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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 expansion of urban areas has heightened concerns about urban flooding due to increased paved surfaces, aging drainage infrastructure, and rising rainfall intensity. Researchers employed a GIS-driven hybrid modeling approach combining the Soil and Water Assessment Tool (SWAT) and Storm Water Management Model (SWMM) to analyze flood behavior in the Wakad Watershed of the Mula River within the Pimpri Chinchwad Municipal Corporation (PCMC), Pune District, Maharashtra, India. The SWAT model used historical rainfall data from 1993 to 2023 for calibration and validation of hydrological simulations at the catchment level. To simulate urban drainage during the major flood events of 2007 and 2019, SWMM was integrated with the SWAT outputs. Model performance was evaluated using the Nash-Sutcliffe Efficiency (NSE) and Root Mean Square Error (RMSE). The hybrid SWAT–SWMM model showed excellent predictive accuracy, with NSE scores above 0.85 and peak flow estimation errors under 3%. Notably, the combined optimization reduced RMSE by 41%, marking a significant improvement over individual models and emphasizing its suitability for urban flood research. Integrating SWAT and SWMM within a GIS framework provides a powerful decision-support tool for urban planners, water managers, and policymakers. This approach delivers more precise, spatially detailed flood forecasts, supporting proactive drainage planning, climate-resilient infrastructure development, and sustainable resource management in expanding cities.

INTRODUCTION

Modern urban areas face significant flooding challenges due to rapid development and increased impervious surfaces, exacerbated by climate change. Unplanned expansion has disrupted watershed hydrology by generating excessive surface runoff, resulting in higher flood peaks and stormwater surcharge (Ahiablame & Shakya 2016). Conventional modeling approaches often fail to accurately depict the natural interactions between hydrological processes and drainage infrastructure in regions like Wakad, Pune, India. However, integrating Geographic Information Systems (GIS) with hydrologic and hydraulic models can significantly improve the spatial accuracy of urban flood simulations, as noted by Abdul-Aziz and Al-Amin (2016) and Berhanu (2018).

As a fundamental hydrologic modeling system, the Soil and Water Assessment Tool (SWAT) enables nationwide applications by conducting semi-distributed operations across sub-basins and hydrologic response units (HRUs) (Arnold et al. 1998). Within each watershed, SWAT transforms the landscape by creating sub-basins and HRUs that represent various land and soil types. However, SWAT cannot model urban drainage systems or simulate surface flooding in engineered environments. To address this limitation, the model can be integrated with EPA SWMM, which specializes in piped stormwater routing, pipe overpressure management, and floodplain control, thereby extending SWAT's functionality (Rossman 2010).

By integrating SWAT and SWMM, users can achieve a comprehensive analysis of hydrological processes along with real-time observation of city drainage system responses (Babaei et al. 2018). SWAT offers extensive capabilities for long-term simulations of land use and climate change impacts on hydrology, while SWMM is particularly effective in rapidly responding to stormwater system dynamics during heavy precipitation events. (Gao et al. 2020, Akhter & Hewa 2016).

The process of modeling urban floods has become increasingly complex due to the impacts of climate change. Rising rainfall intensities and shifting patterns have rendered historical datasets less reliable for forecasting purposes (DeGaetano & Castellano 2017). According to Ahmad et al. (2016) and Gado et al. (2021), short-duration heavy rainfall events are occurring more frequently across South Asia and Indian territories. Incorporating real-time models necessitates dynamic approaches that integrate climate-adjusted rainfall patterns with urban system responses, as climate conditions continue to evolve. Watershed behavior can be analyzed using SWAT models (Dudula & Randhir 2016), while SWMM effectively assesses drainage system performance during climate-modified storm events (Berggren et al. 2014). However, the integration of GIS-based tools remains infrequent throughout the development of urban centers across India.

