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ORIGINAL ARTICLE

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Hydrological Modeling for Environmental Flow Estimation under Data-Scarce Condition

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ABSTRACT

Estimating environmental flows is crucial for mitigating anthropogenic impacts and restoring their ecological functions; however, such assessments remain challenging, particularly in data-scarce and regulated basins. This study addresses this gap by estimating environmental flows for the Sankh River (4,027.4 km²), a regulated and hydrologically data-limited tributary in eastern India, using an integrated Soil and Water Assessment Tool (SWAT)– Global Environmental Flow Calculator (GEFC) modeling framework. Despite its widespread use, the SWAT-GEFC approach is limited in small- to medium-sized Indian basins, especially in ecologically sensitive and under-monitored rivers such as the Sankh. The SWAT model performed satisfactorily in simulating streamflow, as evidenced by the test statistics obtained during calibration and validation (NSE: 0.81 and 0.90; R^2: 0.81 and 0.92; RSR: 0.44 and 0.32, respectively). To assess ecological flow requirements, the GEFC was used to derive environmental flow regimes through Flow Duration Curves (FDCs) and Environmental Management Classes (EMCs). Results indicate a systematic decline in Mean Annual Runoff (MAR) allocations from EMC “A” to “F”, with SWAT-simulated values (39.5 to 0.9%) closely matching with the observed trends (47.1 to 1%), thereby supporting the model robustness. Seasonal analysis identified December and January as the most flow-stressed months, with a minimum ecological flow threshold of 5.72 $m^3 s^{-1}$ required to sustain riverine health. The findings offer practical benchmarks for integrating environmental flows into reservoir management, regional water allocation, and policy planning, particularly within the framework of India's National Water Policy (2012). Integrating hydrological modeling with ecological considerations can lead to sustainable river management. Future research should integrate habitat simulation models and climate-change-driven flow scenarios to support resilient and adaptive environmental flow management.

1 | INTRODUCTION

Disruption of the river's natural flow, especially downstream, threatens aquatic habitats, water quality, ecosystems, and local stakeholders relying on the river. This mainly results from non-compliance with environmental flow regulations, which were inadequately addressed during project planning. Environmental flows (E-flows) replenish groundwater and support ecosystems, benefiting all flow aspects-high, medium, and low. Low flows maintain river connectivity and water quality; medium flows aid fish development and migration; high flows are vital for channel flushing, flooding, and riparian vegetation. Although E-flows are recognized as valuable by water planners, they are often overlooked in practice, possibly due to a lack of discharge data (Arthington *et al*., 2023).

A 2003 global survey showed 88% of respondents saw environmental flow assessment as vital for sustainable water management. The Brisbane Declaration (2007), backed by over 750 practitioners from 50+ countries, reinforced this. By 2010, many nations adopted environmental flow regulations, but practical implementation remains limited. In India, despite advances, implementation is still early (Acreman *et al*., 2014). India has nine of the 30 priority river basins for aquatic biodiversity, mostly affected by flow regulation. Recognizing environmental flows as key in water management is growing (Bussettini, 2018). Approaches to flow assessment include Standard-Setting, which prescribes fixed flows, and Incremental methods that assess habitat responses via field data (Dunbar *et al*., 1998). Tharme and Smakhtin (2003) classify methods as hydrological, hydraulic, habitat-simulation, and holistic. Hydrological methods, used in data-limited basins, rely on discharge records and often use flow duration curves or express e-flows as a proportion of mean flow.

After reviewing hydrology-based techniques, Smakhtin and Anputhas (2006) proposed an FDC-based strategy linking e-flow needs to Environmental Management Classes (EMCs). This approach is used in applications like the Global Environmental Flow Calculator (GEFC), which uses FDC–EMC analysis to recommend flows based on duration and ecology (Kumar *et al.*, 2021). Rivers are categorized into EMCs based on ecological and management needs. Researchers like Govind *et al*., (2024) combined the Sustainable Management of Hydrological Alteration with Bayesian Belief Networks and FDC analysis. Kumar and Jayakumar (2020) studied dam impacts on hydrology and flow. Gleeson *et al*., (2020) offered methods for estimating flows in data-scarce regions. These studies highlight the importance of environmental flows for ecosystems and communities (Sahoo *et al*., 2016).

The SWAT–GEFC approach has been used globally to estimate environmental flows in regulated and unregulated rivers (Smakhtin & Anputhas, 2006; Gleeson *et al*., 2020). Later studies confirmed its usefulness in reconstructing natural flow patterns, evaluating flow changes, and aiding environmental flow decisions with limited data (Kumar & Jayakumar, 2020; Govind *et al.*, 2024). These studies show that the framework can combine hydrological models with flow-duration ecological classification, enabling flow assessments even without long-term pristine data. While widely used, SWAT-GEFC's application in small to medium Indian basins, especially ecologically sensitive and under-monitored rivers like the Sankh, is limited. This method is particularly relevant for the Sankh River basin, which has significant flow regulation, seasonal variability, and limited data. The basin faces increasing pressures from mining, deforestation, and water abstraction but lacks prior environmental flow assessments or ecological thresholds (JSPCB, 2019; Sharma & Singh, 2024). In these data-scarce, regulated contexts, relying only on observed flow data may underestimate ecological water needs. By combining SWAT-predicted natural flows with GEFC-based ecological classifications, this study provides a scientific basis for defining suitable flow regimes, tailored to the Sankh's conditions. This approach demonstrates the transferability of the SWAT-GEFC framework to less-studied rivers and offers a model for regulated Indian rivers lacking flow or ecological data monitoring.

SWAT has been used to assess ecological flow and water shortages in basin-scale hydrology, linking simulated flows with environmental flow methods (Fang *et al.*, 2025). It is also applied in ecosystem services like water yield, soil retention, and flow regulation under changing environments (Zhao *et al.*, 2024). SWAT+ improves streamflow simulations under climate change scenarios in regulated basins (Mishra *et al.,* 2025). The model helps simulate hydrological balance and component distribution, such as in Wadi Mina (Mebarki *et al.*, 2024). The SWAT model has been used across various hydrological environments (Singh, 2015). This study focuses on the Sankh River, originating in Gumla, Jharkhand, flowing through Odisha and Jharkhand, and joining the South Koel River to form the Brahmani River. Its environmental flow is estimated using the Global Environmental Flow Calculator (GEFC), which uses hydrological data and FDC analysis. In data-scarce conditions, flows are determined by applying GEFC to SWAT-simulated and observed data. Unlike earlier large-basin studies, this research applies SWAT–GEFC to the ecologically sensitive, regulated, and data-scarce Sankh River basin, a tributary of the Brahmani system in Eastern India.

HIGHLIGHTS

- A coupled SWAT–GEFC framework enables environmental flow estimation in regulated, data-limited basins.
- Consistent MAR reduction across EMC classes (A–F) confirms close agreement between simulated and observed flows.
- The methodology is adaptable for reservoir operation and environmental flow planning in India.

