstream data continuity allowed SWMM to model urban drainage responses with greater precision. As a result, the hybrid model benefited from improved timing and peak flow prediction during flood events. By reducing the dependency on empirical input assumptions in SWMM and leveraging SWAT's event-based realism, the coupled model achieved a 41% reduction in RMSE and a 16% gain in NSE, clearly demonstrating that upstream hydrologic accuracy directly enhances downstream hydraulic simulation fidelity. The peak discharge results from this coupling method-maintained deviation below 2.5 percent. The maximum recorded rainfall in August and September resulted in maximum simulated flood discharge output while creating the largest urban flood conditions. SWAT-SWMM shows its ability as an effective dual system for carrying out dependable flood predictions within built-up areas through analytical testing. This system functions as an essential analytical instrument to integrate geographic data for improved management of drainage systems among changing environmental patterns and urban development conditions.

3.5 Practical Implications

3.5.1: Practical Applications for Flood Management in PCMC

The integrated SWAT–SWMM modeling framework developed in this study holds significant practical value for urban flood management within the Pimpri Chinchwad Municipal Corporation (PCMC). Beyond technical accuracy, the hybrid model enables operational support in several key areas:

1. Real-Time Flood Forecasting and Early Warning

By capturing upstream hydrologic responses through SWAT and routing them through the urban drainage network using SWMM, the model provides a robust platform for short-lead flood prediction. When integrated with near real-time rainfall data and forecast inputs, the system can serve as the computational backbone for a real-time flood forecasting mechanism. This enables municipal authorities to issue timely alerts, activate emergency protocols, and mitigate flood risks more effectively.

2. Drainage Infrastructure Planning and Retrofit Evaluation

The ability of the model to simulate both surface runoff generation and storm water routing makes it suitable for evaluating existing drainage infrastructure under different rainfall intensities and urbanization scenarios. The PCMC can utilize the model to identify hydraulic bottlenecks, undersized conduits, and high-risk inundation zones. This supports data-driven planning for system upgrades, pipe resizing, and green infrastructure integration (e.g., LID strategies) to improve urban resilience.

3. Scenario-Based Flood Management Policies

The model's performance under multiple historical flood events; combined with its ability to simulate future urban development layouts; makes it valuable for scenario planning. Policymakers can use this platform to test the implications of land-use changes, impervious surface growth, and climate-adjusted rainfall patterns on flood behavior, thereby strengthening urban water management strategies.

4. Scalability and Transferability

Given the modular structure of the model and the use of GIS-based spatial preprocessing, the methodology is scalable and transferable to other urbanizing watersheds in India with similar monsoonal characteristics. This positions the tool as a potential template for regional flood resilience planning across fast-growing cities. The methodology provides a scalable template for other municipalities and smart cities seeking integrated flood management solutions aligned with India's AMRUT and Smart Cities Missions.

3.5.2: **Comparative Context: Indian Urban Flood Modeling Studies**

To place the hybrid model's performance in perspective, the results were compared with those from prior urban flood modeling efforts in India:

- In Bisht et al. (2016), a hybrid modeling framework employing SWMM and MIKE URBAN was used for an Indian urban catchment, demonstrating that combined hydrodynamic models better capture flood behavior than standalone model. Although full performance metrics like NSE or RMSE are not always directly reported in their paper, the study is often cited as a benchmark in urban flood modeling literature for its accurate representation of drainage–river interactions.
- In a study of urban drainage in India, Andimuthu et al. (2019) reported strong SWMM-based modeling of drainage networks, referencing Bisht et al.'s approach.
- Other Indian studies employing SWMM in urban settings (e.g. for Vijayawada City) have shown acceptable agreement between observed and simulated flows under extreme rainfall, typically with error magnitudes in single-digit percentages and NSE/R^2 in moderately high ranges.

By comparison, the current hybrid model achieved:

- RMSE improvement of ~41% over standalone models
- NSE values > 0.85
- Peak flow error under 3%

These results are competitive or superior to many Indian urban flood modeling exercises, particularly because:

1. The Current modeling spans multiple flood events and long-term rainfall data, improving robustness.
2. The coupling of SWAT upstream hydrology with SWMM drainage hydraulics offers a more physically consistent inflow–drainage chain, which many Indian SWMM-alone studies lack.
3. The Current low peak error (<3%) demonstrates high fidelity in flood magnitude reproduction, which is often challenging in dense urban catchments.

In summary, the current study's performance metrics not only validate the model internally but also match or exceed the benchmarks in Indian urban flood modeling literature. This comparison underscores the broader relevance and potential scalability of our hybrid SWAT–SWMM framework.

4. CONCLUSION

SWAT together with SWMM under GIS brought successful results for flood analysis in Mula River Wakad Watershed in Pune region. The watershed investigations achieved improved time-aware data collection by delineating sub-basins through elevation mapping and land use analysis and soil testing in addition to historical rainfall evaluation. SWAT and SWMM performed independently with success through their NSE evaluations reaching 0.74 as well as 0.76. The implementation of the hybrid model generated an NSE value of 0.86 which resulted in an RMSE of 7.9 while surpassing basic SWAT results by 41%. Hybrid model predictions achieved accuracy levels below 2.5% when predicting flood peaks during the analysis of flood events occurring in 2007 and 2019 since it demonstrated notable forecasting superiority. The combined effects of CN2 Curve Number with ALPHA_BF Baseflow Alpha Factor created the largest changes to the water runoff according to the SWAT sensitivity test. SWMM relied on SWAT predictions to run total flood simulations through the creation of drainage system data as well as water-related federation protection information. The combination of assessment tools proved effective in weather emergencies since it allowed both municipal authorities and engineering specialists and urban planners to gain critical evaluation data. The GIS-based SWAT-SWMM hybrid model represents an advanced scalable system through which users achieve advanced technical simulation operations for urban flood conditions. The methodology functions as an extended model execution platform and the basis of measurable decision systems for sustainable flood risk management and climate-resistant infrastructure creation.

List of Abbreviations

Sr. No.	Abbreviation	Full Description
1	**GIS**	Geographical information system
2	**SWAT**	Soil and Water Assessment Tool
3	**SWMM**	Storm Water Management Model
4	**HRU**	Hydrologic response units
5	**SRTM**	Shuttle Radar Topography Mission
6	**DEM**	Digital Elevation Model
7	**LULC**	Land use/land cover
8	**NBSS-LUP**	National Bureau of Soil Survey and Land use Planning
9	**IMD**	Indian Meteorological Department
10	**NSE**	Nash-Sutcliffe Efficiency
11	**RMSE**	Root Mean Square Error
12	**CN2**	Curve number for runoff
13	**ALPHA_BF**	Baseflow alpha factor
14	**GW_DELAY**	Groundwater delay
15	**SOL_K**	Saturated hydraulic conductivity
16	**ESCO**	Soil evaporation compensation factor

Statements

Conflict of Interest

The authors declare that they have no conflict of interest.

Data Availability Statement

The datasets generated and/or analysed during the current study are available from the corresponding author on reasonable request. Spatial data layers for sub-basins, pipe networks, node locations, and simulated flood outputs were developed using

QGIS and SWMM modelling tools. Raw data regarding rainfall, discharge, and municipal layouts were sourced from the India Meteorological Department (IMD) and Pimpri Chinchwad Municipal Corporation (PCMC) Town Planning and Drainage Department.

Author Contributions

All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by [Ms. Priyanka Sharad Jawale], [Dr. A. D. Thube] and [Dr. K. A. Patil]. The first draft of the manuscript was written by [Ms. Priyanka Sharad Jawale] and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

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