The definition of watersheds, land use visualization, and drainage integration with output displays were derived from spatial processing facilitated by GIS, as described by Ghimire et al. (2019). SWAT sub-basin data were combined with SWMM sub-catchment hydraulic system data through GIS tool integration. Birhanu et al. (2016) and Chen et al. (2012) demonstrated that hybrid GIS models provide a reliable framework for simulation and testing of models and data, effectively integrating satellite mapping data with soil databases and precipitation records. Multiple studies emphasize that accurate topographic and land use data are vital for flood prediction, as inaccurate inputs can cause significant variations in the predicted results (Del Giudice & Padulano 2016, Dotto et al. 2010).

Although integrated hydrologic–hydraulic modeling has attracted global interest, its application in Indian urban monsoon conditions remains scarce. Rapid urban growth, intense seasonal rainfall, and inadequate drainage systems result in complex flood behaviors that single-model approaches struggle to capture accurately. This study fills that gap by employing a GIS-based hybrid SWAT–SWMM framework in the Wakad Watershed, showcasing its effectiveness in multievent flood forecasting and sustainable water resource management in monsoon-affected urban environments. Recent floods in Mumbai, Chennai, and Pune, caused by drainage failures, unchecked urbanization, and insufficient warning systems, highlight the need for advanced tools (Bisht et al. 2016). The Wakad area in Pune faced severe rainfall in 2007 and 2019, underscoring the importance of robust simulation and planning tools. Researchers have utilized the SWAT-SWMM framework to improve catchment runoff modeling and urban flood prediction with higher resolution. Accurate analysis of model outputs is crucial, as calibration techniques are necessary to reduce uncertainties. According to Behrouz et al. (2020) and Brun et al. (2001), automatic calibration tools in coupled SWMM and SWAT models enhance their reliability. The flow volumes and peak discharges produced depend heavily on the curve number (CN2) and conduit roughness parameters. This study incorporated a rigorous verification process using historical flood and storm data to ensure model accuracy.

The integration of evidence-based principles within hybrid SWAT-SWMM models yields exceptional results in urban flood simulation. These models combine operational practicality with scientific rigor, as supported by recent reviews. They effectively simulate complex urban flood behaviors, offering a scalable, data-driven approach to flood forecasting and sustainable infrastructure development in monsoon-affected cities. Users can easily implement GIS technologies that produce precise models suitable for operational use. Furthermore, integrated modeling frameworks enhance decision-making by supporting both structural development planning and policy formulation, addressing flood risks in expanding urban areas amidst increasing environmental uncertainties and land demands.

To overcome the limitations of traditional flood models in monsoon-affected urban catchments, this study introduces a GIS-integrated hybrid framework combining SWAT and SWMM. This approach merges catchment-scale hydrological modeling with urban hydraulic simulation. Using Python-based GIS tools, temporally disaggregated hydrographs from SWAT sub-basins were dynamically routed to SWMM subcatchments. The goal was to assess the model's performance under multiple flood events in the Wakad Watershed (PCMC, India), utilizing 30 years of rainfall data (1993–2023) and flood records from 2007 to 2019. Model accuracy was evaluated using NSE and RMSE metrics, comparing the hybrid system against standalone models to enhance flood prediction and drainage response analysis.

MATERIALS AND METHODS

Runoff hydrographs generated from QSWAT were spatially linked to SWMM sub-catchments using GIS shapefiles and temporally disaggregated with a Python-supported workflow to produce hourly inflow series. The SWAT runoff outputs, initially simulated at a daily timestep, were disaggregated into hourly data to meet the temporal resolution requirements of the SWMM model. This process employed rainfall distribution curves from observed monsoon events, preserving flow volume while more accurately representing peak runoff for stormwater drainage analysis.