2 | MATERIALS AND METHODS

2.1 | Study Area

The Sankh River lies between latitudes 22°0' N and 23°17' N and longitudes 83°55' E and 84°46' E. It originates at an elevation of 1,020 meters above sea level in Lupungpat village of Gumla district, Jharkhand. The river flows approximately 67.5 km within the state before entering Chhattisgarh. Along its course, it passes through the districts of Gumla and Simdega in Jharkhand and Jashpur in Chhattisgarh. When it enters Odisha's Sundargarh district, the Sankh River joins the South Koel River at Vedvyas, near Rourkela, where the combined flow is called the Brahmani River. The catchment area of the Sankh River Basin (SRB) before entering Odisha is about 4,027.4 km², with an additional 1,319 km² within Odisha (Malik, 2014). The region receives an average annual rainfall of around 1,460 mm, mainly during the southwest monsoon from June to October. Three major irrigation projects — the Upper Sankh Reservoir Project, Ramrekha Reservoir Project, and Kansjore Reservoir Project — are located along the river. They provide irrigation coverage of approximately 7.07, 4.39, and 6.26 thousand hectares, respectively, and play a key role in regional economic growth (Fig. 1). Two main canal systems covering a Culturable Command Area (CCA) of 7.069 thousand hectares are positioned on the left and right banks of the river.

2.2 | Data Preparations

NASA's POWER program provided meteorological datasets for 1998–2021, including temperature, humidity, solar radiation, wind, and precipitation. Bias correction was not applied due to lack of long-term in-basin observations; uncertainties were addressed through SWAT calibration and sensitivity analysis. Discharge data from the Tilga gauge station (2001–2021) was provided by the Central Water Commission, Bhubaneswar. A 30-m DEM from SRTM was used for watershed delineation and stream generation. Land use/cover data were derived from Landsat-8 imagery at 30-m resolution, soil data from FAO's database at ~1 km (Table 1). All datasets were projected to a common coordinate system and resampled to DEM resolution before HRU definition in SWAT. Variations in land use, soil, and slope were represented through HRU discretization within sub-basins. Data was projected to Zone-45 N, UTM 1984. LULC maps were created using the support vector machine (Chowdhury, 2024), a robust machine learning algorithm for classifying land features (Jamsran *et al.*, 2019).

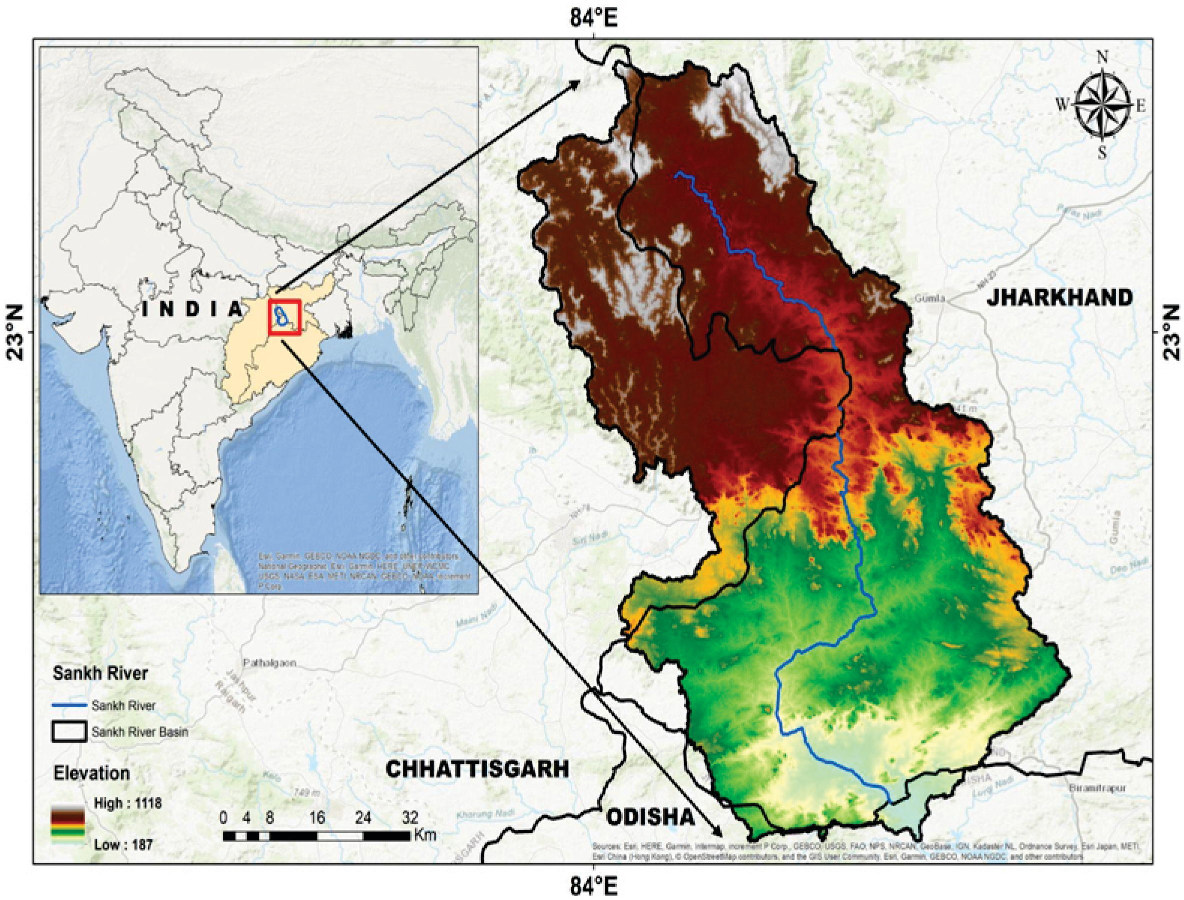

FIGURE 1 Geographical location of the Study area

2.3 | SWAT Model Development, Calibration and Validation

The SWAT model is a freely available, physically based model utilised globally to assess the impact of different land management practices on water flow, soil erosion, and chemical runoff in large and complex watersheds (Singh *et al.*, 2012). It operates continuously over time and calculates the water balance for each Hydrologic Response Unit (HRU), combines it at the sub-basin level, and then sends it to the basin outlet via the stream network. To accurately model the hydrological processes, each HRU is handled separately (Piniewski *et al.*, 2017).

Four HRUs were created across the entire catchment based on slope, soil type, and land use. This was done by overlaying LULC, soil, and DEM maps. The SWAT 2012 version with an ArcGIS interface (ArcSWAT 2012.10.5.24) was used to simulate river discharge. The model simulates streamflow using a water balance equation that depends on rainfall and temperature.

The equation is :

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

where,
SW_t and SW_0 reflect the final and initial soil moisture levels,
P_{day} represents daily precipitation,
R_{surf} is surface runoff,
ET_{day} is daily evapotranspiration *(ET),*
W_{seep} is GW seepage, and
R_{gw} is GW return flow

All values are in mm. The following formula is used by the model to estimate surface runoff using the SCS-Curve Number method:

$$Q = \frac{(P - I_a)^2}{(P - I_a) + S} \qquad ...(2)$$

where,
Q = runoff depth (mm),
S = maximum retention potential,
I_a = water abstraction (initial) (mm), and
P = effective precipitation (mm).

