SWAT HYDROLOGICAL MODEL DEVELOPMENT OF DHARLA RIVER BASIN FOR FUTURE CLIMATE CHANGE IMPACT ASSESSMENT

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ABSTRACT

The Dharla River Basin, a transboundary watershed flowing from India into northern Bangladesh, plays a critical role in regional water supply, agriculture, and flood management. With increasing concern over climate variability and its influence on river flow regimes, establishing a reliable hydrological modelling framework is essential for assessing future changes. This study focuses on the development, calibration, and validation of a Soil and Water Assessment Tool (SWAT) model for the Dharla River Basin to create a scientifically robust baseline for future climate change impact assessments. High-resolution spatial datasets—including a 30 m Digital Elevation Model (DEM) from USGS, FAO global soil data, and ESRI land cover information—were processed and integrated into the QSWAT interface. The watershed was delineated into three sub-basins, and Hydrologic Response Units (HRUs) were generated based on land use, soil type, and slope classes using threshold values of 5%, 10%, and 10%, respectively. Daily climatic inputs consisting of precipitation and temperature were obtained from Bangladesh Meteorological Department (BMD) stations at Rangpur, Saidpur, and Dinajpur. Additional upstream rainfall data from India Meteorological Department (IMD) NetCDF products were extracted for Jalpaiguri, Alipurduar, Cooch Behar, and southern Bhutan to account for transboundary hydrological processes. All datasets were pre-processed, cleaned, and converted into SWAT-compatible formats. The model was calibrated and validated using monthly observed discharge from the Bangladesh Water Development Board (BWDB) at Kurigram station. Daily discharge records for 1991–2021 were aggregated into monthly averages to match SWAT output. Calibration was performed for 2004–2015 and validation for 2016–2021 using the SUFI-2 algorithm in SWAT-CUP. Fourteen sensitive hydrological parameters—including CN2, ALPHA_BF, GW_DELAY, ESCO, and CH_K2—were selected based on literature and sensitivity testing. Model performance was assessed through widely accepted statistical indicators: R^2, NSE, KGE, PBIAS, p-factor, and r-factor. The calibrated model demonstrated strong performance, achieving $R^2 = 0.92$, NSE = 0.85, KGE = 0.73, PBIAS = +24.9%, p-factor = 0.89, and r-factor = 0.80. These results indicate very good correlation, strong predictive skill, and acceptable uncertainty representation. Time series comparisons further confirm that simulated flows reasonably match observed seasonal and inter-annual variability. The successful calibration and validation of the SWAT model confirm its capability to accurately simulate the hydrological behaviour of the Dharla River Basin using available spatial and climatic inputs. This study establishes a comprehensive hydrological modelling framework that can be extended for future analyses of climate change impacts under CMIP6 scenarios. The developed model provides a reliable foundation for evaluating projected discharge changes, flood risk, low-flow variability, and transboundary water resource challenges. The outcomes support both scientific research and water management planning, enabling more informed decision-making for the Dharla River Basin in the context of a changing climate.

Keywords: *SWAT, Hydrological Modeling, Dharla River Basin, Calibration and Validation.*

1. INTRODUCTION

Rivers play a critical role in sustaining ecosystems, supporting livelihoods, and providing water resources for agriculture, industry, and domestic use. The Dharla River, a transboundary river flowing through northern Bangladesh and parts of India, is an important water source for the region. Like many river basins in South Asia, the Dharla Basin is highly sensitive to climatic variability, and changes in precipitation and temperature patterns can significantly affect river discharge, flood frequency, and water availability.

In recent decades, climate change has emerged as a major driver of hydrological variability worldwide. Changes in rainfall intensity, temperature, and evapotranspiration directly influence river flow regimes, posing challenges for water resource management, flood mitigation, and sustainable development. Accurate predictions of hydrological responses under future climate scenarios are therefore essential for effective planning and management, particularly in transboundary river basins where upstream and downstream interactions complicate water allocation.

Hydrological models have proven to be effective tools for simulating river basin responses to climatic and land-use changes. The Soil and Water Assessment Tool (SWAT) is widely used for watershed-scale modeling due to its ability to integrate spatial datasets, simulate hydrological processes, and predict river discharge under different climate scenarios. SWAT has been successfully applied to numerous basins in Bangladesh and South Asia to assess the impacts of climate change, land use changes, and water management interventions.

The main objective of this study is to develop and calibrate a SWAT-based hydrological model for the Dharla River Basin and evaluate its performance in reproducing observed streamflow. The calibrated model provides a foundation for future assessments of climate change impacts using CMIP6-based RCP 4.5 (moderate emission) and RCP 8.5 (high emission) scenarios. By quantifying potential changes in river discharge, seasonal variability, and flood risk, this research contributes to informed water resources planning, sustainable basin management, and the identification of priority areas for adaptation strategies. For hydrological studies, (Baten & Titumir, 2016)found that under RCP 4.5, river basins in South Asia, such as the Ganges-Brahmaputra-Meghna system, may experience moderate increases in runoff during monsoon periods but less dramatic changes in annual discharge compared to higher emission scenarios. (Shrestha et al., 2017)also report heightened flood risks and altered river discharge patterns in the Upper Brahmaputra basin under RCP 8.5.

