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RIVER POLLUTION AND ANTHROPOCENE: SUSTAINABLE RIVER ETHICS WAY TO RIVER BASIN PLANNING AND MANAGEMENT

Hydrological modelling using SWAT for the assessment of streamflow dynamics in the Ganga River basin

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Abstract

Growing concerns over water availability arise from the problems of population growth, rapid industrialization, and human interferences, necessitating accurate streamflow estimation at the river basin scale. It is extremely challenging to access stream flow data of a transboundary river at a spatio-temporal scale due to data unavailability caused by water conflicts for assessing the water availability.

Primarily, this estimation is done using rainfall-runoff models. The present study addresses this challenge by applying the soil and water assessment tool (SWAT) for hydrological modelling, utilizing high-resolution geospatial inputs. Hydrological modelling using remote sensing and GIS (Geographic Information System) through this model is initiated to assess the water availability in the Ganga River basin at different locations. The outputs are calibrated and validated using the observed station data from Global Runoff Data Centre (GRDC). To check the performance of the model, Nash–Sutcliffe efficiency (NSE), percent bias (PBIAS), coefficient of determination (R^2), and RSR efficacy measures are initiated in ten stations using the observed and simulated stream flow data. The R^2 values of eight stations range from 0.82 to 0.93, reflecting the efficacy of the model in rainfall-runoff modelling. Moreover, the results obtained from this hydrological modelling can serve as valuable resources for water resource planners and geographers for future reference.

Keywords Hydrological modelling · Runoff simulation · Water balance · Soil and water assessment tool (SWAT) · Ganga River basin

Introduction

Water stands as a crucial natural resource, indispensable for the survival of all living organisms (Trivedi et al. 2023). The alterations in climate, land use, and soil cover have an impact on water resource management systems due to the presence of diverse cyclic components (Hosseini and Khaleghi 2020). These changes have a direct impact on catchment properties, such as surface roughness and vegetation. These alterations influence streamflow by affecting water content and the timing of surface runoff and groundwater recharge. (Li & Fang 2021). As an illustration, the transformation of forests into agricultural and urban areas leads to increased surface runoff and decreased groundwater recharge (Hu et al. 2020). Hydrological models play a crucial role in comprehending the behavior and responses of catchments. Streamflow simulation is essential for the development of catchments (Uhlenbrook et al. 2010; Tuo et al. 2016; Dakhlalla & Parajuli 2019; Duan et al. 2019), which promotes the sustainable conservation of water resources, including rainfall, groundwater, lateral flow, percolation, and evapotranspiration. Population growth, rapid industrialization and environmental activities, and water scarcity concerns have become more widespread, which has heightened the importance of this issue (Himanshu et al. 2019; Swain et al. 2022). Despite recent technological advancements and the increasing trend in implementing distributed models, the challenges of limited data availability and the high costs associated with obtaining this information in India need to

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be addressed by implementing SWAT hydrological model (Abbaspour et al. 2015; Hosseini & Khaleghi 2020). The SWAT model has proven to be a valuable tool for simulating the potential impacts of climate change on hydrologic and biogeochemical cycles across multiple catchments (Arnold et al. 1998; Lirong and Jianyun 2012). Researchers worldwide have effectively utilized the SWAT model in the domain of distributed hydrologic modelling and water resource management, especially in catchment areas characterized by diverse climatic or topographical features (Shi et al. 2011). The recent integration of remote sensing information into hydrology has spurred the development of various methods for modelling ungauged basins. Remote sensing technologies today provide alternative sources of input data to generate, test and verify mathematics models; they enable massive spatial coverage observations. Large geographical coverage of surface water bodies in the world and sufficiently long monitoring periods are provided by remotely sensed data (Odusanya et al. 2021). SWAT has gained extensive usage in research, emerging as a pivotal model with a robust capacity to encompass both natural and human-induced influences on, river basin hydrology (Chang et al., 2014; Belihu et al. 2020). These studies demonstrate the efficacy of these models in efficiently managing water resources, addressing the diverse water requirements that arise. Numerous research activities have been conducted to assess the reliability of employing freely available Indian weather data as a reference for developing hydrological models for streamflow simulation. These studies specifically utilize freely available gauge precipitation data for their investigations.

The diversity of hydrogeologic features in the watershed system, regarding time and area, makes it extremely difficult to manage water resources (Wei et al. 2020). Therefore, users can easily change the system's variables and parameters through hydrogeological models that enable them to understand how those variables interact to form complex systems (Sokolowski and Banks 2010, 2011; Mengistu et al. 2019). In addition, human activities that significantly influence river systems have been increasingly intensive over the past few decades, including changes to land use, removal of freshwater, and construction of dams. Enhancing basin management programs and effectively mitigating the alarming loss of soil and water resources require imperative hydrological studies conducted at the river basin scale (Vilaysane et al. 2015). The precipitation and temperature are vital atmospheric parameters used as inputs in the hydrogeological models (Duan et al. 2019; Rahman et al. 2020). An appropriate description of rainfall and air temperature variability is provided to enable effective hydrological modelling and prediction based on models. Precise simulation of streamflow, as influenced by the rainfall network imbalance, relies significantly on accurate and temporally detailed rainfall data (Singh & Saravanan 2022) and is emphasized in hydro-meteorological applications such as hydrological simulation, water resource management, and climate modelling (Duan et al. 2019).

The Ganga, one of the world's largest rivers, encompasses one of the most densely populated agricultural regions globally. Approximately 440 million people rely on water from the Ganga and its tributaries, underscoring its vital significance as a source for agriculture, drinking water, hydroelectric power generation, navigation, and ecosystem services. The continuous growth of the population and its impact on water resource developments also have a major effect on water availability, water quality as well as riverine ecosystems (Vairavamoorthy et al. 2008; Ridoutt et al. 2009; Trivedi et al. 2023). The Ganga River basin faces intriguing challenges related to ecosystem health, food security, and irrigation systems, particularly in the context of water supply. Managing water resources in this basin involves addressing complex processes that extend from surface to subsurface interactions. This study employs hydrological and rainfall-runoff models to comprehend the stream flows of the Ganga River, enabling operational management of water resources amid significant spatial and temporal variability (Uhlenbrook et al. 2010; Tuo et al. 2016; Duan et al. 2019). The streamflow in the catchment is intricately linked to rainfall, with each exerting influence on the other. For various reasons, measuring all data about hydrologic systems and procedures is also not feasible. Although the data is easily available, restrictive data-sharing rules may sometimes impose some restrictions on public access to information or its completeness. However, several areas across the basin, especially in the mountains, are concerned by the absence of widespread rain gauge networks. For this reason, water resource management, planning, and forecasting are imperative for the correct discharge of rivers in mountain watershed simulations. In the mid and downstream regions, where precipitation is rare, it is also essential to ensure the long-term sustainability of water resources (Kang et al. 1999; Yu et al. 2011; Lu et al. 2015). The basin exhibits rolling mountain topography in the northern region, marked by a network of scattered rainfall gauges. Simulating streamflow in mountainous or hilly areas becomes challenging due to data scarcity. However, the SWAT model has proven its adaptability, dependability, and utility as a water resource management and planning tool (Dams et al. 2015) by successfully replicating basin hydrology in the Himalayas and tropical rivers. The hydrogeological model can be used to explain, forecast, and estimate several water management processes (Ma et al. 2019; Lv et al. 2022) when ground-based measurements are not possible due to difficulty in accessing, time-consuming or both. Various hydrological models with different degrees of complexity have been developed to accommodate diverse perspectives on alternative management policies, facilitating effective water management practices in the context of climate change (Wang et al. 2010; Bao et al. 2012; Huang et al. 2015; Zhai & Tao 2017). The primary objectives of this research are to utilize the SWAT model with high-resolution geospatial inputs to estimate spatio-temporal variations of streamflow in the Ganga River basin, a transboundary river with data access challenges. The study aims to assess water availability at different locations within the basin, calibrate and validate the model using observed data from the Global Runoff Data Centre (GRDC), and evaluate the model's performance using various statistical measures. Furthermore, it seeks to provide valuable insights for water resource management and planning. Key research inquiries involve understanding the impacts of land use changes on water resources, quantifying surface runoff and groundwater recharge, assessing climate variability effects on hydrological processes, and evaluating water management strategies. This research is critical as it offers insights for sustainable water resource management, aids in mitigating flood and drought risks, and supports agricultural planning in a region facing significant environmental and climatic challenges. In this study, streamflow analysis was conducted using the SWAT model, incorporating satellite data, DEM data, and other climate data. In addition, the validation process is also implemented with river discharge data as much data is available to the simulated data derived from the SWAT model.

Description of the study area

The Ganga basin extends across India, Tibet (China), Nepal, and Bangladesh, spanning an area of 10,86,000 km^2. Within India, it encompasses the states of Uttar Pradesh, Madhya Pradesh, Rajasthan, Bihar, West Bengal, Uttarakhand, Jharkhand, Haryana, Chhattisgarh, Himachal Pradesh, and the Union Territory of Delhi, with a drainage area covering 8,61,452 km^2 (79% of the total basin). This accounts for roughly 26% of the nation's total geographical area. The basin is situated within the east longitudes of 73°2′ to 89°5′ and the north latitudes of 21°6′ to 31°21′. Its dimensions within India measure approximately 1543 km in length and 1024 km in width, marking it as a significant geographical feature with far-reaching socio-economic and environmental implications. The Ganges River is a revered aquatic expanse from the Himalayan Mountain range and traverses to the Bay of Bengal. Gomukh, located in the Himalayas, marks the origin of the Ganges River as it emerges from the Gongotri Glacier. When the ice of this glacier melts, crystal clear waters are formed in the Bhagirathi River. When they merge, as they descend the Himalayas, the Alaknanda and Bhagirathi rivers will officially become Ganges. Occasionally, discussions of a larger river basin, including the Ganges River basin, include the adjacent Brahmaputra and Meghna rivers. One of the world's largest river systems is the Ganges–Brahmaputra-Meghna (GBM) River Basin. The river's main tributaries include the Yamuna, Ramganga, Ghaghra, Gandak, Kosi, Mahananda, and Sone (Fig. 1). The main water supply for rivers is derived from direct surface flows resulting from precipitation, return flows, base flows, and snowfall originating from the Himalayas (Dhami et al. 2018). This basin receives a wide range of rainfall patterns across the area but also during a limited number of months of the year. During the monsoons from June to October, rainfall is mainly limited. This results in low flow conditions in the Ganga and its tributaries during the dry months from November to May. The average annual rainfall in the Ganga River basin ranges from 350 mm on the western end to 2000 mm on the eastern end. Around 66% of the area in the irrigation basin is watered by surface water, while the remaining 24% is watered by groundwater.