Evapotranspiration was calculated with the Penman-Monteith (PM) method. The SWAT model was calibrated and validated using SWAT-CUP with the SUFI-2 algorithm, which provides a framework for automatic calibration, sensitivity analysis, and uncertainty quantification via Monte Carlo simulations (Abbaspour, 2015). SUFI-2 accounts for model uncertainty and observational errors by generating and refining multiple parameter sets. Calibration spanned 2001–2015, validated for 2016–2021, using monthly discharge data from the Tilga gauge station. A three-year warm-up (1998–2000) initialized conditions (Kumari *et al.*, 2024). The process included 1000 simulations, with model performance assessed by NSE, R^2, PBIAS, and RSR (Singh *et al.*, 2012). Sensitivity analysis used key hydrological parameters identified from prior studies on SWAT modeling in Indian basins (Rahman et al., 2022), focusing on those influencing streamflow and groundwater. Details are in (Table 2). To strengthen future calibration, using local sensitivity analysis methods like the Morris method is recommended. This global, one-at-a-time screening tool examines parameter influence by exploring elementary effects with low computational effort (Campolongo *et al.*, 2007). Combining such methods with SUFI-2 can identify key local basin parameters, reduce model uncertainty, and improve predictions. Morris-based screening would supplement the current literature approach and support more reliable environmental flow estimates in data-scarce, regulated basins like the Sankh.

TABLE 1 Summary of datasets used in the study

Dataset	Description	Source
Meteorological	Tmax and Tmin, relative humidity, solar radiation, wind speed, precipitation.	NASA Power
Hydrological	Discharge data from Tilga rain gauge station	CWC Bhubaneswar
DEM	30 m resolution	USGS SRTM
LULC map	2021	Landsat-8
Soil map	1km resolution	FAO

2.4 | Environmental Flow Estimation

Smakhtin and Anputhas (2006) evaluated several hydrology-based techniques for evaluating environmental flows and their applicability in India (Table 3). They developed an approach that combines FDCs with EMCs. The GEFC is open-source software created by the International Water Management Institute. The GEFC uses flow duration curves and EMCs. To analyse environmental flows, GEFC model requires monthly discharge data from rivers for an extended length of time (Kumar & Jayakumar, 2020).

To determine environmental water requirements, the first step is calculating the FDC for sites. Source sites have flow data; destination sites need FDC and time series estimates for EF. The FDC approach used flow values at various exceedance probabilities (0.01% to 99.9%), representing flow variability. FDCs were derived from data from 2001-2021, using nearby upstream site data. Environmental flows aim to maintain or restore river ecosystems, classified as EMCs (A to F). Higher EMCs (e.g., Class A) need more water, while lower classes indicate more human impact. The reference FDC is later adjusted to determine EMCs. After determining the FDC from observed and SWAT data, it was converted into an average monthly flow series.

TABLE 2 Model parameters used for sensitivity analysis

Parameters	Description	Min_Value	Max_Value
r_CN2.mgt	SCS runoff curve number	-0.531206	-0.178936
v_ALPHA_BF.gw	Base flow alpha factor (days)	0.000000	0.000002
v_GW_DELAY.gw	Groundwater delay (days)	1.792297	50.562866
v_GWQMN_gw	Threshold depth of water in the shallow aquifer required for return flow to occur (mm)	250.431952	1000.634944
v_GW_REVAP.gw	Groundwater revap coefficient	0.115274	0.135258
v_ESCO.hru	Soil evaporation compensation factor	0.710739	0.746337
v_CH_N2.rte	Manning coefficient for main channel	0.001182	0.076940
v_CH_K2.rte	Effective hydraulic conductivity of the channel (mm hr^{-1})	0.045151	0.951453

continued on next page

table 2 continued

v_ALPHA_BNK.rte	Base flow alpha factor for bank storage	0.074282	0.271848
r_SOL_AWC(..).sol	Available water capacity of soil layer (mm H_2O mm soil^{-1})	-0.616933	-0.444881
r_SOL_K(..).sol	Saturated hydraulic conductivity (mm hr^{-1})	0.063346	0.207018
r_SOL_BD(..).sol	Moist bulk density	0.168974	0.927353
v_SFTMP.bsn	Snowmelt base temperature (C^0)	0.719767	5.310936
v_SURLAG.bsn	Lag time for surface runoff (days)	0.138594	0.950639

TABLE 3 EMCs Classes (Smakhtin & Anputhas, 2006)

EMC	Ecological Description	Management perspective
A: Natural	Original state or least alteration in river stream and riparian territory.	Applied for safeguarded rivers and basins, Natural reserves, and parks. No new water projects, such as dams, canals, or deviations, are allowed.
B: Slightly modified	Mostly unbroken biodiversity & altered habitats despite water resources expansion and basin amendments.	Agricultural development and water supply structures are present or tolerable.
C: Moderately modified	The environments and dynamics of the changed biota are a concern, but basic ecosystem functions remain. Some sensitive species are lost or diminished, and alien species are present.	Several problems and complexities belong with the requirement of socio-economic development projects (Dams and decline in water quality)
D: Largely modified	Big alterations and modifications in basic natural ecosystems/ habitats have occurred. Species and their population were found to be less than expected. Species that have low tolerance levels are found in much lower numbers. Alien species prevail	Potential and observable problems attached to various water supply and resource development programs (including dams, diversions, transfers, habitat modification, and water quality degradation)
E: Seriously modified	Diversity in habitat was found to have declined extensively, with species richness at a minimum; intolerant species vanished, and only tolerable species remained. Indigenous species in ecosystems are unable to breed. Alien species have almost overtaken the ecosystem	Very high human population density and extreme exploitation of water resources.
F: Critically modified	Modifications have reached a critical level, and the ecosystem has been completely altered, with almost total loss of natural habitat and biota. In the worst case, the basic ecosystem functions have been destroyed, and the changes are irreversible	This status is unacceptable from management's perspective. Management interventions are necessary to restore flow patterns, river habitats, etc. (if still possible/feasible) – to 'move' a river to a higher management category.

3 | RESULTS AND DISCUSSION

3.1 | SWAT Model

The yearly hydrological water balance of the watershed was calculated and compared with observed data. (Fig. 2) shows the observed and simulated discharges during calibration and validation periods, along with their corresponding scatter plots. The calibration and validation periods achieved R^2 values of 0. 82 and 0. 92, respectively. The model results are highly convincing, as indicated by NSE values of 0. 81 during calibration and 0. 90 during validation. The SWAT model was calibrated and validated using the SUFI- 2 algorithm in SWAT- CUP, with 1, 1000 Monte Carlo simulations per iteration over three calibration cycles, allowing parameters to be refined progressively and model fit to improve. The 95 PPU was assessed using the P-Factor (percentage of observed data within the uncertainty band) and R- factor (average thickness of the band normalized by the observed data standard deviation), ensuring a balance between predictive accuracy and uncertainty. The SUFI- 2 calibration and uncertainty analysis setup used in this study is detailed below and in Appendix 1. Table 4 summarizes statistical results, while Table 5 lists the calibrated SWAT parameters. Additionally, the low RSR values of 0. 44 and 0. 32 further support the SWAT model' s effectiveness, indicating minimal differences between observed and simulated data. Collectively, these results confirm the reliability of the model outputs for water resource management in the Sankh river basin. The model' s PBIAS values of- 8. 9 and- 19. 1 suggest that, on average, the model slightly overestimates observed values by 8. 9% during calibration and 19. 1% during validation. The robustness of the SWAT results improves our understanding of the basin' s hydrology and aids in sustainable water planning. The catchment is forested, as reflected by the average curve number of 35. 02. Discharges over 250 m ^{3}/s were not accurately simulated, especially in 2001 and 2011, though lower flows were modeled more precisely. This mismatch may stem from antecedent moisture conditions. The model assumes a constant soil storage capacity, but in reality, heavy rainfall events can increase infiltration. The static soil storage capacity may therefore cause inaccuracies during high-discharge events, as it does not reflect dynamic field conditions.