To enable hydrologic–hydraulic coupling, a semi-automated integration workflow was established between QSWAT and SWMM. This involved three main steps:

1. Hydrograph Extraction from QSWAT: The SWAT model was calibrated at the sub-basin level to simulate daily runoff, which was exported from the QSWAT database (.dbf and .txt formats) and used as inflow data for urban drainage modeling.
2. GIS-Based Spatial Mapping: SWAT sub-basins were overlaid with SWMM subcatchments using GIS software (QGIS), ensuring consistent spatial referencing. Each SWAT sub-basin was matched to the nearest or contributing SWMM subcatchment based on flow direction and drainage boundaries.
3. Python-Assisted Temporal Disaggregation and Formatting: A partially scripted Python routine disaggregated daily SWAT runoff data into hourly time series utilizing rainfall intensity profiles and adjustment factors from observed storm events. The resulting data were formatted into SWMM-compatible INFLOW, INP, or .txt files for direct model import.
4. Model Execution and Validation: The coupled SWAT–SWMM model was executed for flood simulation scenarios corresponding to the 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 the predicted hydrographs against observed flow records at key outfall locations.

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

The schematic in Fig. 1 represents the stepwise integration of the SWAT and SWMM models through a GIS-assisted data conversion process. SWAT outputs (daily runoff hydrographs) were extracted from QSWAT and spatially matched to the urban subcatchments defined

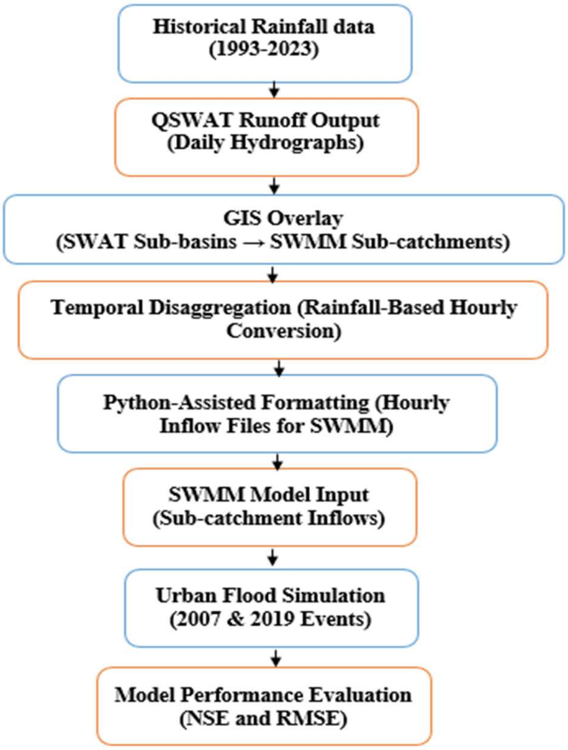

Fig. 1: Workflow for SWAT–SWMM integration via Python-GIS-based data conversion.

in SWMM. Using a Python-assisted workflow, the runoff values were temporally disaggregated to an hourly resolution and formatted into SWMM-compatible inflow files. The processed data were then imported into SWMM for urban-drainage simulations under different flood scenarios.

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 leading to the Bhima River. Wakad has experienced rapid urban development because farmers have transformed their farmland into residential properties, combined with industrial buildings and shopping centers. The expansion of human-made structures has created more waterproof surfaces, causing elevated storm runoff and recurring flooding events in the area. The landscape features 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 the Mula River. The repetitive flood situations from 2007 to 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.

Historically, the watershed has been vulnerable to urban flooding because of inadequate drainage and high runoff coefficients. Flood events have been documented in 2007, 2010, 2013, 2015, and 2016, with major flooding recorded in 2019, caused by intense monsoonal precipitation events