Methodology

SWAT model for hydrological simulation

The SWAT hydrological model, renowned for its process-based and distributed nature, accurately mirrors the hydrological processes within watersheds daily (Arnold et al. 2012a, b; Brighenti et al. 2019). Through the subdivision of the watershed into sub-basins (Fig. 2) and subsequently, into hydrologic response units (HRUs), which are amalgamations of specific soil characteristics, land use patterns, and management practices, SWAT offers a detailed representation of the water balance dynamics (Singh & Saravanan 2022). HRUs, being the fundamental computational units, encapsulate a range of attributes such as slope, soil type, and land use, and directly interface with the river network. To effectively operate, SWAT necessitates daily climate data encompassing temperature, humidity, wind speed, precipitation, and solar radiation (Tripathi et al. 2004; Swain et al. 2022). Precise locations of streamflow and rainfall gauge stations are imperative for accurate model outputs. The fundamental components of evapotranspiration are computed using the Penman–Monteith method, and a comprehensive water balance assessment for each HRU, considering meteorological parameters (Guug et al. 2020). The hydrological response in each HRU is simulated employing the hydrologic water balance equation, encompassing lateral flow, environmental evapotranspiration, infiltration, percolation, and soil moisture dynamics, including return flows from shallow aquifers (Anand et al. 2018a, b). Potential evapotranspiration is estimated using the Hargreaves method, while potential surface runoff is derived utilizing the modified USDA Soil Conservation Service curve number approach. Surface runoff not infiltrating the groundwater may either undergo

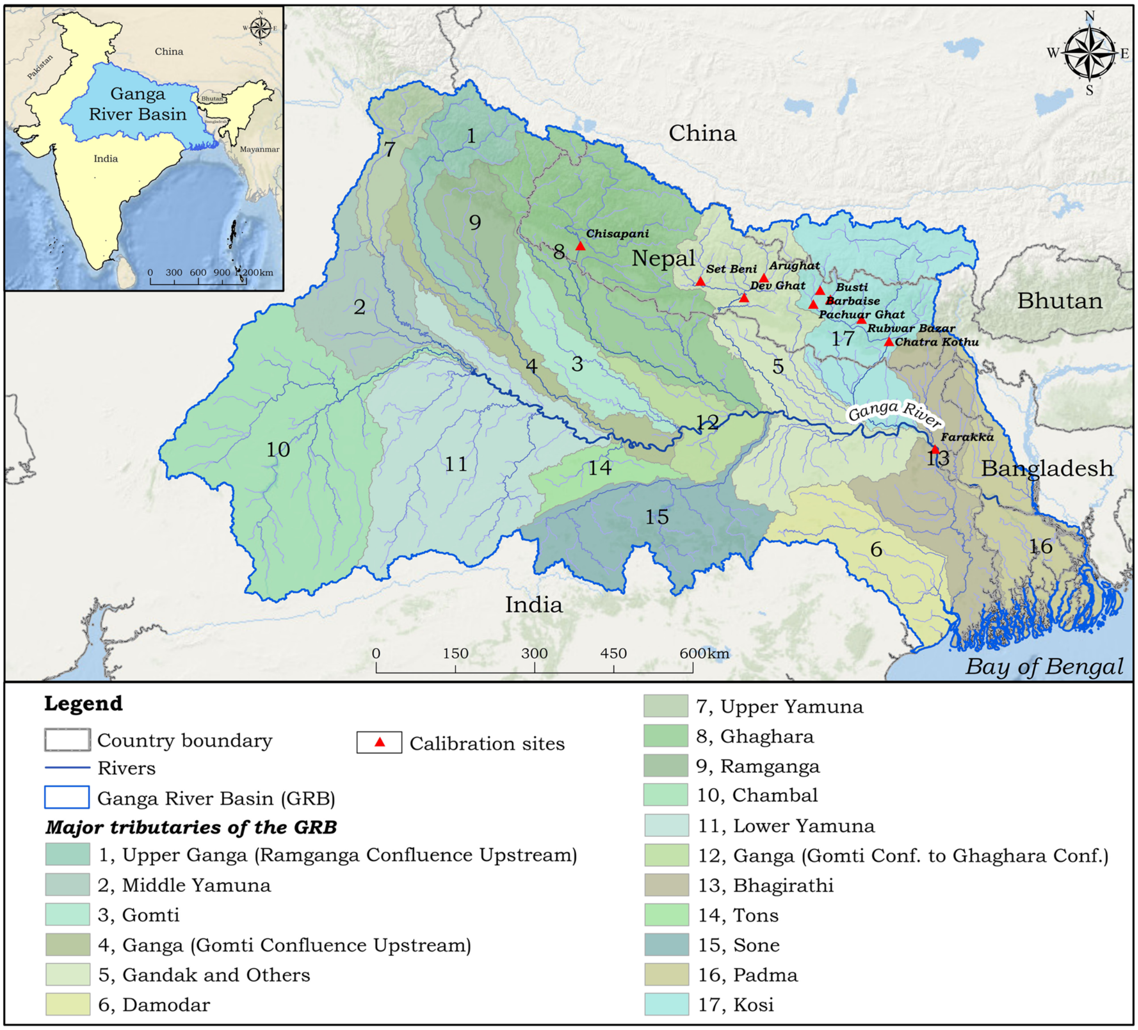

Fig. 1 Location map of the Ganga River basin, rivers with all the major the sub-basins showing spatial shares of the river basin in different countries

evapotranspiration, percolate into the aquifer, or contribute to lateral flow in the soil column, ultimately influencing streamflow. SWAT's selection as the modelling framework was underpinned by its capacity to simulate intricate physical processes governing water movement, supplemented by robust documentation and calibration/validation support.

To accurately simulate snowfall and snowmelt, a detailed understanding of the temperature variation with altitude and its impact on precipitation distribution is crucial, as it directly influences watershed dynamics in the SWAT model (Anand et al. 2018a, b). In SWAT, precipitation within a HRU is classified as snow when the daily mean air temperature drops below a threshold known as the snowfall temperature, determined by the variable SFTMP, and when liquid water equivalent is added to an existing snowpack. The snowpack accumulates with each new snowfall event but diminishes during snowmelt periods.

SWAT facilitates the division of elevation within each HRU into zones, allowing for the extrapolation of meteorological conditions, such as temperature and precipitation gradients, along elevation gradients. Elevation serves as a key factor in distributing the topographical influences on snowmelt and subsequent discharge.

Each HRU conducts water balancing and land surface operations independently. The water balance equation, integral to SWAT's surface hydrology section, is computed daily to determine the rainfall component for the model. The following equation encapsulates various hydrological processes and is instrumental in simulating the complete hydrologic cycle within the watershed.

$$SW_t = SW_o + \sum_{i=1}^{i} \left(R_{day} - Q_{suf} - E_a - W_{seep} - Q_{gw}\right)_i \quad (1)$$

where R_{day} is the amount of precipitation on day i (mm), Q_{surf} is the amount of surface runoff on day i (mm), Q_{gw} is the amount of return flow on day i (mm), and SW_{t} and SW_{o} are the final and

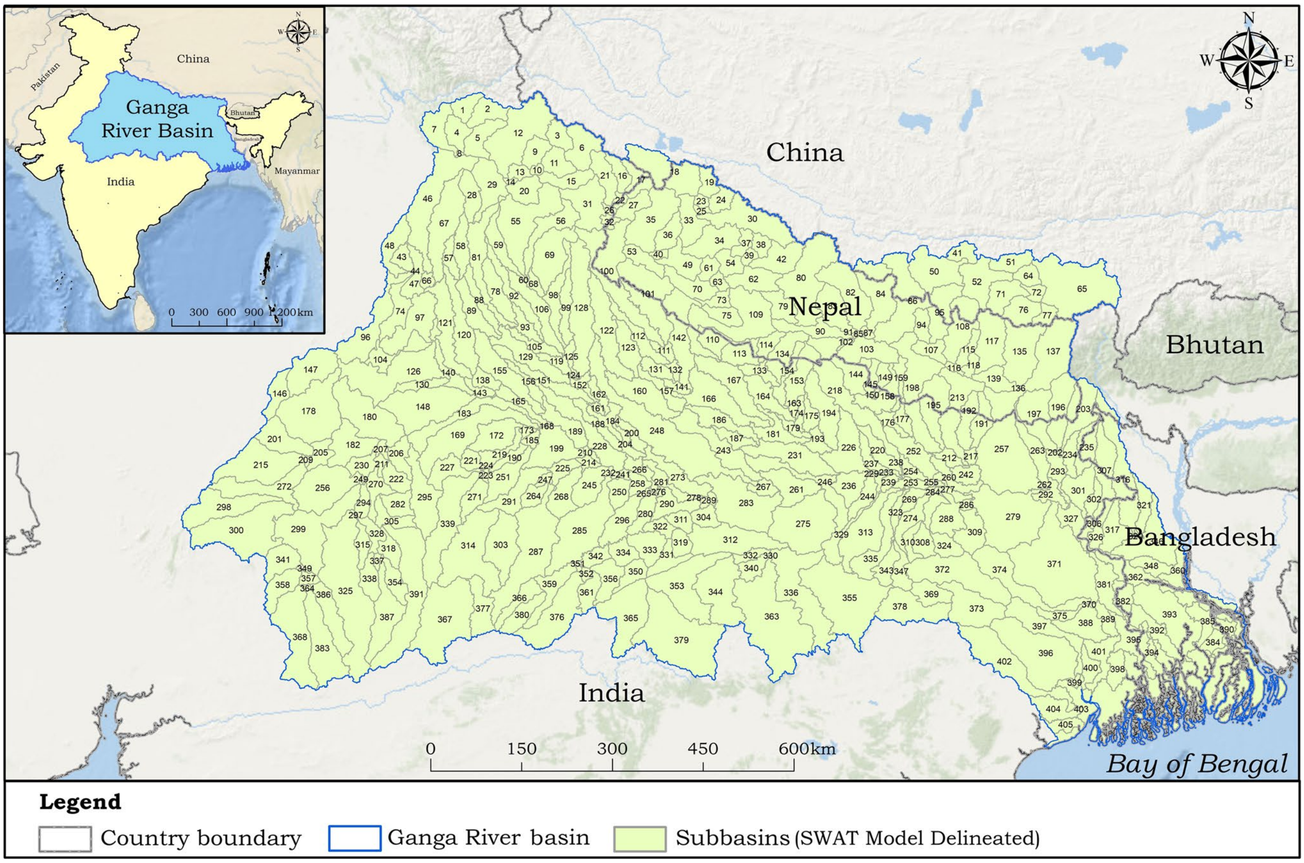

Fig. 2 The Ganga River basin and its 405 sub-basins were delineated utilizing the SRTM DEM through the watershed delineation command within the ArcSWAT tool as this allowed for the precise identification and delineation of sub-basins within the Ganga River basin, enabling detailed hydrological analysis and modelling studies within the basin

initial soil water contents (mm), respectively. Water entering the vadose zone from the soil profile is designated as W_{seep} and E_{a} is represented by evapotranspiration in millimeters (mm).

In SWAT, surface runoff computation employs either the modified Green and Ampt technique (Mein and Larson, 1973) or the Curve Number (CN) method derived from USDA-SCS guidelines (USDA-SCS, 1972), utilizing daily rainfall data. Specifically, the CN technique is utilized to assess surface runoff, wherein the depth and volume of surface runoff for each HRU are determined based on CN values and antecedent moisture conditions.

The surface runoff estimation via the SCS curve number method is expressed by the following equation:

$$Q_{\text{surf}} = \frac{(R_{\text{day}} - I_a)^2}{(R_{\text{day}} - I_a + S)} \quad (2)$$

where I_{a} (mm) represents the initial abstraction for the day, considering interception, infiltration, and surface storage, and S (mm) represents the retention factor. The storage parameter has a global influence on soil, slope, land use change, and temporary variations in soil moisture.