Although the SWAT model demonstrated generally satisfactory performance, the validation phase revealed a relatively high PBIAS of -19.1%, indicating that the model tends to overpredict streamflow compared to observed data. NSE, R^2, and RSR are primarily influenced by the model's ability to reproduce flow variability and peak discharges, as these metrics emphasize larger deviations that typically occur during high-flow events. In contrast, PBIAS is influenced by the cumulative water balance and indicates systematic over- or underestimation of total runoff volume throughout the simulation period. This consistent overestimation could lead to inflated environmental flow (e-flow) values, particularly under low-flow Environmental Management Classes (EMCs), where precision is essential. Despite this bias, the NSE (0.90) and R^2 (0.92) values suggest strong agreement and predictive accuracy. Nonetheless, the level of bias warrants additional statistical analysis to confirm the reliability of e-flow estimates.

A paired t-test on monthly observed and simulated discharge values (n=12) showed a mean difference of 3.12 cumecs, a standard deviation of 27.49, and a t-statistic of 0.39 with 11 degrees of freedom. The p-value (0.702) exceeds 0.05, indicating no significant difference at 95% confidence. Despite a negative PBIAS, the model is statistically sound for estimating monthly flows, capturing patterns and seasonality (high NSE/R^2). Its positive bias may lead to overestimation of e-flow volumes in lean months if used directly, especially under altered scenarios like EMC "E" or 'F,' which could cause conservative ecological recommendations. Future improvements like bias correction or multi-model ensembles are recommended to reduce uncertainty and enhance accuracy in data-limited conditions (Table 6).

TABLE 4 Summary statistics for the calibration and validation period

Statistic	Calibration period (2001-2015)	Validation period (2016-2021)
NSE	0.81	0.90
R^2	0.81	0.92
RSR	0.44	0.32
PBIAS	-8.9	-19.1

TABLE 5 SWAT model parameter and their calibrated values

Parameter	Calibrated value	Parameter	Calibrated value
CN2	38.37	GW_REVAP	0.13
SOL_AWC	0.04	ESCO	0.71
SOL_K	12.31	CH_N2	0.04
SOL_BD	2.49	CH_K2	0.22
ALPHA_BF	0	ALPHA_BNK	0.10
GW_DELAY	8.49	SFTMP	3.86
GWQMN	996.50	SURLAG	0.52

TABLE 6 Summary of Paired t-Test

Parameter	Value
Number of Observation (n)	12
Mean Difference (Observed-Simulated)	3.12 cumecs
Standard Deviation of Differences	27.49 cumecs
Standard Error	7.94 cumecs
t-statistic	0.39
Degree of freedom (df)	11
p-value (two-tailed)	0.702
Statistical Significance	Not significant

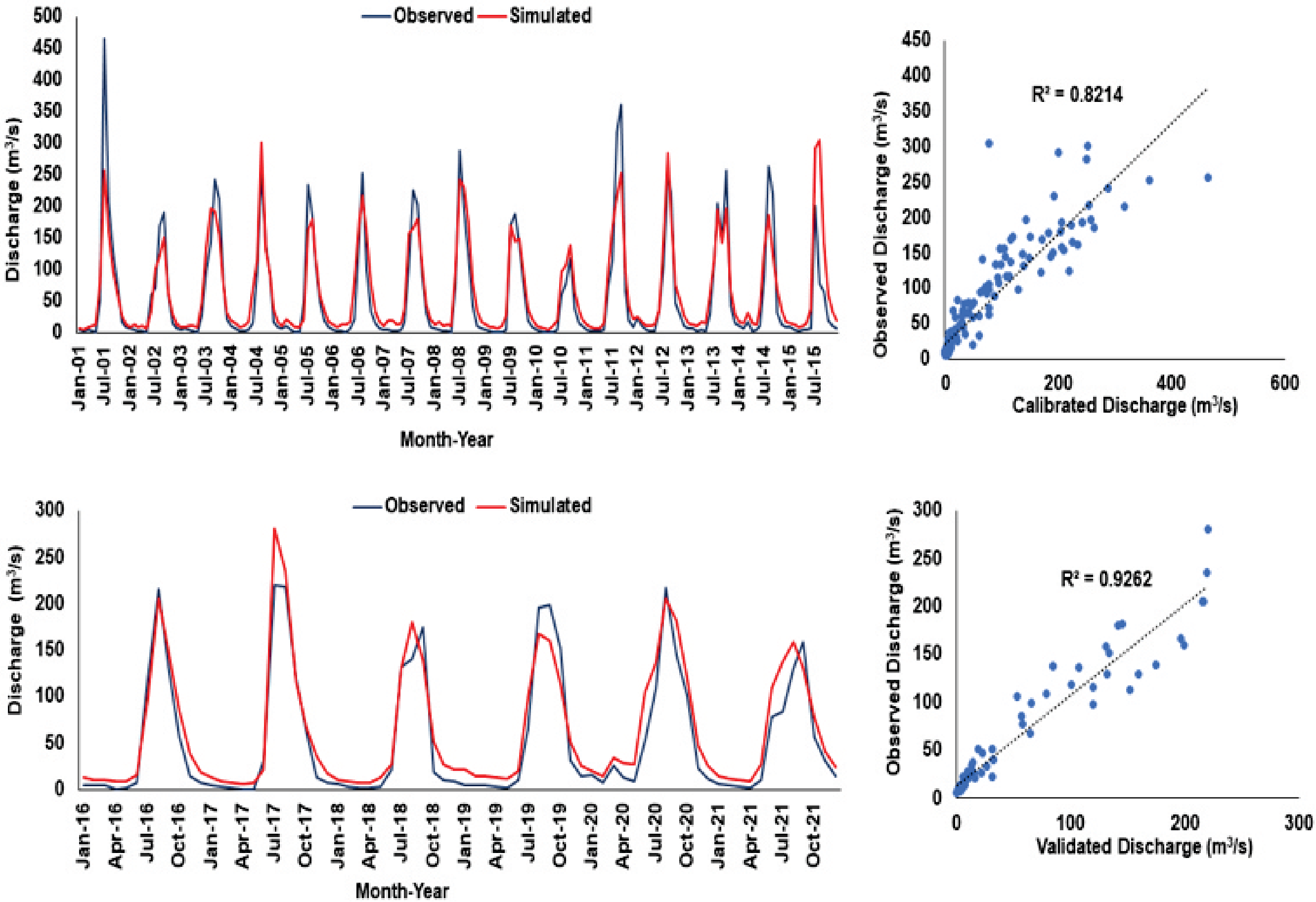

FIGURE 2 Comparison of observed and SWAT-simulated monthly discharge for the Sankh River during calibration (2001–2015) and validation (2016–2021) periods

3.2 | Environmental Flow Analysis

The study used monthly discharge data to analyze environmental flows. Fig. 3 shows FDCs for various EMCs along Sankh River. Discharges drop from EMC A to EMC F and remain steady during lean season. EMC "A" has the least discrepancy between estimated and natural flows, which widens from EMC "A" to EMC "F," indicating greater flow deviation at F. Flow values across EMCs are comparable. Fig. 4 displays Sankh river's environmental flows using observed data, with MAR percentage decreasing from EMC A (47.1%) to EMC F (1%). Flows are lowest in December. Fig. 5 shows FDCs based on simulated discharge, with discharges declining from EMC "A" to EMC "F" during lean season with little fluctuation. Fig. 6 shows average monthly environmental flows from simulated SWAT data, with the smallest deviation between estimated and natural flows in EMC "A." Deviation increases from EMC "A" to EMC "F," indicating more flow alteration at lower management levels. MAR percentage declines from EMC "A" (39.5%) to EMC "F" (0.9%), with flows lowest in December. For EMC "A," observed e-flows are about 50% of a 435.04 cumec peak, while simulated e-flows are about 44% of a 455.04 cumec peak.