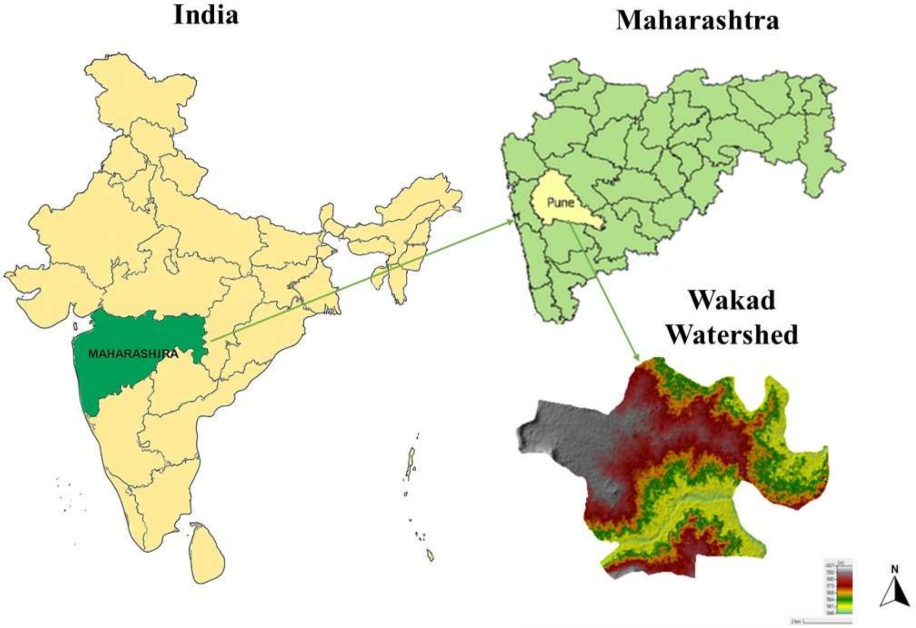

Fig. 2: Study Area Map.

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

and infrastructure bottlenecks along the Pavana and Mula rivers. Most recently, 2023 witnessed local inundations, confirming the ongoing stress on the drainage network in high-density zones in Pimpri-Chinchwad, such as Wakad. The study area is shown in Fig. 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″)

Data Used

This study employs an integrated hydrologic-hydraulic modeling protocol that links SWAT with SWMM and utilizes GIS to forecast urban flooding in the Wakad Watershed, located in Pimpri Chinchwad, a rapidly expanding region of Pune. The project aimed to simulate runoff generation within the catchment area, along with the responses of the urban drainage system during intense rainfall events recorded in 2007 and 2019.

The India Meteorological Department (IMD) supplied daily rainfall data spanning from 1993 to 2023 to initiate the modeling process. Topographical information was obtained from a 30-meter resolution Digital Elevation Model (DEM), while land use and soil data were sourced from the National Bureau of Soil Survey and Land Use Planning (NBSS&LUP) and the National Remote Sensing Center (NRSC) of ISRO. The data sets used, along with their sources, are detailed in Table 1. Using QSWAT, the SWAT model delineated sub-basins and generated Hydrologic Response Units (HRUs), executing surface runoff, infiltration, base flow, and channel flow simulations. Model calibration and validation were performed using observed streamflow data, resulting in accurate measurements validated by the NSE and RMSE statistical metrics.

SWAT Model

The Soil and Water Assessment Tool (SWAT) is an automated, comprehensive hydrological model developed by the USDA to evaluate how land use practices, climate variability, and human activities influence water resources, sediment transport, and agricultural chemicals across large, complex watersheds. SWAT utilizes daily weather data-including precipitation, temperature, solar radiation, humidity, and wind, and integrates Digital Elevation Models (DEMs) of land use, soil types, and streamflow to divide watersheds into sub-basins and Hydrologic Response Units (HRUs), which represent unique combinations of land use, soil, and slope. The model is primarily operated through GIS interfaces such as ArcSWAT or QSWAT. Calibration and validation are conducted using SWAT-CUP, and scenario analysis facilitates the evaluation of best management practices (BMPs), urbanization impacts, and climate change effects. The following provides a detailed overview of the key mathematical components underlying 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 ($mm.day^{-1}$)

R_a: Extraterrestrial radiation ($MJ.m^{-2}.day^{-1}$)

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)

Calibration of SWAT using SWAT-CUP

The 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.