This method facilitates the calculation of surface runoff by considering CN values and prevailing moisture conditions, contributing to a comprehensive hydrological assessment within the SWAT framework.

$$S = 24.5\left(\frac{1000}{CN} - 100\right) \quad (3)$$

where CN is the curve number of the day.

Data used in the SWAT hydrological model

SWAT relies on comprehensive spatial datasets encompassing meteorological parameters at daily or sub-daily intervals, alongside detailed topographic, soil, and land use/land cover (LULC) data (Fig. 3). The primary inputs for the SWAT model comprise Digital Elevation Model (DEM), LULC classifications, soil properties, and daily weather records, including precipitation, maximum and minimum air temperatures, relative humidity, wind speed, and solar radiation (Table 1).

It is widely recognized that the quality of the DEM significantly influences the accuracy and reliability of the

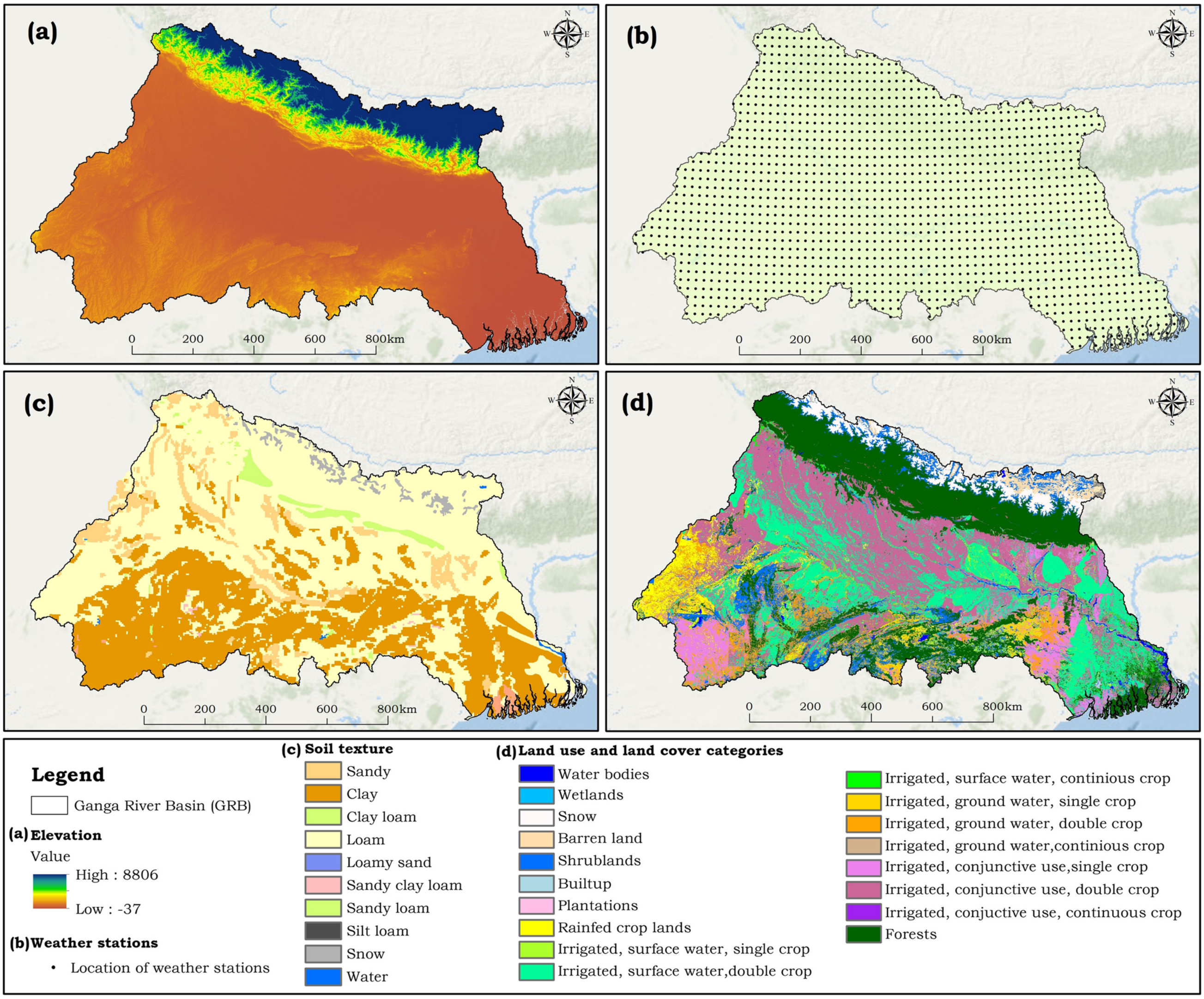

Fig. 3 Glimpse of the key parameters of the SWAT hydrological model for the Ganga River basin. **a** The digital elevation model showcasing elevation variations across the basin. **b** The locations of meteorological stations within the river basin. **c** Soil texture map highlighting the distribution of different soil types across the basin. **d** Land use and land cover categories, providing insights into the spatial distribution of land use patterns within the study area

hydrological model outputs (Romanowicz et al. 2005). Thus, ensuring the high quality and resolution of DEM data is imperative for optimizing the performance and fidelity of the SWAT model in simulating watershed hydrology.

Digital elevation model

The global datasets utilized in this study were sourced from publicly available data repositories. Among these datasets, a 90 m resolution Digital Elevation Model (DEM) was acquired from the Shuttle Radar Topography Mission (SRTM) provided by NASA EARTHDATA. Given that the topographic attributes of the catchment, sub-catchments, and HRUs are derived from this dataset, the DEM serves as a critical component of the analysis. It provides essential information regarding topographic characteristics, including area, slope, length, channel width, and depth. The utilization of a 90 m spatial resolution SRTM DEM was deemed appropriate for this investigation, ensuring detailed and accurate representations of the terrain for hydrological modelling purposes.

Land use and land cover data

Detailed information on land use and land cover is crucial for hydrologic modelling, particularly in the context of SWAT, as it forms the basis for delineating HRUs. In this study, the land use map of the study area was derived from ESRI Land cover data with a spatial resolution of 10 m for 2017.

Table 1 Description of the datasets used for the SWAT hydrological model to delineate the water availability in the Ganga River basin

Data inputs	Resolution	Data source
Meteorological data [Temperature (°C), rainfall (mm/day), wind speed (m/s), solar radiation (MJ/m^2)]	Daily [Temperature (0.5° × 0.5°), rainfall (0.25 × 0.25), wind speed (0.5° × 0.5°), solar radiation (0.5° × 0.5°)]	https://www.imdpune.gov.in/cmpg/Griddata/Rainfall_25_Bin.html (daily) https://www.imdpune.gov.in/cmpg/Griddata/Max_1_Bin.html (daily) https://www.imdpune.gov.in/cmpg/Griddata/Min_1_Bin.html (daily) Global Weather Data for SWAT https://globalweather.tamu.edu (daily) ArcSWAT 2012 Global Weather Database https://swat.tamu.edu/media/99082/cfsr_world.zip (monthly)
SRTM digital elevation model (DEM) data	90 m	NASA EARTHDATA http://srtm.csi.cgiar.org/
Land use and land cover map merged with irrigated area map	90 m	Esri Land Cover (2017) https://livingatlas.arcgis.com/landcover/ (converted into 90 m) Land use https://swat.tamu.edu/docs/swat/india-dataset/2012/Landuse_GIAM_IWMI.7z (converted into 90 m)
Soil	90 m	FAO Digital Soil Map of the World (DSMW) https://www.fao.org/soils-portal/data-hub/soil-maps-and-databases/en/ Indian Soil Data Sets https://bhuvan-app3.nrsc.gov.in/data/download/index.php (converted into 90 m)
Hydrological data	Monthly discharge data (station-wise)	GRDC discharge data https://portal.grdc.bafg.de/applications/public.html?publicuser=PublicUser#dataDownload/Subregions

Additionally, the Global Irrigated Area Mapping (GIAM), International Water Management Institute (IWMI) irrigated area map, with a resolution of 500 m, was incorporated and merged into a unified dataset with a resolution of 90 m.

The utilization of a 90 m spatial resolution allowed for the identification and classification of 18 land use and land cover (LULC) types, including the delineation of irrigated areas. Furthermore, adjustments were implemented to ensure compatibility with the SWAT plant database, thereby enhancing the accuracy and applicability of the LULC dataset for hydrological modelling within the SWAT framework.

Soil type and characteristics

Soil data is a vital component of input datasets, significantly impacting the hydrological processes within a watershed. To compile soil data for constructing the soil layer, a combination of Indian soil datasets from the Bhuvan NRSC website and FAO digital soil data for regions outside India was utilized. A comprehensive user database was developed, containing descriptions of each soil type, to facilitate HRU analysis.

The compilation process involved integrating spatial data covering topography, climate, and soil distribution patterns. Specifically, the soil map for the Ganga River watershed was extracted from the Digital Soil map layer. Subsequently, a user-defined soil database was created based on existing references and search tables, tailored to define HRUs in the SWAT model for the Ganga River catchment area.

Overall, a total of eight distinct soil types were identified across the entire basin and incorporated into the SWAT modelling framework, ensuring a comprehensive representation of soil variability and its influence on hydrological processes.

Meteorological and hydrological data

For the SWAT 2012 model, daily variables including precipitation, temperature, relative humidity, solar radiation, and wind speed are essential inputs. In cases where specific periods lack data, the SWAT program includes a weather generator function to interpolate missing values during simulation times. To facilitate this, long-term daily precipitation rates, maximum and minimum temperatures, relative humidity, and solar energy data are utilized.

In this study, rainfall and temperature data from the Indian Meteorological Department (IMD) gridded dataset were employed for daily reanalysis and recalibration purposes from 1949 to 2022. The IMD dataset provides daily rainfall data at a resolution of 0.25° latitude by longitude grid points and daily temperature data at a resolution of 0.5°.

For regions beyond India, the Climate Forecast System Reanalysis Dataset (CFSR) was utilized to acquire temperature and precipitation data. Due to challenges in obtaining accurate measurements of wind speed, relative humidity, and solar radiation, these variables were derived from the CFSR dataset and a global reanalysis product (Gao et al. 2019). Access to such weather information is also available through SWAT's official website, www.theworldweather.tamu.edu.

Given the significance of actual rainfall data in hydrological modelling, it is recommended to prioritize its use. For model calibration and validation, observed daily flow data from various Global Runoff Data Centre (GRDC) stations across Nepal and India were obtained over different time frames. These datasets serve as crucial inputs for ensuring the accuracy and reliability of the SWAT model outputs.

Calibration and validation

The calibration process of the model was executed through a systematic approach involving careful selection of input parameters within their respective ranges. Model outputs were compared against observed data under similar assumptions to assess the model's performance. Additionally, the validation method aimed to evaluate the model's ability to accurately predict site-specific conditions by testing its assumptions against independent datasets.