Environmental flow estimates derived from both observed and SWAT-simulated discharge data exhibit a consistent trend across EMCs. The simulated data indicate that the MAR percentage decreases steadily from EMC "A" to EMC "F", with EMC "A" having the highest allocation at 39.5% and EMC "F" the lowest at 0.9%. Similarly, results obtained from observed data follow the same pattern, with EMC "A" showing a MAR of 47.1% and EMC "F" showing the lowest at 1%. This close alignment of observed and simulated data demonstrates the SWAT model's capacity to estimate environmental flows, especially in data-scarce locations. Fig. 7 shows that the flow regime generated from SWAT-simulated data closely matches the pattern observed in discharge records. This high level of agreement confirms the SWAT model's ability to accurately replicate natural flow dynamics, which is essential for environmental flow estimation. The consistency between the two datasets validates the application of SWAT in regions with limited hydrological data and enhances the credibility of GEFC-derived environmental flow assessments.

To assess the accuracy of environmental flows estimated from SWAT-simulated discharges, a statistical comparison was conducted against observed values over the full calendar year, from January to December. Three key metrics were employed: Root Mean Square Error (RMSE), Mean Absolute Error (MAE), and the Pearson Correlation Coefficient (R^2), all based on monthly environmental flow estimates. The RMSE was calculated at 26.51 cumecs, reflecting the average deviation between simulated and observed flow values. The MAE, representing the average of absolute errors over the year, was 13.77 cumecs. A high Pearson correlation coefficient of 0.984 indicates a very strong positive relationship between observed and simulated flows, suggesting that the SWAT model effectively captures seasonal flow variations in the Sankh River. These metrics fall within acceptable ranges for hydrological modeling and are noteworthy given the presence of extreme flow events, such as the simulated peak of 455.04 cumecs in March. The performance summary is presented in (Table 7), reinforcing the suitability of the SWAT-GEFC approach for monthly-scale environmental flow planning and assessment, particularly in regulated, data-constrained river basins such as the Sankh.

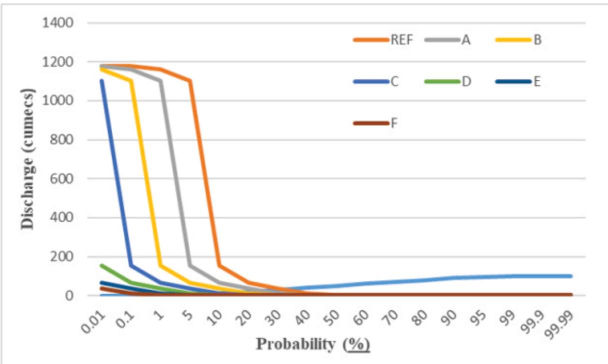

FIGURE 3 Flow Duration Curves (FDCs) for different Environmental Management Classes (EMCs) based on observed discharge data for the Sankh River

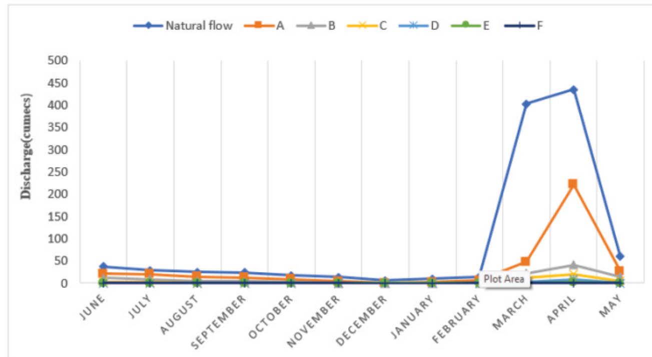

FIGURE 4 Estimated monthly environmental flows under different EMCs (A–F) using observed discharge data for the Sankh River

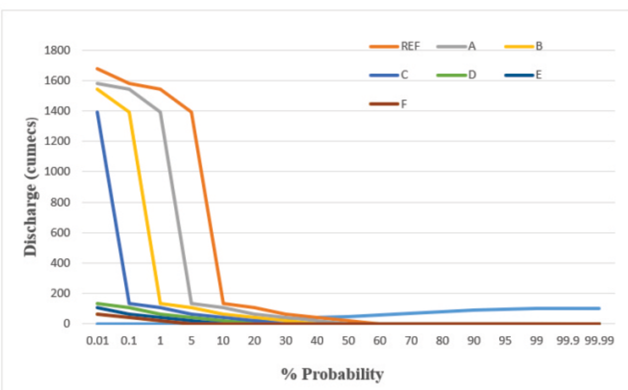

FIGURE 5 Flow Duration Curves (FDCs) for various EMCs based on SWAT-simulated discharge data for the Sankh River

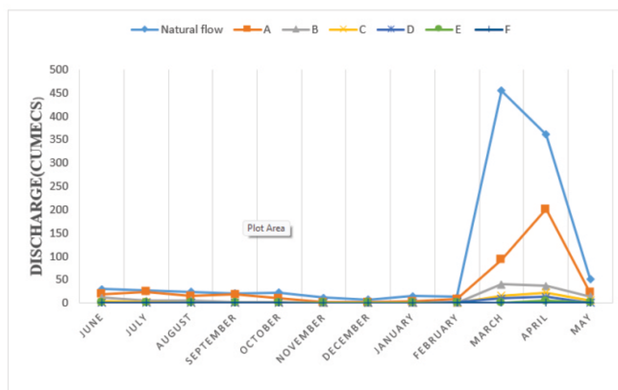

FIGURE 6 Estimated monthly environmental flows under different EMCs (A–F) using SWAT-simulated discharge data for the Sankh River

TABLE 7 Statistical comparison between observed and simulated environmental flows (January–December)

Statistical Parameter	Value
Root Mean Square Error (RMSE)	26.51 cumecs
Mean Absolute Error (MAE)	13.77 cumecs
Correlation Coefficient (R)	0.984 unitless

Establishing a scientifically grounded environmental flow regime is essential for ensuring the long-term health of river ecosystems. For the Sankh River, assessing environmental flows is vital to understanding its ecological dynamics. Environmental Management Classes (EMCs), which link ecological conditions to flow variability, serve as key indicators of ecosystem health (Sharma & Singh, 2024). In areas with limited ecological data, such as specific flow-depth needs or habitat thresholds for species, EMC categories "B" and "C" offer practical benchmarks to maintain ecological balance. Choosing these categories for the Sankh River aims to balance ecological conservation with the basin's socio-economic needs. EMC "B" indicates a slightly altered ecology that supports biodiversity and near-natural functions, crucial during the monsoon and post-monsoon for the river's role as a habitat and migration route for aquatic species. Conversely, EMC "C" reflects a moderately modified state compatible with regulated river conditions and human activities like irrigation, reservoirs, and land use changes. This category preserves key ecosystem functions, although some sensitive species may be affected. Local observations and community accounts reveal native cyprinid species such as Labeo rohita, Catla catla, and Bagarius bagarius, which depend on seasonal hydrological cues for upstream migration and spawning. The IUCN Red List classifies Bagarius bagarius as Near Threatened, citing habitat fragmentation and declining river flows (IUCN, 2024). Reports from communities in Gumla and Simdega districts indicate that reduced dry-season flows over recent years have fragmented habitats, disrupting fish movement and aquatic diversity. EMC "B" maintains sufficient flow depths and velocities to support these migration and ecological processes, while EMC "C" provides a conservative flow range under current water use pressures. The states of Jharkhand and Odisha fall under identified regional conservation zones due to their high freshwater biodiversity and their inclusion in the Eastern Ghats–Chotanagpur dry deciduous ecoregion, which supports vulnerable and endemic species. EMCs "B" and "C" offer ecologically viable standards for maintaining ecosystem services while accommodating agricultural and domestic water needs. Their adoption aligns with India's environmental flow frameworks and policies, including the National Water Policy (2012), emphasizing maintaining flows in moderately impacted rivers. Thus, EMC "B" and "C" serve as ecological safeguards and practical flow management guidelines tailored to the Sankh River's hydrological and ecological setting.