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 a nonlinear reservoir by using the continuity equation and 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 follows:

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, $mm.h^{-1}$)

Q: Outflow (runoff, $mm.h^{-1}$)

E: Evaporation losses ($mm.h^{-1}$) (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 ($m^3.s^{-1}$)

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 ($m.m^{-1}$)

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 ($m^3.s^{-1}$)

Q_{out}: Outflow ($m^3.s^{-1}$)

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

E_s: Evaporation from surface ($m^3.s^{-1}$)

SWMM Calibration

Calibrating the SWMM involves fine-tuning essential hydrologic and hydraulic parameters to minimize discrepancies between simulated and observed runoff. Reliable rainfall and flow data, careful parameter selection, iterative adjustments, and validation are crucial for ensuring the model accurately reflects the drainage system's behavior. The calibration employed an iterative approach, utilizing Monte Carlo-based simulations to optimize parameters automatically on a daily basis. The model's performance showed strong agreement with observed data, as evidenced by statistical metrics such as the Nash–Sutcliffe Efficiency (NSE) and Root Mean Squared Error (RMSE).

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 (Nash & Sutcliffe 1970).

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

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.

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

Where:

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

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

n: Total number of observations

RESULTS AND DISCUSSION

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, 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 deliver information about drainage performance, as well as flow patterns and vulnerable flood zones in the watershed area. This study explored the pipe connectivity layout, evaluated drainage pipe performance, and identified critical overloaded sections based on simulation outputs from the SWMM model for the 2007 and 2019 flood events.

SWAT Model Calibration and Validation

The findings regarding the SWAT and SWMM models, 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 the 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 the Wakad Watershed between 1993 and 2023, as displayed in Fig. 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 m^3.s^{-1} in 1998 and 113.02 m^3.s^{-1} in 2003, corresponding to the observed high runoff conditions of 112.46 m^3.s^{-1} and 114.26 m^3.s^{-1}. The model reacts to different hydrological scenarios by generating matching results of 70.44 m^3.s^{-1} during 2002 when observed runoff reached 66.74 m^3.s^{-1}.

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.

Seasonal bias analysis revealed that the SWAT model tended to underpredict flow during the pre-monsoon period,

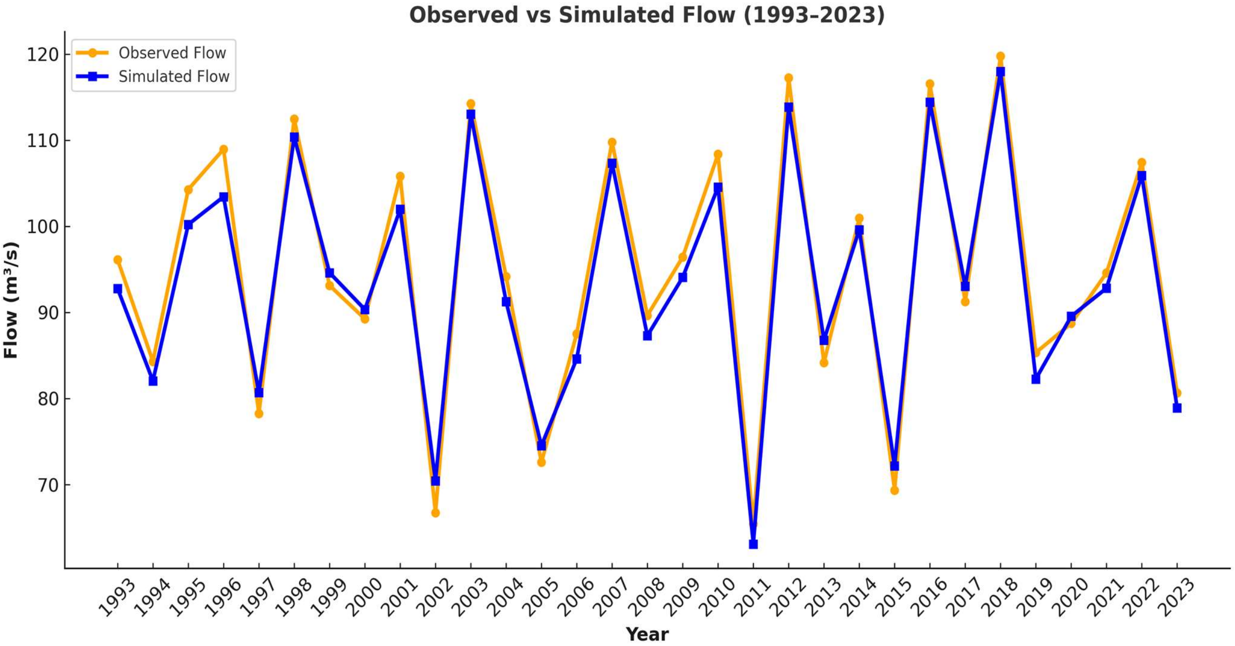

Fig. 3: yearly comparison of observed Vs simulated flow (1993-2023) using SWAT model.