During calibration, parameter values were optimized to ensure consistency between model predictions and observed data. These calibrated parameter values were then retained and applied during response simulations beyond the calibration period to maintain model accuracy. The table (Table 2) provides a detailed overview of calibrated parameters for SWAT applied to the Ganga River basin, which is essential for accurate hydrological modelling in this diverse region. Key parameters include CN2 (60–85), which affects surface runoff based on land use, soil type, and hydrological conditions, and ESCO (0.5–1), influencing soil evaporation rates. EPCO (0.5–1) is crucial for plant water uptake, and SURLAG (1–12 days) impacts runoff timing. SOL_AWC (0.1–0.3 mm H_2O/mm soil) determines soil water holding capacity, while ALPHA_BF (0.01–0.1 days) influences baseflow recession rates. GW_REVAP (0.01–0.1) controls water movement from the shallow aquifer to the unsaturated zone, and GW_DELAY (10–150 days) affects groundwater discharge timing. GWQMN (0–2500 mm) sets the minimum water depth in the aquifer for streamflow contribution, and REVAPMN (0–100 mm) defines the minimum water depth for water movement back to the soil surface. SHALLST_N (0–1000 mm) sets initial shallow groundwater storage conditions, while RCHRG_DP (0.02–0.2) controls percolation to the deep aquifer. SFTMP and SMTMP (− 2 to 2 °C) set snowfall and snowmelt temperature thresholds, and SMFMX and SMFMN (2–6 mm H_2O/°C/day) determine snowmelt rates. TIMP (0.01–1) affects snowpack temperature changes, SNOCOVMX (50–200 mm H_2O) sets maximum snow cover water content, SNOMELT (1–7 mm/°C/day) controls snowmelt rates, and SNO50COV (0.3–0.7) affects snow-covered area fraction at 50 mm snow water equivalent. These parameters are vital for enhancing SWAT model accuracy, aiding in reliable water resource management and planning in the Ganga River basin.

The calibration process involved analyzing discharge data at both daily and monthly intervals, utilizing discharge data from multiple gauge stations. SWAT-CUP, a software tool, facilitated the calibration process by iteratively adjusting model parameters to minimize the discrepancy between model predictions and observed data.

The robustness of the model was evaluated through SWAT-CUP calibration and by assessing the model's performance in predicting monthly and daily discharge. This involved identifying the best-fit results for each month and assessing the overall accuracy of daily simulations.

In the calibration and validation process of the SWAT model within the Ganga River basin, data spanning from 1949 to 1993, covering a period of 45 years, were utilized. This dataset comprised hydrological data from ten stations located across Nepal and India. Subsequently, hydrological simulations were conducted for the remaining 29 years to facilitate additional hydrological analyses for future reference and further investigation. This extended simulation period allowed for a comprehensive assessment of the model's performance and its applicability in capturing long-term hydrological patterns within the basin.

Model performance evaluation

This study utilized a comprehensive set of statistical evaluation criteria, including the NSE, PBIAS, R^2, and root mean square error to standard deviation ratio (RSR). Among these, the NSE is widely recognized as a primary metric for comparing hydrological model simulations with observed data. A higher NSE value, closer to 1, indicates better performance of the SWAT model, reflecting a stronger agreement between simulated outputs and observed data. NSE values range from negative infinity to 1, with 1 representing a perfect match between model simulations and observations.

The PBIAS metric evaluates whether the average trend of the model simulations is higher or lower than that of the

Table 2 Calibrated parameters for SWAT hydrological modelling in the Ganga River basin

Parameters		Description	Units	Calibrated range	Sources
Surface runoff	CN2	Curve number	Dimensionless	60–85	Neitsch et al. (2011)
	ESCO	Soil evaporation compensation factor	Dimensionless	0.5–1	Arnold et al. (2012a, b)
	EPCO	Plant evaporation compensation factor	Dimensionless	0.5–1	Neitsch et al. (2011)
	SURLAG	Surface runoff lag time	Days	1–12	Arnold et al. (2012a, b)
	SOL_AWC	Available water capacity of the soil layer	mm H_2O/mm soil	0.1–0.3	Kannan et al. (2007)
Baseflow	ALPHA_BF	Baseflow alpha factor	Days	0.01–0.1	Arnold et al. (2012a, b)
	GW_REVAP	Groundwater "revap" coefficient	Dimensionless	0.01–0.1	Arnold et al. (2012a, b)
	GW_DELAY	Groundwater delay time	Days	10–150	Gassman et al. (2007)
	GWQMN	Threshold depth of water in the shallow aquifer for return flow to occur	mm	0–2500	Moriasi et al. (2007)
	REVAPMN	Threshold depth of water in the shallow aquifer for "revap" to occur	mm	0–100	Neitsch et al. (2011)
	SHALLST_N	Initial shallow groundwater storage	mm	0–1000	Neitsch et al. (2011)
	RCHRG_DP	Deep aquifer percolation fraction	Dimensionless	0.02–0.2	Gassman et al. (2007)
Snow	SFTMP	Snowfall temperature	°C	−2 to 2	Arnold et al. (2012a, b)
	SMTMP	Snowmelt base temperature	°C	−2 to 2	Arnold et al. (2012a, b)
	SMFMX	Melt factor for snow on June 21	mm H_2O/°C/day	2 to 6	Arnold et al. (2012a, b)
	SMFMN	Melt factor for snow on December 21	mm H_2O/°C/day	2 to 6	Arnold et al. (2012a, b)
	TIMP	Snowpack temperature lag factor	Dimensionless	0.01 to 1	Arnold et al. (2012a, b)
	SNOCOVMX	Maximum snow water content	mm H_2O	50 to 200	Arnold et al. (2012a, b)
	SNOMELT	Snow melt factor	mm/°C/day	1 to 7	Arnold et al. (2012a, b)
	SNO50COV	Snow cover fraction for 50% area	Fraction	0.3 to 0.7	Arnold et al. (2012a, b)

observed data. A positive PBIAS value indicates an overestimation bias, while a negative value suggests an underestimation bias. This parameter provides insights into the overall accuracy of the model in capturing the observed trends.

Additionally, R^2 measures the proportion of the variance in the observed data that is explained by the model simulations. A higher R^2 value indicates a stronger correlation between the model outputs and observed data, highlighting the model's ability to replicate the observed variability.

Furthermore, the RSR metric assesses the goodness-of-fit of the model by comparing the root mean square error to the standard deviation of the observed data. Lower RSR values signify better model performance in terms of both bias and variability.

These performance indices were calculated to rigorously evaluate the accuracy and reliability of the SWAT model in simulating hydrological processes within the study area.

Those four parameters have been calculated to determine the performance indices are given in below:

$$NSE = 1 - \frac{\sum_{i=0}^{n} (Q_{m,i} - Q_s)^2}{\sum_{i=0}^{n} (Q_{m,i} - \overline{Q_m})^2} \tag{4}$$

$$PBIAS = 100 \times \frac{\sum_{i=0}^{n} (Q_m - Q_s)_i}{\sum_{i=0}^{n} Q_{m,i}} \tag{5}$$

$$R^2 = \frac{\left[\sum_{i=0}^{n}(Q_{m,i} - \overline{Q_m})(Q_{s,i} - \overline{Q_s})\right]^2}{\sum_{i=0}^{n} (Q_{m,i} - \overline{Q_m})^2 \sum_{i=0}^{n} (Q_{s,1} - \overline{Q_s})^2} \tag{6}$$

$$RSR = \frac{\sqrt{\sum_{i=1}^{n} (Q_m - Q_s)_i^2}}{\sqrt{\sum_{i=1}^{n} (Q_{m,i} - Q_m)^2}} \tag{7}$$

where Nash–Sutcliffe coefficient stands for NSE, PBIAS, R^2, RSR is root mean square error to standard deviation of measured data, Q is a variable (such as discharge), m and s are variables that have been measured or simulated, and i represents data that has been measured or simulated.

To assess the performance of this model, NSE, PBAIS, R^2, and RSR have been calculated from observed to simulated streamflow. The basic flow conditions have been met with respect to all three indices since the NSE 0.50, $R^2 > 0.70$, PBIAS 0.25 and RSR < 0.75 to 0.50. The results from this model will be relevant to the catchment area.

Results

The SWAT model can generate several outputs at the outflow of each sub-watershed, but the streamflow at the outlet of the whole catchment is the subject of this study since the streamflow into the Ganga River basin can be monitored. The discharge reported by SWAT was calibrated to the available data, since it was previously noted that the outflow of the whole catchment lies in sub-basin 405 with a total contributing area of 1 million km^2. For each parameter range and for each watershed, an annual mean streamflow based on simulated data is obtained by means of a SWAT ensemble model. Significant differences between simulations of various parameter sets have been observed in the ensembles' monthly average streamflow. Monthly stream flow data has been used in this study to analyze the data to calibrate and validate the data. In this study, ten station data have been calibrated and validated the result and the performance test of all data has been through statistical analysis (Figs. 4 and 5). All these data were calibrated with the Observed data from various years based on their data availability on the website. On the other hand, the data were simulated from 1981 to 2022 to analyze the long-term water balance of each watershed with seasonal variability.

Figure 6 clearly depicts that the annual runoff was very high in the eastern watershed as compared to the entire sub-watershed. Rivers originating from hilly areas generate the highest surface runoff, whereas those flowing through plains produce the least runoff. The run off of the river was very diversified in each sub-watershed where river flow pattern changed based on the slope of the region, rainfall, evapotranspiration, and other parameter also affect the stream flow of the river. The highest run off of the river has been seen in the sub-watershed (SW) 198 and minimum in sub-watershed 51. The average annual stream flow of the ten sub-watershed is significantly different from each other. In the diversity of river systems, this model effectively performs the basic flow, which is primarily controlled by the delicate interaction of the return currents and the melting of the snow. During the calibration period, the authors had carefully evaluated the well-known measures NSE, RSR, R^2, and PBIAS, focusing on the various locations within sub-basins. As NSE, R^2, RSR, and PBIAS soar above 0.47, 0.77, 0.77, and 0.29, these statistical indicators at monitoring gauge stations point a magnificent picture of performance perfection, revealing the core of our model's delicacy. In this study, the output of SWAT was correlated with discharge data from GRDC across ten hydrological sites. The scoring performance of four parameters was very distinctive where one or two stations have unsatisfactory value in the case of those four parameters, but the rest of the stations perform good to very good result that increase the acceptance in real world. When these numerical signals are analyzed, the SWAT model emerges as a master conductor because it effectively captures the unique character of the watershed as it flows with surface water. Looking at how this model precisely analyzes the huge deference that flows through rivers, explaining them with excellent NSE, R^2, RSR, and PBIAS values (Fig. 7). However, in view of the small PBIAS values it would not be worth overlooking its delicate performance and subtle depiction of low flows, particularly those that are embedded with snowmelt threads. A visual picture that captures a score of NSE, R^2, RSR, and PBIAS performances at each gauge station carefully examined in the basin's calibration and validation.

Role of snow to change the runoff

Snowmelt plays a crucial role in altering runoff patterns, particularly in the upper Ganga River basin. During the non-monsoon season, snowmelt significantly contributes to surface water discharge, while rainfall during the melt period does not affect total flow. The influence of rainfall on runoff varies regionally and temporally. The upper Ganga River basin, entirely covered by snow, experiences substantial changes in stream flow due to seasonal variations in snowmelt volume, as depicted in Fig. 6, which illustrates the annual snowmelt across the study area.