Fig. 8 illustrates the recommended environmental flows for the Sankh River under EMC "B" and EMC "C," based on observed discharge data. The assessment shows seasonal variations, with flow minima in December (6.53 cumecs) and January (9.59 cumecs), likely due to less precipitation during winter. The highest flows occurred in March (403.06 cumecs) and April (435.04 cumecs), reflecting spring hydrological patterns. A minimum flow of 5.72 cumecs is recommended to protect the river's ecological functions, crucial for aquatic biodiversity, water quality, and ecosystem health. These e-flows align with India's 2012 National Water Policy, which emphasizes ecological flows in regulated rivers. They can be incorporated into operational schedules for major irrigation infrastructure like the Upper Sankh, Ramrekha, and Kansjore reservoirs, ensuring ecological releases in dry periods. They also support regulatory frameworks, assisting agencies such as MoEFCC and JSPCB in enforcing flow standards during environmental clearances or basin planning. Ecologically, this study provides a foundational benchmark for river health. The Sankh River sustains migratory fish like Labeo rohita, Catla catla, and Bagarius bagarius, the latter listed as Near Threatened due to habitat fragmentation and flow changes. Community reports from Gumla and Simdega indicate declining dry-season flows have affected breeding and habitat connectivity. EMC “B” maintains the ecological depth and velocity needed for these species, while EMC “C” balances environmental needs with existing water withdrawals for agriculture and domestic use. These EMCs are suitable given the Sankh basin's location within the Eastern Ghats–Chotanagpur dry deciduous ecoregion, an area rich in freshwater biodiversity requiring conservation efforts. The chosen EMCs are based on ecological needs and regional water management realities. EMC “B” supports slightly altered river conditions, preserving dry-season flows critical for habitat, dissolved oxygen, and water quality during stressed months like December and January. It also sustains hydrological pulses that trigger migration and spawning for native fish, including Labeo rohita, Catla catla, and Bagarius bagarius. Maintaining natural flow variability is especially important for protecting habitats of Near Threatened species like Bagarius bagarius. EMC “C” offers a balanced level of protection by retaining core ecological functions while acknowledging existing abstractions and the presence of irrigation reservoirs such as Upper Sankh, Ramrekha, and Kansjore. This class allows for realistic implementation of environmental flows in a regulated river system while still ensuring minimum flow thresholds to maintain connectivity, support aquatic life, and avoid excessive habitat fragmentation.

Field interactions and local observations from communities in Gumla and Simdega districts also suggest that reduced dry-season flows have led to pool isolation, lower fish availability, and decreased water quality, highlighting the socio-ecological importance of maintaining adequate baseflows. The use of these classes aligns with India's National Water Policy (2012), which emphasizes ecological flow maintenance in regulated basins. This combined approach ensures that environmental flow targets are ecologically meaningful yet adaptable to on-ground hydrological and management constraints.

The study further endorses broader environmental governance efforts by providing a replicable scientific method for establishing e-flow regimes in other Indian rivers with similar regulatory and ecological environments. The validation PBIAS of −19.1% shows a tendency to systematically overestimate flows, potentially inflating GEFC-based e-flows, especially under low-flow EMCs, resulting in a more conservation-oriented approach. Nevertheless, the high NSE of 0.90, R^2 of 0.92, and the strong correlation between observed and simulated e-flows ($R = 0.984$), along with a non-significant mean difference (paired t-test $p = 0.702$, 95% CI −14.35 to 20.59 cumecs), support the overall reliability of the monthly e-flow patterns.

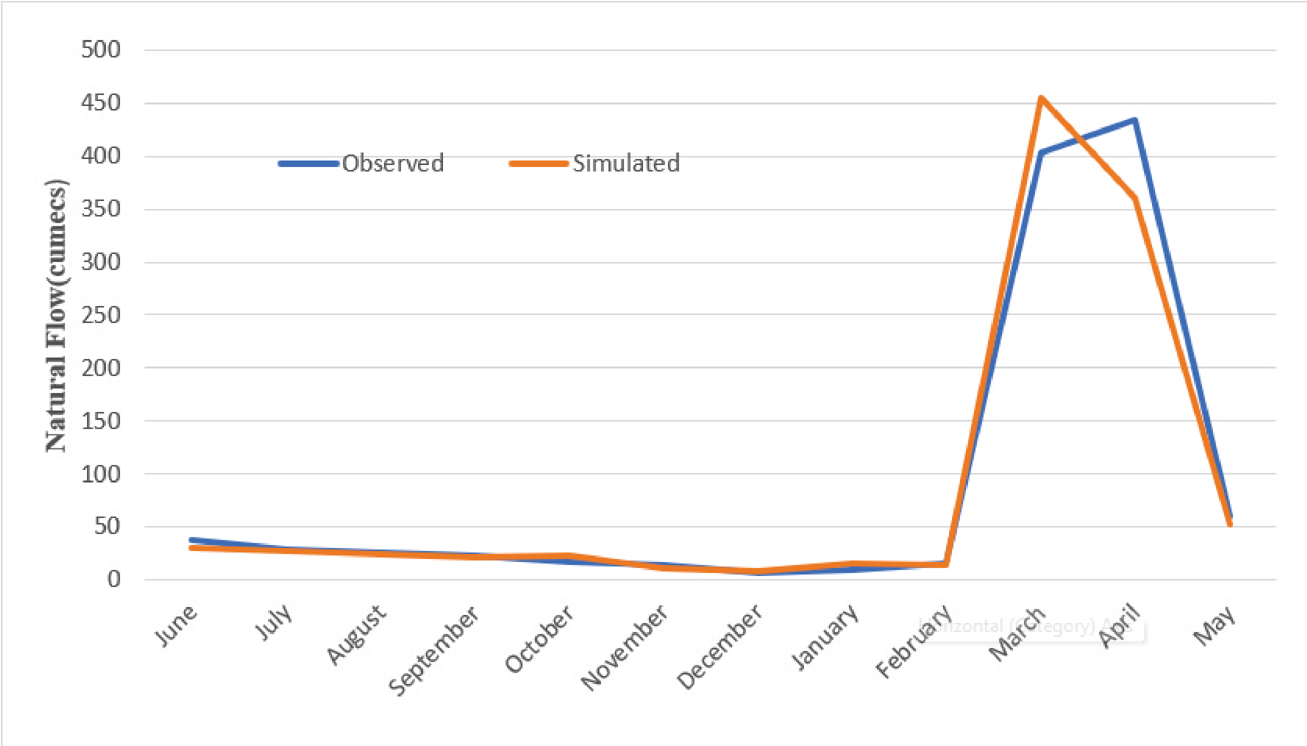

FIGURE 7 Comparison of natural flow regimes using observed discharge and SWAT-simulated discharge for the Sankh River