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.h^{-1}
ESCO	Soil evaporation compensation factor	5	0.95

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.

A local sensitivity analysis was carried out using the SUFI-2 algorithm within the SWAT-CUP interface to identify parameters with the strongest 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 the data display successful calibration, which matches the distinctive characteristics of the local watershed area. The accuracy of analysis is essential to obtain high model accuracy, coupled with reliable runoff prediction results in the Wakad watershed.

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 Fig. 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 $m^3.s^{-1}$ and simulated 175.42 $m^3.s^{-1}$. SWMM achieved accurate identification of the 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 the Wakad regions.

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 Fig. 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

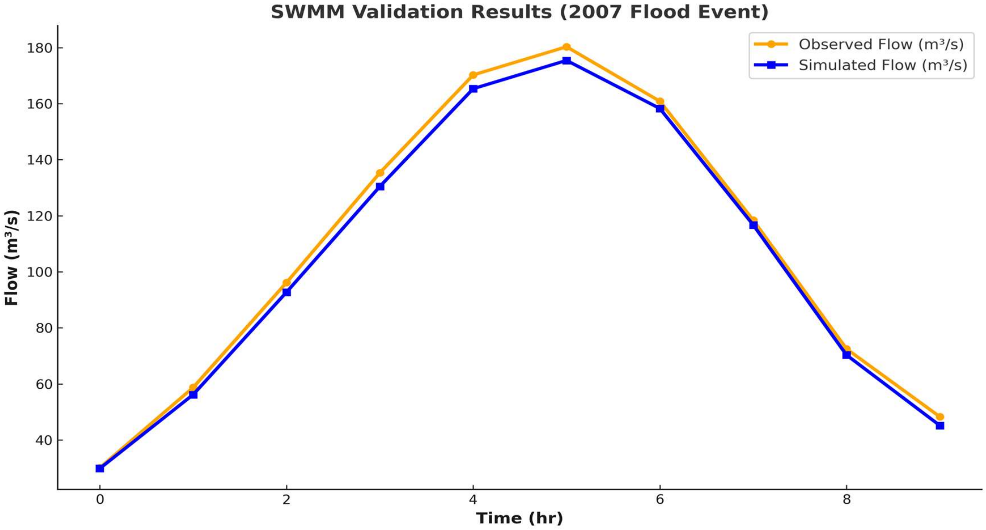

Fig. 4: SWMM calibration and validation results (2007 flood event).

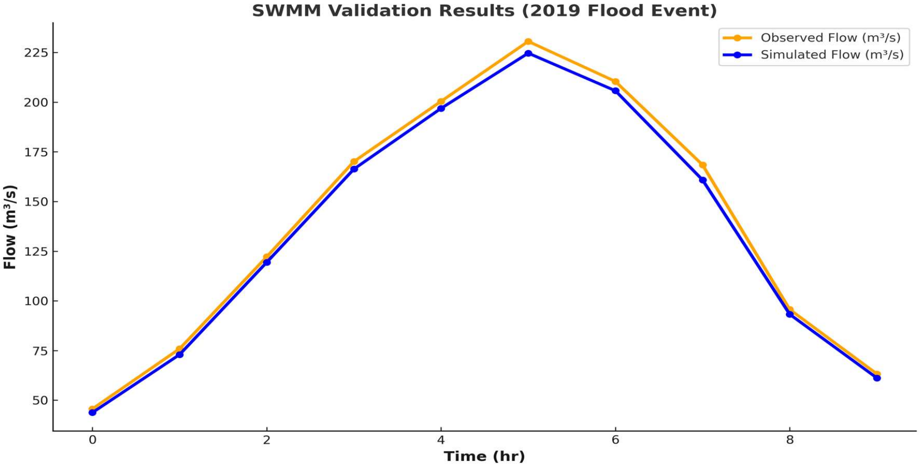

Fig. 5: SWMM calibration and validation results (2019 flood event).

reached 224.66 m3.s^{-1} and observed discharge reached 230.58 m^3.s^{-1}. 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.