Increased annual snowmelt from the upper stream regions influences the water flow patterns downstream, especially in moderately elevated areas. During the monsoon season, snowmelt decreases as the high-altitude mountains block sufficient rainfall, leading to lower temperatures and snow formation. Despite only 3% of annual precipitation falling as snow, snowmelt contributes to 8% of the yearly runoff in Ganga River basin, particularly from higher elevation catchments covered in snow. The highest elevations, especially in winter, experience significant snowfall.

Catchment runoff coefficients, representing the ratio of precipitation to runoff, were higher for snowmelt than for rainfall. Reduced actual evapotranspiration during winter contributes to this higher snow-generated runoff percentage. In snowy years, the difference between seasonal and annual snow runoff increases with elevation, highlighting the importance of snow catchments. A future decrease in snow could significantly impact annual runoff volumes. Warmer years with less snowfall show an increased relative snow contribution to runoff due to more frequent snowmelt events during winter, leading to higher runoff. Conversely,

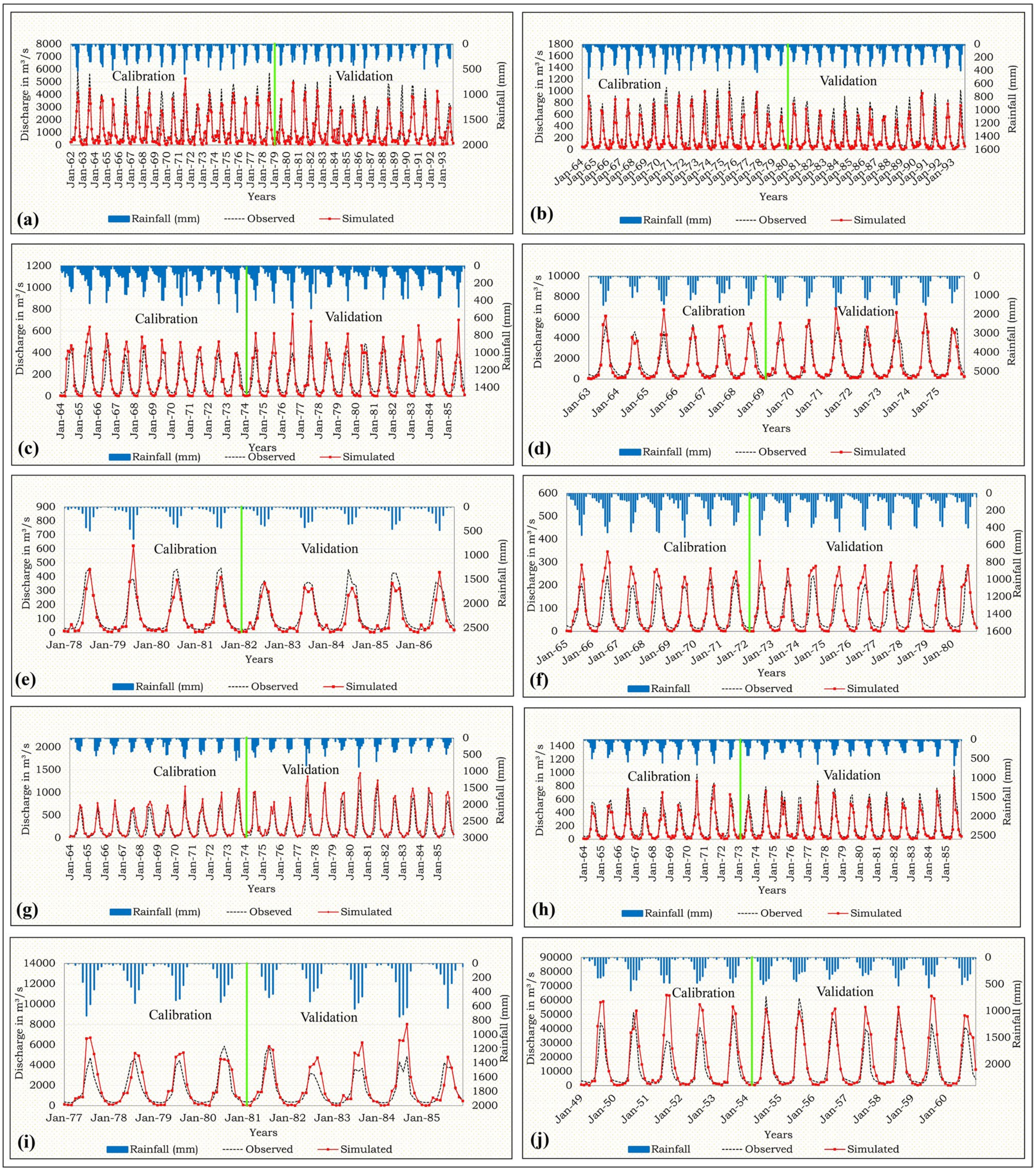

Fig. 4 Comparison of simulated and observed flow during model validation for the period 1949–1993 at monthly scale across ten locations within the Ganga River basin: **a** Chisapani, **b** Seti-beni, **c** Arughat, **d** Devghat, **e** Busti, **f** Barbaise, **g** Pachuar ghat, **h** Rubwar bazar, **i** Chatra kothu, and **j** Farakka

a decrease in snow contribution to summer runoff (June to August) indicates earlier snowmelt, reducing spring groundwater recharge and subsequent summer runoff.

The annual melting of Himalayan snow is pivotal in shaping the hydrology of the Ganga River basin. In spring and early summer, gradual snowmelt significantly enhances river

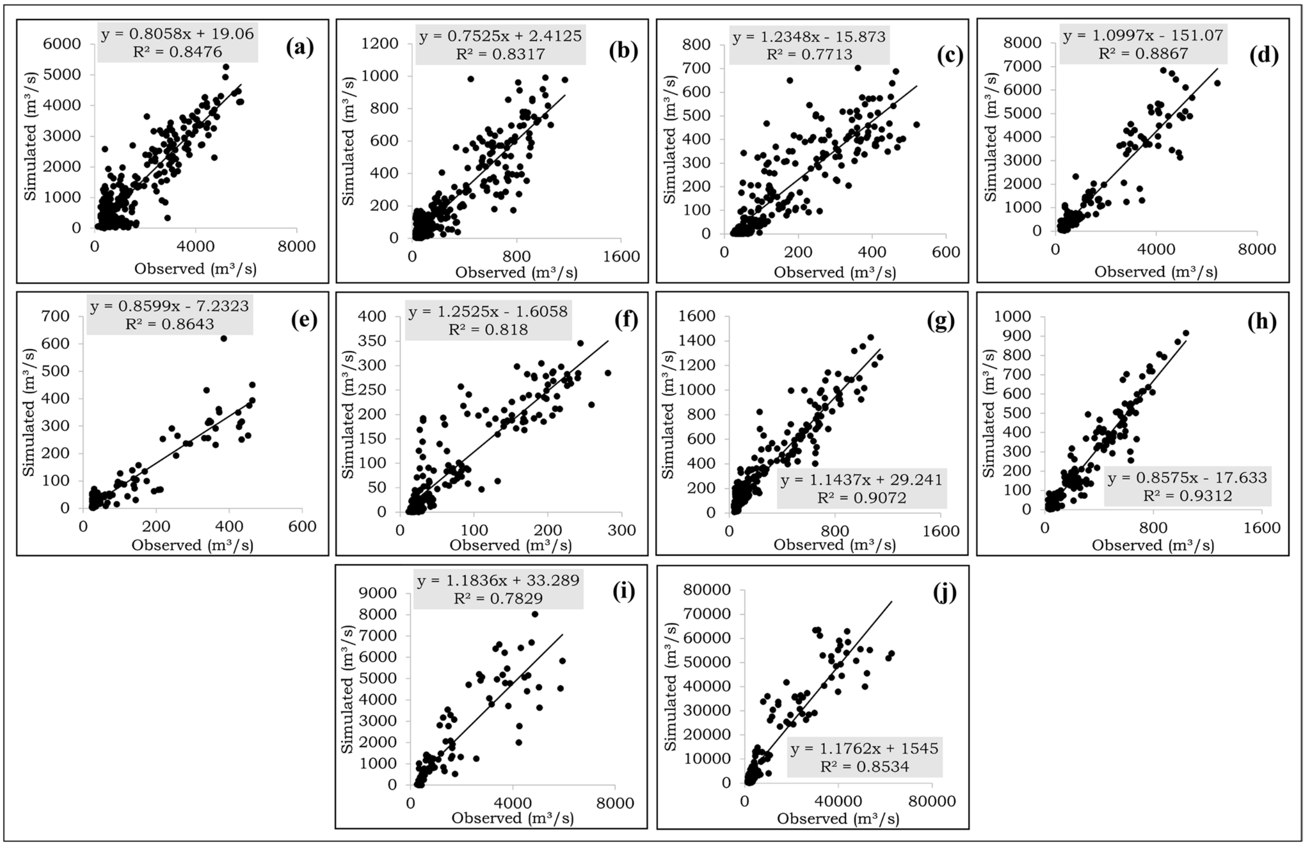

Fig. 5 Comparison of the correlation between observed discharge data and SWAT model simulated discharge data at ten gauge stations within the Ganga River basin: **a** Chisapani, **b** Seti-beni, c Arughat, **d** Devghat, **e** Busti, **f** Barbaise, **g** Pachuar ghat, **h** Rubwar bazar, **i** Chatra kothu, and **j** Farakka

water flow, compensating for the typically reduced winter flow. This increased runoff is essential for sustaining agriculture, replenishing groundwater, and meeting the diverse water needs of the basin's population. Consistent snowmelt timing and volume are vital for maintaining ecological balance and ensuring water availability. Effective water resource management during the crucial pre-monsoon drought period relies on the regularity of snowmelt, supporting agriculture, residential consumption, and industrial operations. Additionally, this period of increased water flow from snowmelt is critical for river health and mitigating water scarcity risks.

Climate change is markedly affecting snowmelt patterns in the Ganga River basin, altering runoff dynamics. Global warming accelerates snow thawing, causing earlier and faster melting. This shift results in peak river flows in late spring and early summer, increasing flood risks during these times. Warmer winters with reduced snow accumulation diminish the available snowmelt, leading to a reduced water supply during the critical pre-monsoon period. The decrease in snowmelt runoff impacts water availability, potentially causing insufficient river flow for agriculture, drinking water, and hydropower. Altered snowmelt timing and volume challenge traditional water management, complicating efforts to maintain water security and support livelihoods in the Ganga River basin. Understanding these patterns is essential for effective water resource management and planning in light of seasonal variations and long-term climate changes.

Water balance

After running a SWAT model in the Ganga River basin, the water balance analysis is integral to understanding and addressing the region's water management challenges. This model helps estimate various components of the hydrological cycle, providing insights into the causes of water shortages and informing sustainable management strategies. Understanding both surface and groundwater resources' behavior and availability is crucial for their effective use with minimal environmental impact. Due to inadequate rainfall, many parts of the Ganga River basin face significant water shortages, making it difficult to extract additional groundwater for agriculture, industry, and other activities. Ensuring a balanced water supply is essential for sustainable growth plans.