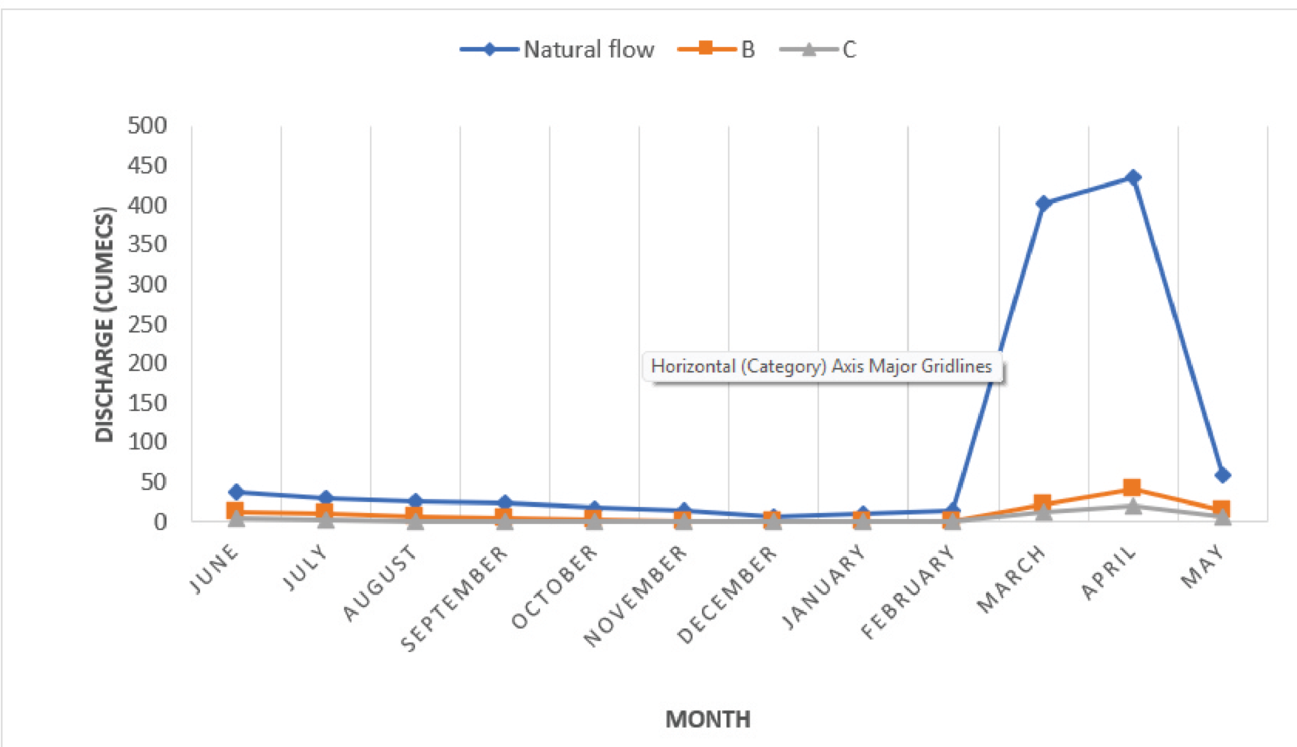

FIGURE 8 Environmental flows of Sankh river for EMC 'B' and EMC 'C’

4 | Limitations and Policy Recommendations

Despite the SWAT–GEFC framework's robustness, there are data and method limitations. NASA POWER meteorological data have uncertainty due to coarse resolution and potential bias in representing localized rainfall extremes, possibly underestimating high-intensity events affecting peak flows and sediment. Calibration with data from one station (Tilga) limits spatial representation and may mask local discrepancies, especially in heterogeneous catchments. Coarse-resolution DEM, soil, and land-use data can affect watershed features and hydrological process simulations at small scales. The environmental flow assessment relies mainly on hydrology without incorporating biological, ecological, or geomorphological data, and the lack of long-term ecological monitoring restricts validation of flow–ecology relationships and species-specific thresholds. Additionally, the model doesn't account for dynamic human activities like sand mining, reservoir rule changes, or groundwater use, which can influence low flows and ecological connectivity over time.

5 | CONCLUSIONS

An integrated SWAT-GEFC modeling framework for e-flow estimation in the Sankh River basin in Eastern India, a region that is both regulated and ecologically sensitive, was demonstrated through the successful application of this study. During both calibration and validation periods, the SWAT model showed high predictive performance with NSE and R2 values exceeding 0.80. The statistical comparison of observed and simulated environmental flows indicated a strong correlation (R = 0.984), with low RMSE and MAE values. These results confirm the model's ability to simulate discharge and estimate e-flows in basins with limited data and human influences. The decline in Mean Annual Runoff (MAR) percentages from EMC 'A' to EMC 'F' was evident in both observed and simulated environmental flow estimates. The most ecologically sound condition (47.1% observed; 39.5% simulated) is EMC 'A', while critical degradation (1% observed; 0.9% simulated) corresponds to EMC 'F'. This study highlights December as the month with the lowest flow, suggesting that a minimum environmental flow of 5.72 cumecs is necessary to maintain ecological continuity. This threshold helps support aquatic species during dry seasons and sustains essential ecosystem functions such as nutrient cycling, fish migration, and water quality. The quantified e-flows under EMCs "B" and "C" are particularly important because they align with India's National Water Policy (2012), which emphasizes maintaining ecological flows in regulated rivers. In regions lacking continuous ecological or discharge data, the SWAT-GEFC approach provides a prototype for integrating hydrological simulation with policy development. Its applications extend beyond river ecology to reservoir operation, catchment restoration, and climate-resilient water planning. Future research on ecological indicators and climate variability will be crucial for refining environmental flow recommendations and promoting sustainable water management amid anthropogenic and climate changes. These results affirm the model's robustness for discharge simulation in data-scarce basins, supporting its use in environmental flow estimation. Sustainable river management can be achieved by combining hydrological modeling with ecological considerations.

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CONFLICT OF INTEREST

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DATA AVAILABILITY STATEMENT

Data can be made available on request.

AUTHOR'S CONTRIBUTION

First author: Data collection, model set up and evaluation and analysis. Second author: Supervision, Drafting the manuscript.

REFERENCES

Abbaspour, K. C. (2015). SWAT-CUP: SWAT Calibration and Uncertainty Programs – A User Manual. Eawag: Swiss Federal Institute of Aquatic Science and Technology.