Hybrid Model Calibration and Validation

The hybrid system generated precise peak flow rate calculations during both events, as shown in Fig. 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.

Comparison of Data by Various Models

The performance evaluation of the 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.

- The RMSE Bar Chart, as shown in Fig. 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.

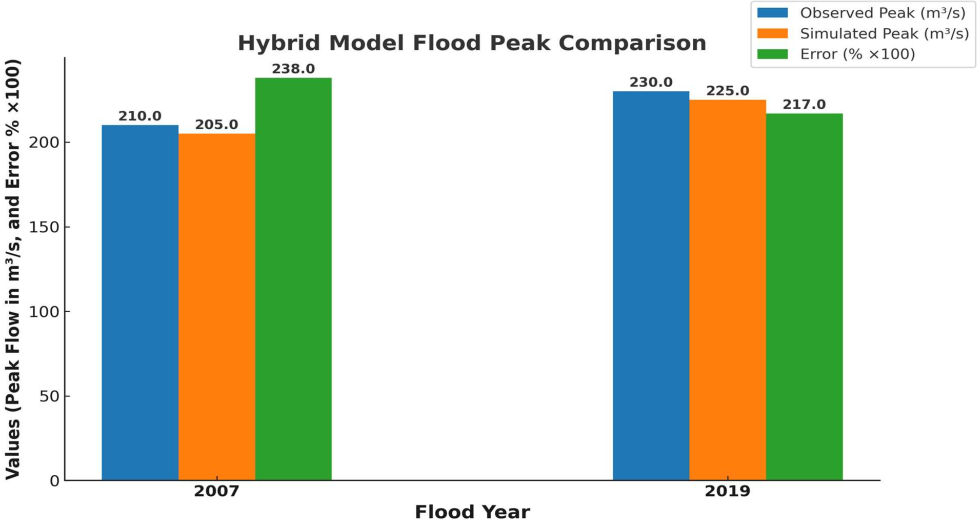

Fig. 6: Peak flow comparison using the integrated SWAT–SWMM hybrid model.

Table 3: Hybrid model flood peak comparison.

Flood Year	Observed Peak [m^3.s^{-1}]	Simulated Peak [m^3.s^{-1}]	Error [%]
2007	210	205	2.38
2019	230	225	2.17