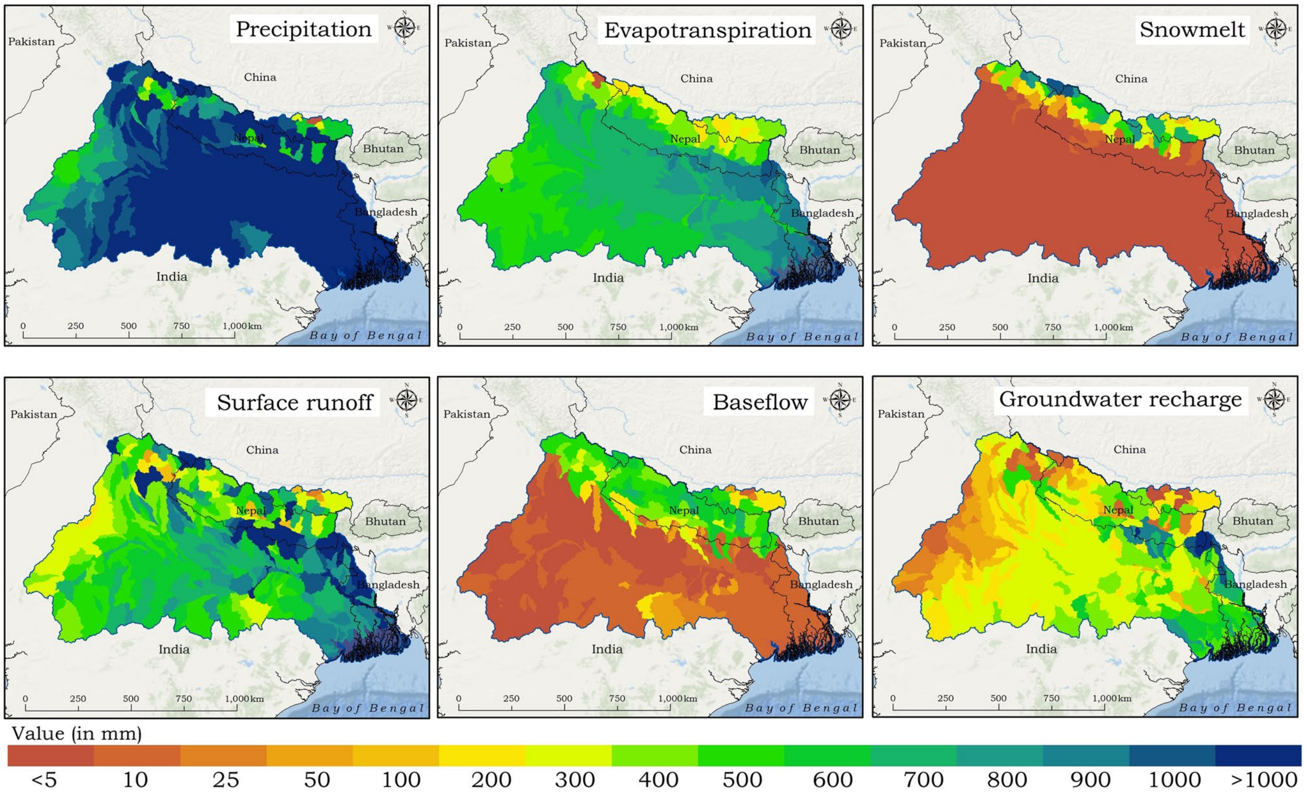

Fig. 6 Spatial distribution of annual average value of the parameters precipitation, evapotranspiration, snow melt, surface runoff, base flow, and groundwater recharge

To calculate the water balance components, it is necessary to collect meteorological, hydrological, and hydrogeological data. The SWAT model predicts key water balance elements beyond just monthly stream flow, facilitating an analysis of how each sub-watershed contributes to the overall water supply during the simulation period through calibrated models. The estimated runoff, which is the largest water balance component, represents a significant input to the region. On average, the Ganga River basin receives an annual rainfall of 1199 mm, with runoff consuming about 511 mm, or approximately 43% of the total rainfall. When base flow is included, the total discharge is 543 mm per year, which equates to 45.25% of the annual precipitation, with 42.57% from surface runoff and 2.68% from base flow. This high runoff is primarily due to precipitation and prevailing high temperatures.

Evapotranspiration is another critical component of the water balance, consuming about 497 mm annually, which is 41.41% of the total rainfall. Groundwater recharge, although relatively smaller, accounts for approximately 14.24% of the rainfall. A long-term analysis of the monthly water balance data reveals that the Ganga River basin experiences water shortages during the lean season. The key water balance parameters include precipitation, evapotranspiration, snowmelt, surface runoff, base flow, and groundwater recharge.

Seasonal analysis shows significant water surpluses during the monsoon season (June to September), as depicted in Fig. 8, due to high precipitation levels. In contrast, the post-monsoon (October to December) and lean seasons (January to May) face water shortages, as shown in Fig. 9 and Fig. 10, respectively. To accurately quantify these variables, except precipitation, forecasts are necessary due to the difficulty in direct estimation.

Figure 6 illustrates the average annual basin values of various water balance components, derived as proportions of the annual average rainfall over the calibration and validation periods simulated by the model. This comprehensive analysis of water balance components, including runoff, evapotranspiration, and groundwater recharge, underscores the importance of addressing seasonal variations in water availability. The SWAT model's ability to simulate these components accurately provides valuable data for developing effective water management strategies. These strategies must consider the geographical and seasonal variations within the basin to mitigate water shortages and support sustainable growth. By addressing the hydrological processes and their components, the SWAT model aids in understanding the region's water dynamics and identifying areas requiring targeted management interventions. The detailed analysis highlights the necessity of balancing water supply to meet

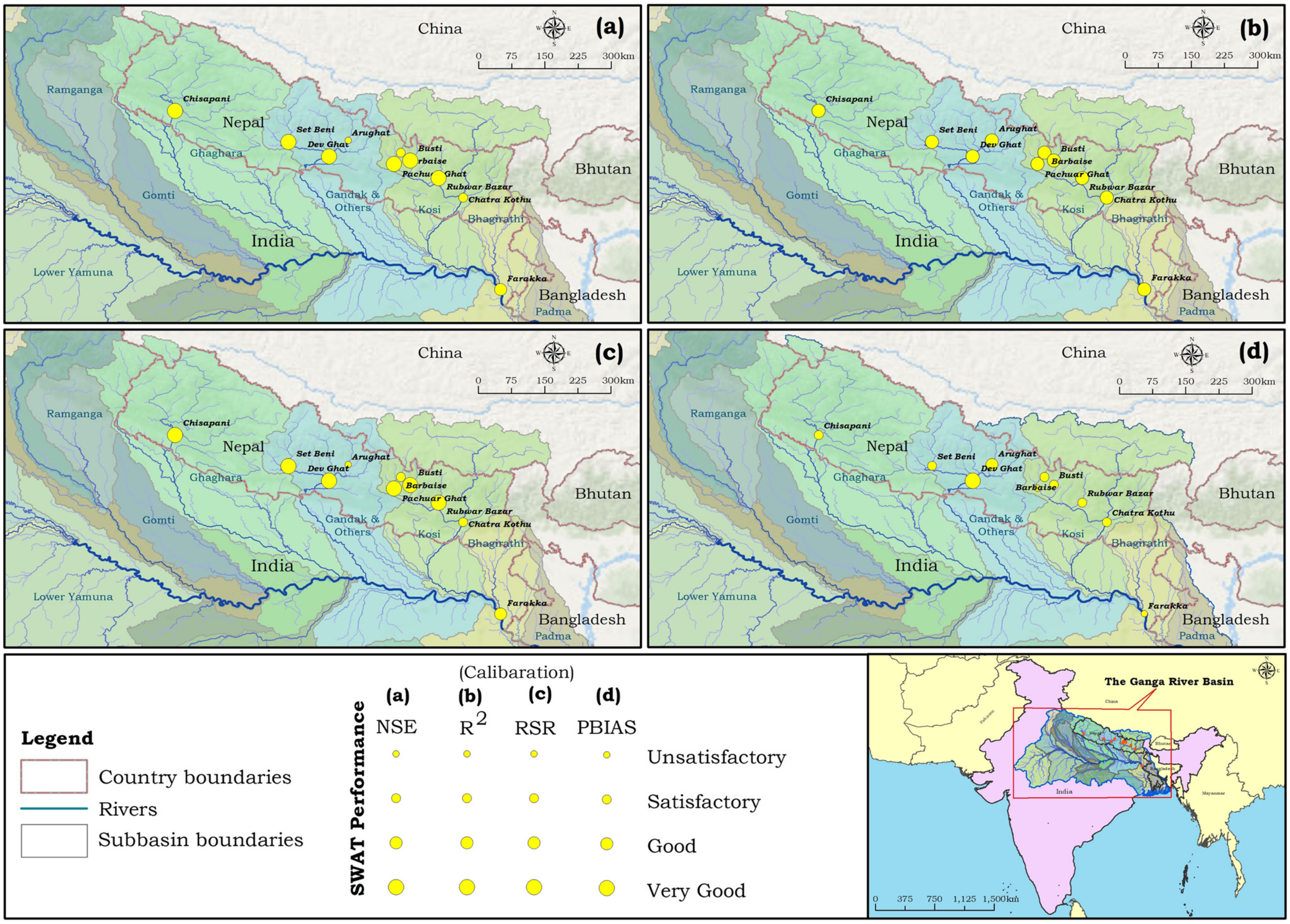

Fig. 7 Visual representation of NSE, R-squared, PBIAS, and root mean square error ratio (RSR) for the SWAT model performance evaluation

various demands while minimizing environmental impact. Such insights are crucial for formulating policies that ensure sustainable water resource management in the Ganga River basin, particularly in the face of climatic variability and increasing water demands.

Water yield

Water yield is crucial for effective water management and planning in the Ganga River basin. Using the calibrated SWAT model, the contribution of each sub-watershed to the overall water yield was analyzed for the period from 1981 to 2022. This analysis included assessing evapotranspiration (ET) rates across the sub-watersheds, as ET is a significant indicator of water availability and yield. Figure 11 illustrates the average ET for each sub-watershed over the study period. Sub-watershed 262 exhibited the highest ET rate at 1188 mm, which can be attributed to the dense vegetation and the prevalence of warm weather in the region. This high ET rate indicates significant water loss through evaporation and plant transpiration, which affects the overall water availability in the area. In contrast, sub-watershed 51 had the lowest water production, with an ET rate of only 14 mm. The low ET in this region is due to minimal rainfall and potentially sparse vegetation cover, leading to reduced water retention and availability.

Snow plays a vital role in the water resources of the Ganga River basin, particularly in the eastern section of the watershed. This region experiences high rainfall due to the presence of a mountain range, which also leads to substantial snow accumulation. Snowmelt is critical in replenishing water supplies during dry periods, contributing significantly to the river system's flow.

Effective water management in the Ganga River basin necessitates thoroughly analyzing various hydrological processes, including precipitation, evapotranspiration, and snowmelt. Understanding the interplay between these elements is essential for predicting water yield under different climatic conditions and land use scenarios.