Acreman, M.C., Overton, I.C., King, J., Wood, P.J., Cowx, I.G., Dunbar, M.J., Kendy, E. and Young, W.J. 2014. The changing role of eco-hydrological science in guiding environmental flows. *Hydrological Sciences Journal*, 59:3–4. doi:10.1080/02626667.2014.886019

Arthington, A. H., David, T., McClain, M. E., Acreman, M. C., Anderson, E. P., Babu, S., Dickens, C.W.S., Horne, A.C., Kaushal, N., Monk, W. A., O'Brien, G. C., Olden, J. D., Opperman, J. J., Owusu, A. G., Poff, N.L., Richter, B. D., Salinas-Rodríguez, S. A., Shamboko-Mbale, B. S., Tharme, R. E. and Yarnell, S. M. 2023. Accelerating environmental flow implementation to bend the curve of global freshwater biodiversity loss. *Environmental Reviews*. 32: 387-413, https://doi.org/10.1139/er-2022-0126

Bussettini, M. 2018. Environmental Flows in Sustainable Integrated Water Resources Management. WMO, Institute for Environmental Protection and Research, Italy, https://wmo.int/media/magazine-article/environmental-flows-sustainable-integrated-water-resources-management, (accessed on January 10, 2025)

Campolongo, F., Cariboni, J., & Saltelli, A. (2007). An effective screening design for sensitivity analysis of large models. *Environmental Modelling & Software*, 22(10), 1509–1518. https://doi.org/10.1016/j.envsoft.2006.10.004

Chowdhury, M. S. 2024. Comparison of accuracy and reliability of random forest, support vector machine, artificial neural network and maximum likelihood method in land use/cover classification of urban setting. *Environmental Challenges*, 14:100800. https://doi.org/10.1016/j.envc.2023.100800

Dunbar, M.J., Gustard, A., Acreman, M.C. and Elliot, C.R.N. 1998. Review of Overseas Approaches to Setting River Flow Objectives, Environment Agency R and D Technical Report W6B 96 (4). Institute of Hydrology, Wallingford, U.K. 61.

Fang, X., He, W., Wen, F., An, M., Wang, B. and Cheng, B. 2025. SWAT model application for calculating ecological flow in sub-basins of the Huangshui River Basin, *Journal of Environmental Management*, 380:124837, https://doi.org/10.1016/j.jenvman.2025.124837

Gleeson, T., Wada, Y., Bierkens, M. F. P. and van Beek, L. P. H. 2020. Illuminating water cycle modifications and Earth system resilience in the Anthropocene. *Water Resources Research*, 56(4), e2019WR024957. https://doi.org/10.1029/2019WR024957

Govind, M. P., Pandey, R. U. and Kumar, P. 2024. A framework for implementation of environmental flow requirements through community perceptions – The case of Bargi Dam, Jabalpur District, Madhya Pradesh. *Hydrological Sciences Journal*, 70(10). https://doi.org/10.1080/02626667.2024.2434139

IUCN. 2024. The IUCN Red List of Threatened Species. https://www.iucnredlist.org/

Jamsran, B. E., Lin, C., Byambakhuu, I., Raash, J. and Akhmadi, K. 2019. Applying a support vector model to assess land cover changes in the Uvs Lake Basin ecoregion in Mongolia. *Information Processing in Agriculture*, 6(1):158-169. https://doi.org/ 10.1016/ j.inpa. 2018. 07. 007

Jharkhand State Pollution Control Board (JSPCB). 2019. *Water Quality and Ecological Status of Rivers in Jharkhand.* Ranchi: JSPCB.

Kumar, A. U. and Jayakumar, K. V. 2020. Assessment of flow regime alteration in the Krishna River basin. *ISH Journal of Hydraulic Engineering*. 28(3):1-7. https://doi.org/ 10.1080/ 09715010. 2020. 1852979

Kumari, P., Singh, A. and Parhi, P. K. 2024. Assessment of the Effect of Land Use and Climate Change on Natural Resources and Agriculture in the Subarnarekha Basin, India, Using the SWAT. *Natural Resources Research*, 1-19. https://doi.org/10.1007/s11053-024-10356-y

Malik, S. 2014. Determination of Stages of Landscape Evolution of Sankha Nadi, Jharkhand; An Integrated Approach of Morphometry and GIS. *Journal of Environment and Earth Science*, 4(3):46-55.

Mebarki, H., Maref, N. and Dris, M. E. A. 2024. Modelling the monthly hydrological balance using Soil and Water Assessment Tool (SWAT) model: A case study of the Wadi Mina upstream watershed. *Journal of Groundwater Science and Engineering*, 12(2):161-177, https://doi.org/10.26599/JGSE.2024.9280013

Mishra, D., Singh, H., Kumar, M. and Mohanty, M. P. 2025. Advanced hydrological assessment with SWAT+ under climate change: An integrated framework over large climate-sensitive and reservoir-regulated watershed, *Science of The Total Environment*, 994:180062, https://doi.org/10.1016/j.scitotenv.2025.180062

Piniewski, M., Szcześniak, M., Kardel, I., Berezowski, T., Okruszko, T., Srinivasan, R., Vikhamar Schuler, D. and Kundzewicz, Z. W. 2017. Hydrological modelling of the Vistula and Odra river basins using SWAT. *Hydrological Sciences Journal*, 62(8):1266–1289. https://doi.org/10.1080/02626667.2017.1321842

Piniewski, M., Szcześniak, M., Kardel, I., Berezowski, T., Okruszko, T., Srinivasan, R., Vikhamar Schuler, D. and Kundzewicz, Z. W. 2017. Hydrological modelling of the Vistula and Odra river basins using SWAT. *Hydrological Sciences Journal*, 62(8):1266–1289. https://doi.org/10.1080/02626667.2017.1321842

Rahman, K. U., Pham, Q. B., Jadoon, K. Z., Shahid, M., Kushwaha, D. P., Duan, Z., Mohammadi, B., Khedher, K. M. and Anh, D. T. 2022. Comparison of machine learning and process-based SWAT model in simulating streamflow in the Upper Indus Basin. *Applied Water Science*, 12(8): 178. https://doi.org/10.1007/s13201-022-01692-6

Sahoo, S., Khare, D., Mishra, P. K., Behera, S. and Krishan, R. 2016. A Comparative Study on Environmental Flows Assessment Methods in Lower Reach of Mahanadi River. *International Journal of Engineering Trends and Technology*, 32(2): 82.

Singh, A., Imtiyaz, M., Isaac, R. K. and Denis, D. M. 2012. Comparison of soil and water assessment tool (SWAT) and multilayer perceptron (MLP) artificial neural network for predicting sediment yield in the Nagwa agricultural watershed in Jharkhand, India. *Agricultural Water Management*, 104:113-120. https://doi.org/10.1016/j.agwat.2011.12.005

Singh, A. 2015. Modeling Stream Flow with prediction uncertainty by using SWAT hydrologic and RBNN Neural Network models for agricultural watershed in India. *Natl. Acad. Sci. Lett.*, 39: 213.

Sharma, A. and Singh, A. 2024. Environmental sustainability of major rivers of Jharkhand, India, *Indian Journal of Soil Conservation*, 52(2): 103-111. IDOI: 10.59797/ijsc.v52.i2.165**S**

Smakhtin, V.U. and Anputhas M. 2006. *An assessment of EF requirements of Indian river basins. Colombo*. International Water Management Institute, Research Report, 107

Tharme, R.E. and Smakthtin, V. 2003. Environmental Flow Assessment in Asia: Capitalizing on existing momentum. Proceedings of the First Southeast Asia Water Forum, 2, 301-313, 17, 21 November 2003, Chiang Mai, Thailand.

Zhao, J., Zhang, N., Liu, Z., Zhang, Q. and Shang, C. 2024. SWAT model applications: From hydrological processes to ecosystem services, *Science of The Total Environment*, 931:172605, https://doi.org/10.1016/j.scitotenv.2024.172605 The Brisbane Declaration. (2007). https://www.conservation gateway. org/Documents/Brisbane-Declaration-English.pdf [accessed on January 10, 2025]

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