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

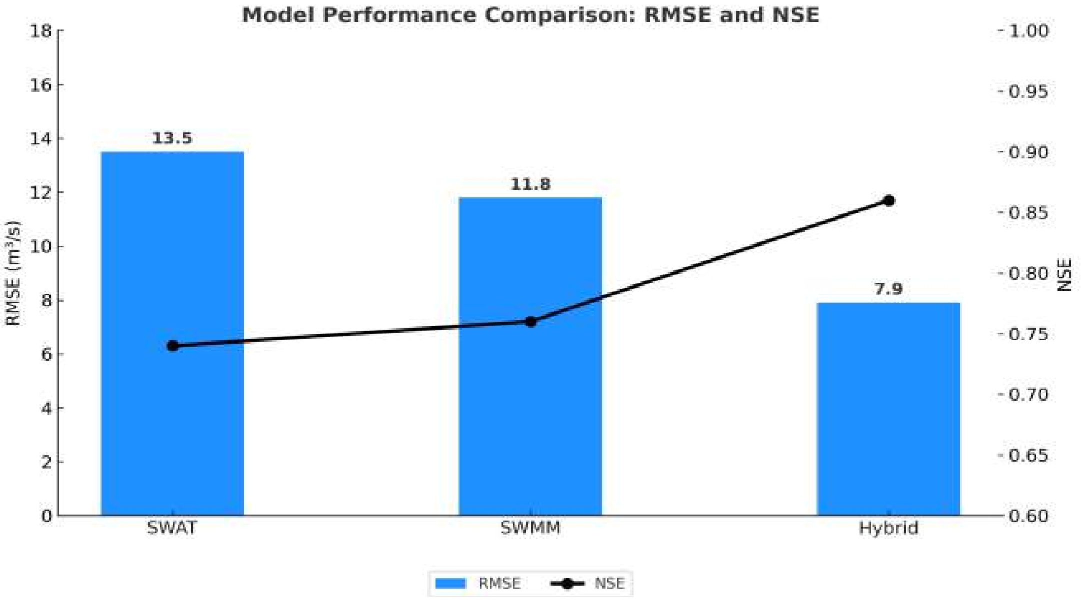

Fig. 7: Model performance comparison: RMSE and NSE.

- The NSE line chart, as shown in Fig. 7, confirms model efficiency improvements, with the Hybrid model achieving 16.2% higher efficiency over SWAT.

When operated together as a unified simulation platform, SWAT and SWMM deliver superior flood modeling performance compared to standalone hydrologic and hydraulic models. The SWAT models demonstrated reliable calibration and validation results, showing proper correlations between observed and simulated water flow patterns, with NSE scores exceeding 0.74 and appropriate RMSE ranges. However, SWAT alone proved insufficient for accurately capturing urban drainage characteristics. Conversely, SWMM successfully modeled urban drainage during the 2007 and 2019 floods, though it required improved representation of upstream runoff and low-scale catchment behavior. The integrated approach combined SWAT's hydrological functions with SWMM's hydraulic modeling, significantly enhancing simulation accuracy. This integration, driven by SWAT's ability to simulate spatially distributed runoff and base flow across upstream catchments, provided more accurate, physically-based inflow hydrographs to SWMM. The continuity of upstream data enabled SWMM to simulate urban drainage responses more precisely, resulting in better timing and peak flow predictions during flood events. By minimizing reliance on empirical assumptions in SWMM and utilizing SWAT's event-based realism, the coupled model reduced RMSE by 41% and increased NSE by 16%, demonstrating that accurate upstream hydrology directly improves downstream hydraulic simulation. Peak discharge estimates from this coupling maintained deviations below 2.5%. The maximum recorded rainfall in August and September led to peak flood discharges and the largest urban flood conditions in simulations. Overall, SWAT-SWMM proves to be an effective dual system for reliable flood predictions in urban areas, serving as a vital tool for integrating geographic data to improve drainage management amid changing environmental and urban development conditions.

Practical Implications

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:

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.

Drainage infrastructure planning and retrofit evaluation: The ability of the model to simulate both surface runoff generation and stormwater 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.

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.

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.

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 a 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.

CONCLUSION

SWAT, together with SWMM under GIS, brought successful results for flood analysis in the Mula River Wakad Watershed in the Pune region. The watershed investigations achieved improved time-aware data collection by delineating sub-basins through elevation mapping, 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 and 0.76, respectively. 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 the CN2 Curve Number with the 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 flood protection information. The combination of assessment tools proved effective in weather emergencies since it allowed both municipal authorities, 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.

ABBREVIATIONS

Abbreviation	Full Description
GIS	Geographical information system
SWAT	Soil and Water Assessment Tool
SWMM	Storm Water Management Model
HRU	Hydrologic response units
SRTM	Shuttle Radar Topography Mission
DEM	Digital Elevation Model
LULC	Land use/land cover
NBSS-LUP	National Bureau of Soil Survey and Land Use Planning
IMD	Indian Meteorological Department
NSE	Nash-Sutcliffe Efficiency
RMSE	Root Mean Square Error
CN2	Curve number for runoff
ALPHA_BF	Baseflow alpha factor
GW_DELAY	Groundwater delay
SOL_K	Saturated hydraulic conductivity
ESCO	Soil evaporation compensation factor

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