The calibrated SWAT model was used to quantify the contributions of each sub-watershed to the overall water yield from 1981 to 2022. Significant disparities in ET across the

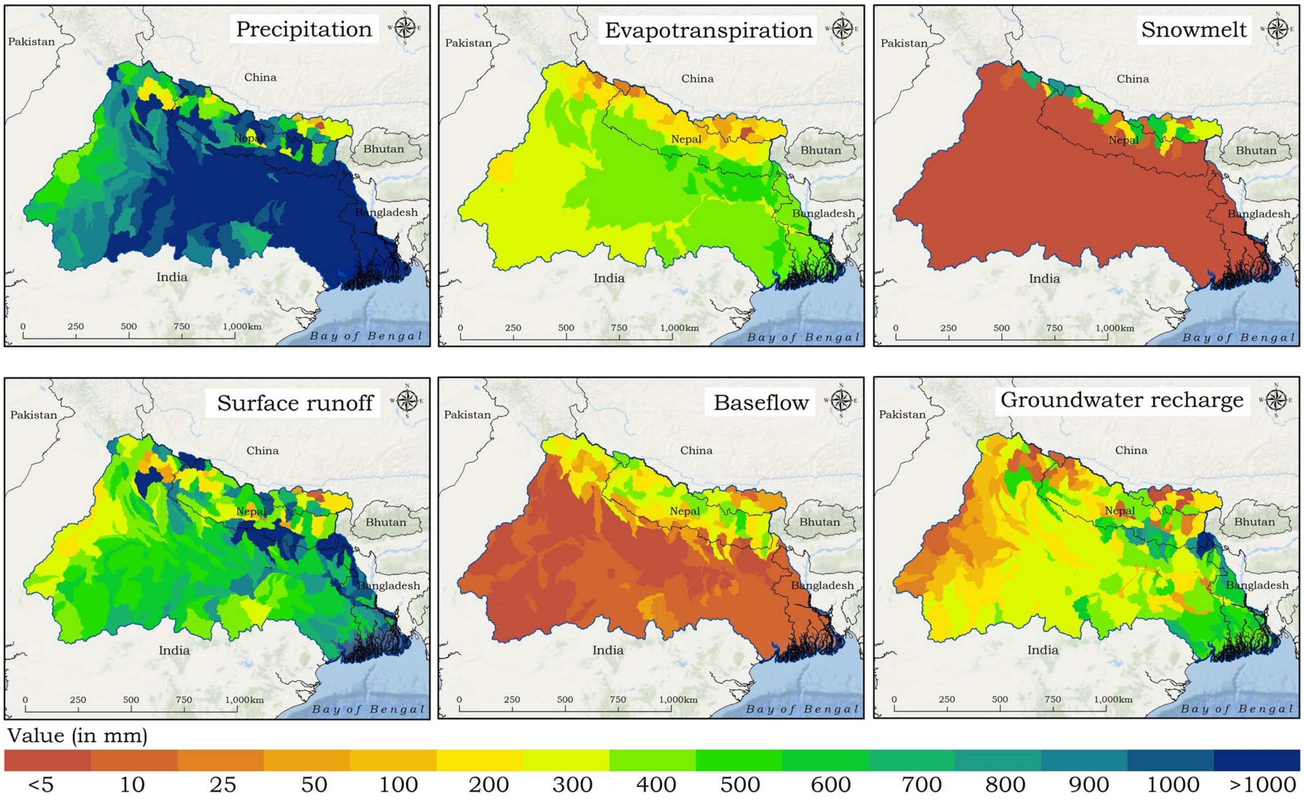

Fig. 8 Spatial distribution of Monsoon (June to September) average value of the parameters precipitation, evapotranspiration, snowmelt, surface runoff, baseflow, and groundwater recharge

sub-watersheds highlight the variability in water availability within the basin. Sub-watershed 262 has the highest ET rate of 1188 mm. This sub-watershed's high water loss is due to its lush vegetation and warm climate, which promote high evapotranspiration rates. Sub-watershed 51 exhibits the lowest ET rate of 14 mm; this area suffers from low rainfall and sparse vegetation, leading to minimal water production and availability. The presence of snow in the eastern region of the basin, influenced by mountainous terrain, results in significant snow accumulation and subsequent snowmelt. This process is crucial for maintaining water supplies during the lean season and mitigating drought impacts. Understanding the dynamics of water yield in the Ganga River basin is critical for developing effective water management strategies.

Utilizing hydrological models to forecast water production under various climatic and land use scenarios, ensuring preparedness for future conditions. Planning the allocation of water resources to meet the demands of agriculture, industry, and domestic use while maintaining ecological balance. Formulating strategies to adapt to changing environmental conditions and population pressures, ensuring sustainable water use.

The study of water yield in the Ganga River basin using the SWAT model reveals significant variability in ET and highlights the importance of snowmelt in sustaining water supplies. These findings are crucial for informed water management and planning, aiming to ensure the long-term availability and sustainable use of water resources in the region. Analyzing the relationships between precipitation, evapotranspiration, and snowmelt is essential for addressing the challenges of climate change and increasing water demands. By integrating these insights into water resource management strategies, policymakers can develop robust plans to maintain the natural balance of the river basin, support agricultural and industrial activities, and meet the domestic water needs of the growing population.

Discussion

This study presents realistic operation strategies for the rivers, dams, and reservoirs in the Ganga River, utilizing the SWAT model combined with a Genetic Algorithm (Garg & Karlberg 2021). These strategies aim to enhance dam and reservoir management in both dry and wet conditions (Singh et al. 2020). By optimizing water release schedules, the storage-governed priority approach can significantly improve the reservoirs' ability to meet immediate water demands and future needs, especially during anticipated droughts

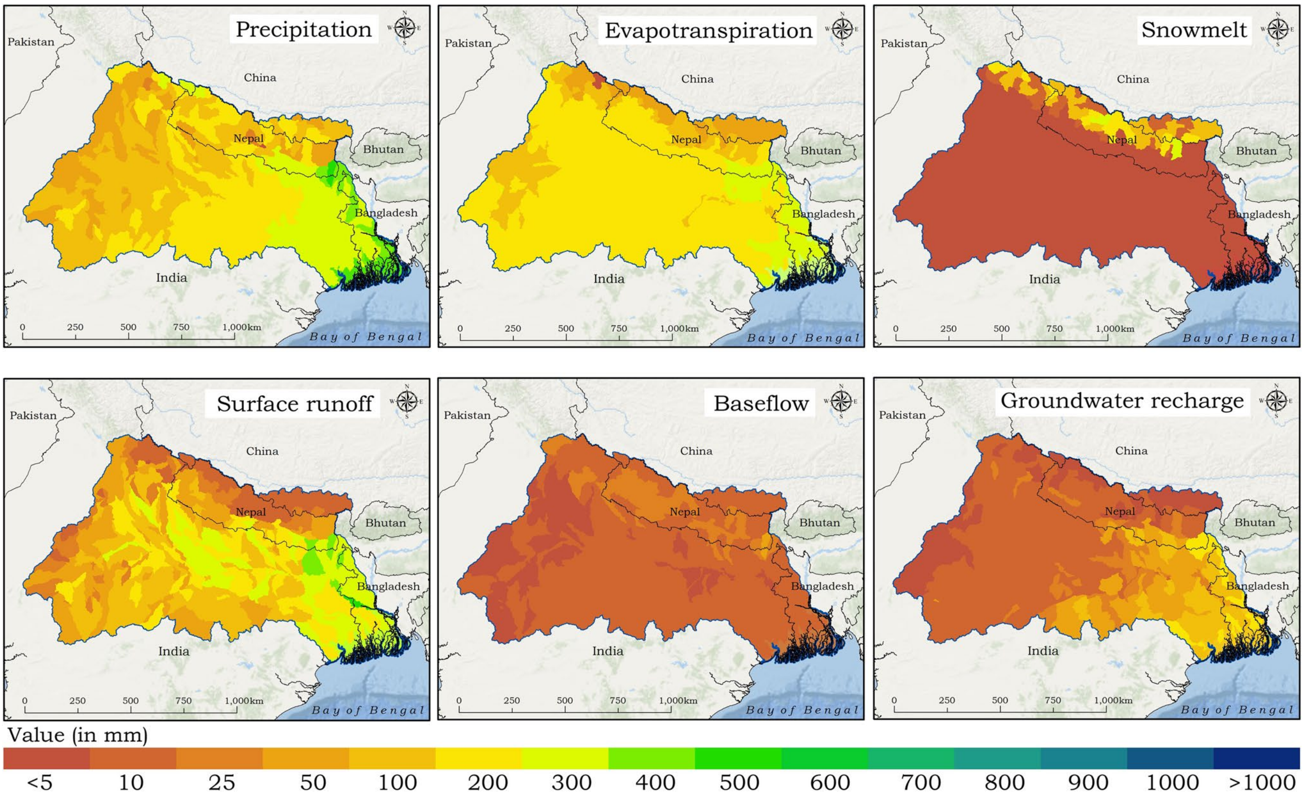

Fig. 9 Spatial distribution of Post Monsoon (October to December) average value of the parameters precipitation, evapotranspiration, snowmelt, surface runoff, baseflow, and groundwater recharge

(Shrestha et al. 2018). This method involves adjusting water releases to increase storage capacity, which is critical for establishing effective drought response strategies (Kumar et al. 2022). Conversely, the hydropower production-governed priority focuses on maximizing hydropower output when water is abundant and scarcity is not anticipated (Jain et al. 2019).

The SWAT model proves invaluable in understanding the hydrological dynamics of the Ganga River basin, one of the world's major river systems (Arnold et al. 2012a, b). The model's ability to accurately simulate various water balance components—such as precipitation, evapotranspiration, surface runoff, baseflow, and groundwater recharge—offers deep insights into the hydrological processes within the basin (Neitsch et al. 2011). Calibration and validation against streamflow data from ten hydrological stations primarily based on data availability show that the SWAT model performs well, indicated by favorable statistical measures like NSE, R^2, RSR, and PBIAS for most stations (Moriasi et al. 2007). These sites include major tributaries and their respective sub-watersheds, with gauge stations strategically placed (Gassman et al. 2007). Among these sites, one significant location is upstream of the Farakka Barrage, which is the largest river site of the Ganga River (Gupta et al. 2015). By incorporating data from both small and large watershed gauge stations, the study ensures a more precise calibration and validation of the model. However, the study faces a major limitation due to data unavailability, which is exacerbated by the transboundary nature of the river and intra-country water disputes (Sharma et al. 2016). Also, localized calibration is necessary to address inadequacies in some stations, ensuring precise modelling of hydrological responses across diverse sub-watersheds (Nash & Sutcliffe 1970).

The study highlights significant variations in annual streamflow among sub-watersheds, influenced by factors such as terrain, rainfall patterns, and land use (Sang et al. 2016). For instance, higher runoff in the eastern watershed is attributed to mountainous river sources, whereas flat areas experience less runoff, underscoring the impact of geographical differences on streamflow volumes (Vaze et al. 2010).

The SWAT model's predictions reveal that the Ganga River basin receives an average annual rainfall of 1199 mm, with approximately 43% converting to runoff. Evapotranspiration is a major component, accounting for about 41.41% of the total rainfall annually. In the upper basin regions, snowmelt significantly contributes to runoff, particularly

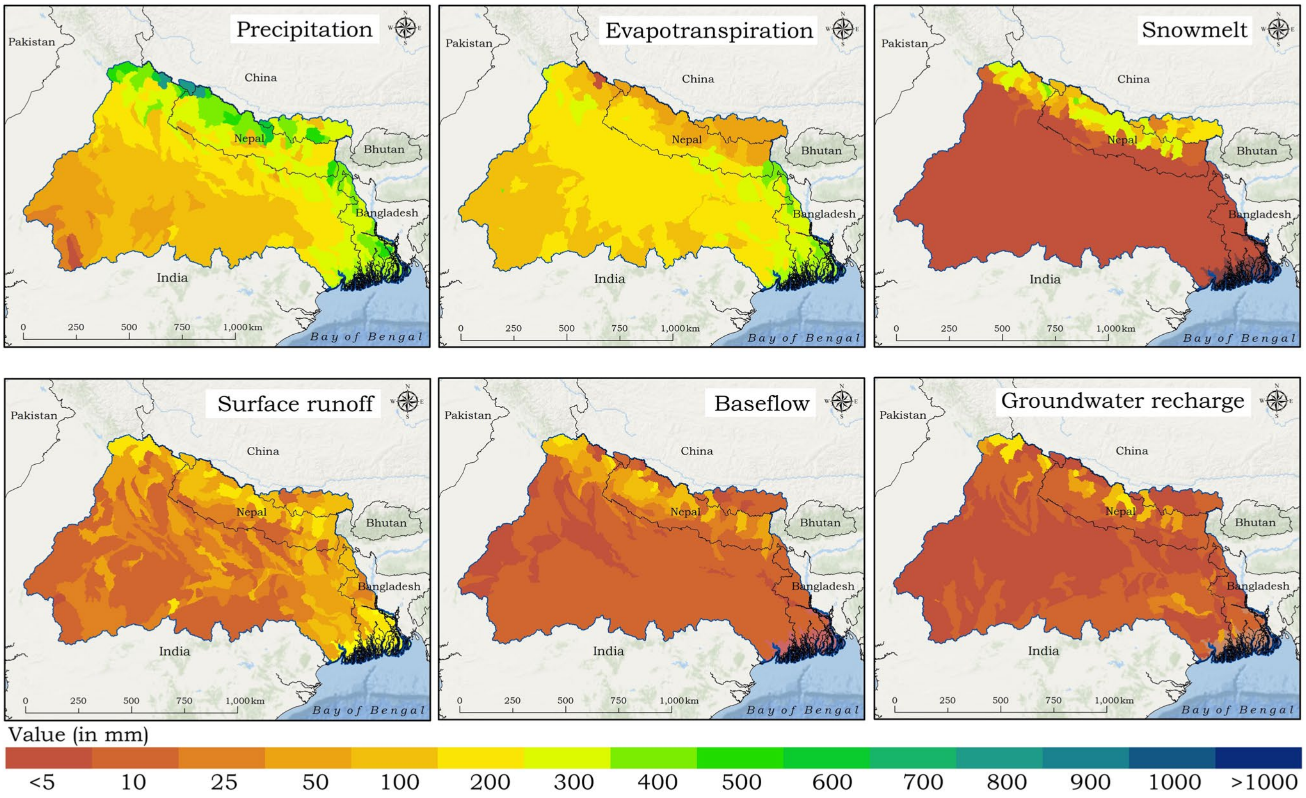

Fig. 10 Spatial distribution of Lean Period (January to May) average value of the parameters precipitation, evapotranspiration, snowmelt, surface runoff, baseflow, and groundwater recharge

during non-monsoon seasons, affecting streamflow dynamics (Immerzeel et al. 2010). Seasonal water balance analysis indicates water surpluses during the monsoon and shortages during post-monsoon and lean seasons, posing challenges for water management during dry periods (Chawla & Mujumdar 2015).

The study also notes considerable variation in water output and evapotranspiration across sub-watersheds. For example, sub-watershed 262, with its dense vegetation and favorable climate, exhibits the highest evapotranspiration rates, while sub-watershed 51 shows the lowest water production. These findings highlight the necessity for targeted water management strategies to address seasonal variations and ensure sustainable water supply (Mango et al. 2011).

Future research should focus on enhancing model calibration in areas with suboptimal performance metrics and examining the impacts of climate change on Ganga River basin's hydrological dynamics (IPCC 2021). This will help maintain the SWAT model's efficacy in providing accurate and actionable data for water resource management. The comprehensive understanding and robust forecasting capabilities of the SWAT model are crucial for developing sustainable water management practices and mitigating the adverse effects of climate variability in the Ganga River basin.

The innovative approach of optimizing water release schedules based on storage and hydropower production priorities is a significant advancement, offering adaptive management solutions tailored to both drought and surplus water conditions (Sharma et al. 2020). The study's ability to accurately simulate hydrological processes, such as streamflow, precipitation, evapotranspiration, and groundwater recharge, underscores the robustness of the SWAT model. However, limitations include the need for localized calibration to address discrepancies in certain hydrological stations, which indicates a potential gap in the model's precision across diverse sub-watersheds. Additionally, while the model performs well in simulating current hydrological dynamics, further research is required to assess its accuracy under future climate change scenarios. The scientific contributions of this work are substantial, providing a deeper understanding of the Ganga River basin's hydrological behavior and offering practical insights for sustainable water resource management. The research underscores the importance of targeted water management strategies that consider geographical and seasonal variations, thus laying the groundwork for more resilient water management policies in the face of climatic variability.

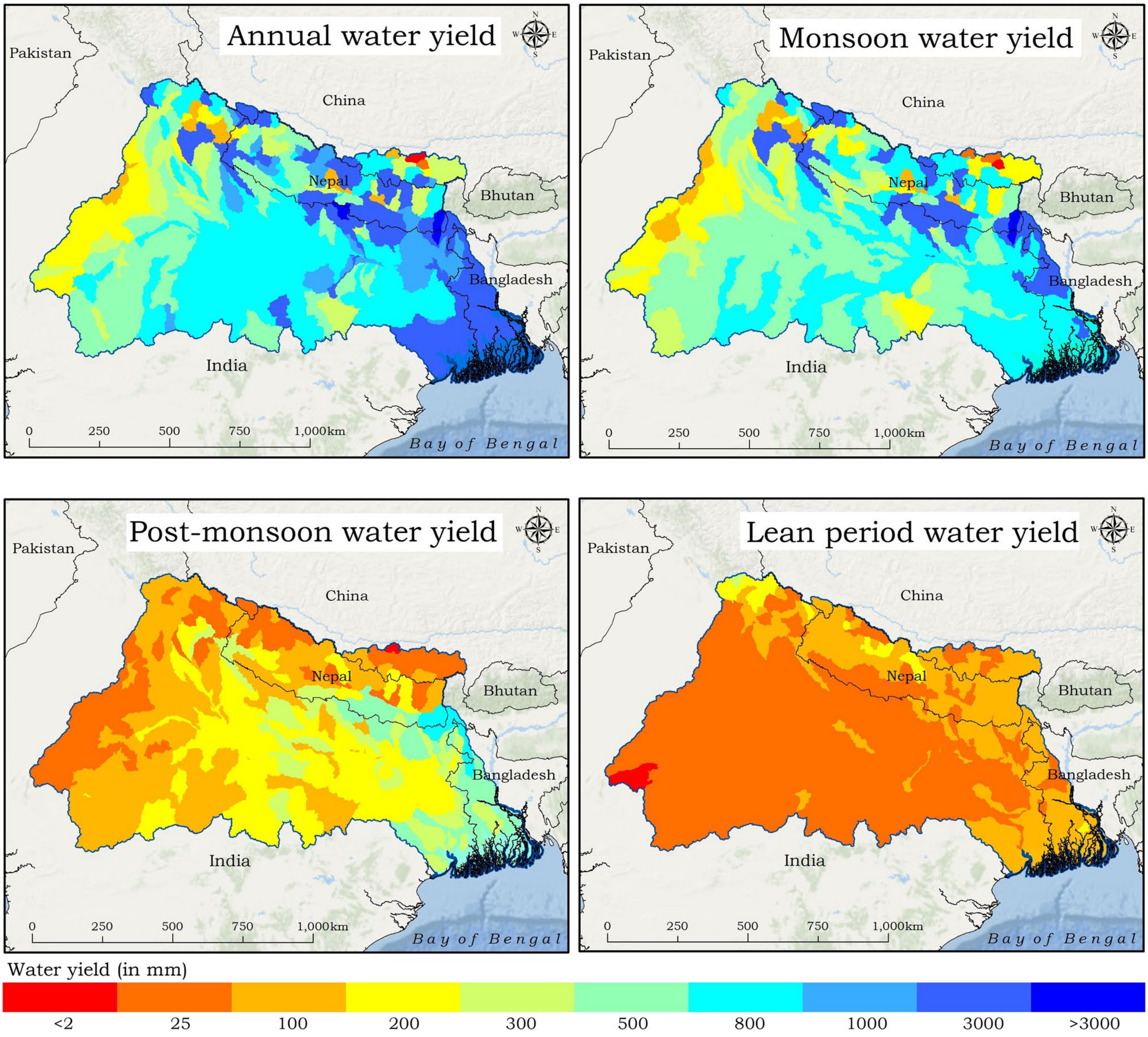

Fig. 11 Spatial and seasonal distribution of water yield of Ganga River basin

Conclusion

Performing hydrological modelling in large basins like the Ganga, which spans over 1 million km^2, is a challenging and time-consuming task that requires a high level of computational performance. To achieve accurate results, meticulous parameterization of the model is essential, often requiring multiple iterations. In this study, SWAT hydrological model to the Ganga basin was applied. High-resolution geospatial inputs were utilized, including ESRI land cover data merged with the IWMI irrigated area map at a resolution of 90 m and SRTM DEM data at a resolution of 90 m. Soil data were obtained from the Food and Agriculture Organization (FAO) digital soil map and Indian Soil Data sets from Bhuvan NRSC, which were converted to a resolution of 90 m. Additionally, rainfall and temperature data were sourced from the Indian Meteorological Department (IMD) gridded data and other meteorological datasets such as the CFSR data. Calibration and validation of the model were performed using 45 years of data (1949–1993) at ten different locations within the basin, with observed data obtained from the GRDC monthly datasets. Up to 2022, simulated discharge data were derived for water balance calculation and further processing. The results demonstrated excellent performance of the model in simulating streamflow, with R-square values ranging from 0.83 (Seti-beni) to 0.93 (Rubwar bazar) during the validation period at most locations, except for two locations: Arughat and Chatra kothu. In the regions where data on river discharge are scarce, particularly in transboundary river basins where water disputes may exist, hydrological modelling tools like SWAT are invaluable for estimating discharge for flood frequency analysis and other hydrological process analyses. The calibrated and validated model presented in this study holds significant utility for water resources planning and management across the Ganga basin.

Moreover, this study underscores the importance of utilizing high-resolution remotely sensed information for hydrological modelling, particularly in mountainous and snow-covered catchments and alluvial channels. Such data provide critical insights for geomorphologists and hydraulic engineers alike, facilitating better understanding and management of water resources in complex river basins.

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Author contribution Kunal Chakraborty: conceptualization, data curation, methodology, figure generation, and writing (original draft); Debasish Mandal: conceptualization, data handling, writing (review and editing); Snehasish Saha: supervision, review and editing).

Data availability Various secondary freely available datasets have been used to develop such novel results of this study. The datasets generated during the current study are available from the corresponding author on reasonable request.

Declarations

Ethical approval Not applicable.

Consent to participate Not applicable.

Consent for publication All authors approved the manuscript for publication.

Competing interests The authors declare no competing interests.

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