2. MATERIALS AND METHODOLOGY

The methodology of this study was designed to systematically develop, calibrate, and validate a hydrological model of the Dharla River Basin using the Soil and Water Assessment Tool (SWAT). A combination of high-resolution spatial datasets observed hydro-climatic records and transboundary rainfall inputs was integrated to construct a strong modelling framework. The methodological workflow consisted of four major components: (i) preparation and pre-processing of spatial datasets, (ii) compilation and formatting of climate and discharge data for model forcing; (iii) model setup and simulation; and (iv) calibration and validation of simulated streamflow using SWAT-CUP. Each step was executed following established SWAT modelling guidelines to ensure consistency, reliability, and applicability of the model for future climate change impact assessments.

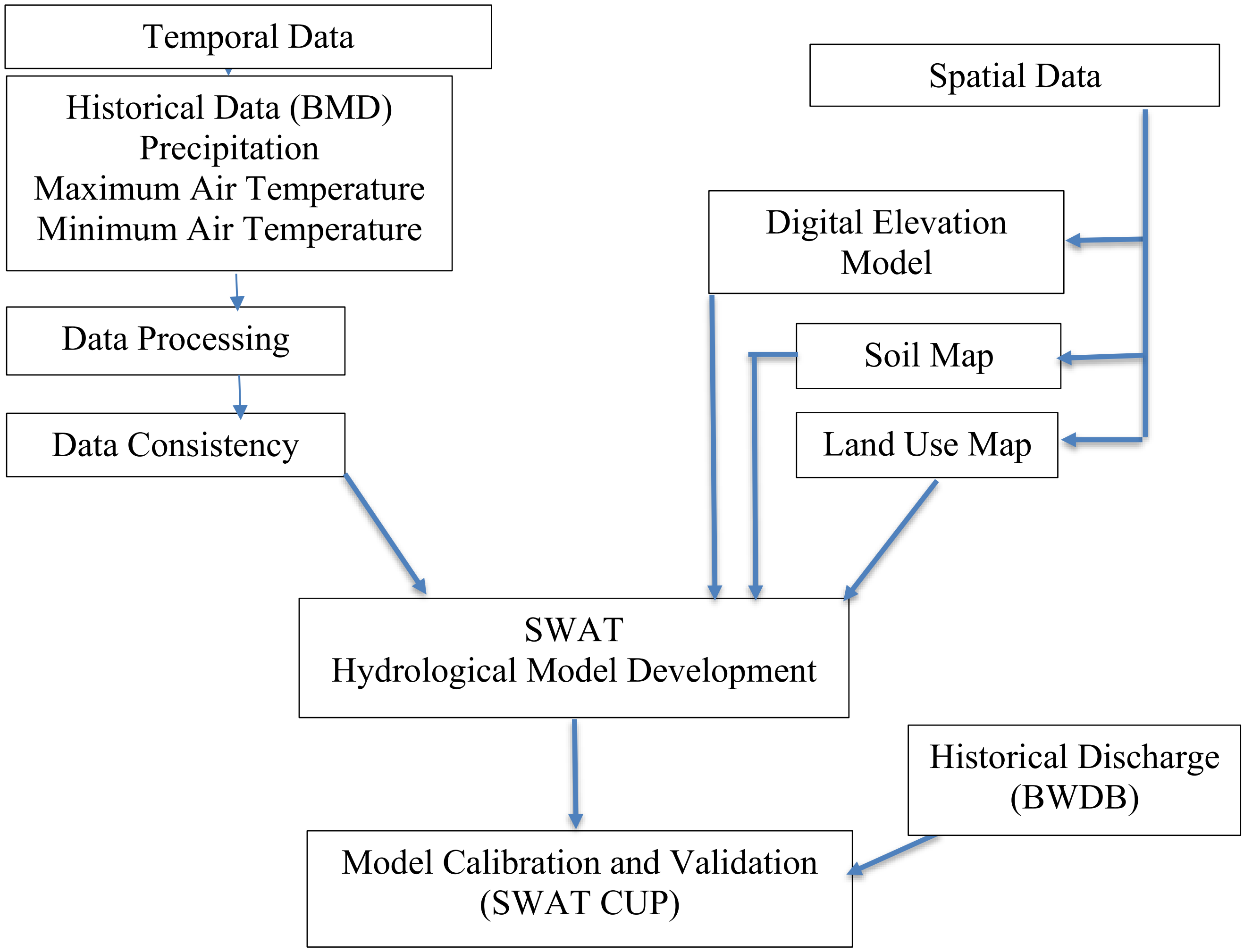

Figure 2: Methodology Flowchart

2.1 Study Area

The Dharla River Basin is a transboundary watershed originating from the foothills of the Himalayas in Bhutan, flowing through the Indian districts of Jalpaiguri and Cooch Behar, and finally entering Bangladesh through the Lalmonirhat district before joining the Brahmaputra River. The basin supports agriculture and livelihoods in northern Bangladesh but frequently experiences seasonal flooding and dry-period water scarcity. The region lies within a subtropical monsoon climate zone characterized by high rainfall during June–September and distinct dry conditions in winter. The terrain varies from hilly upstream catchments in Bhutan to flat alluvial plains in Bangladesh, creating diverse hydrological responses across the basin.

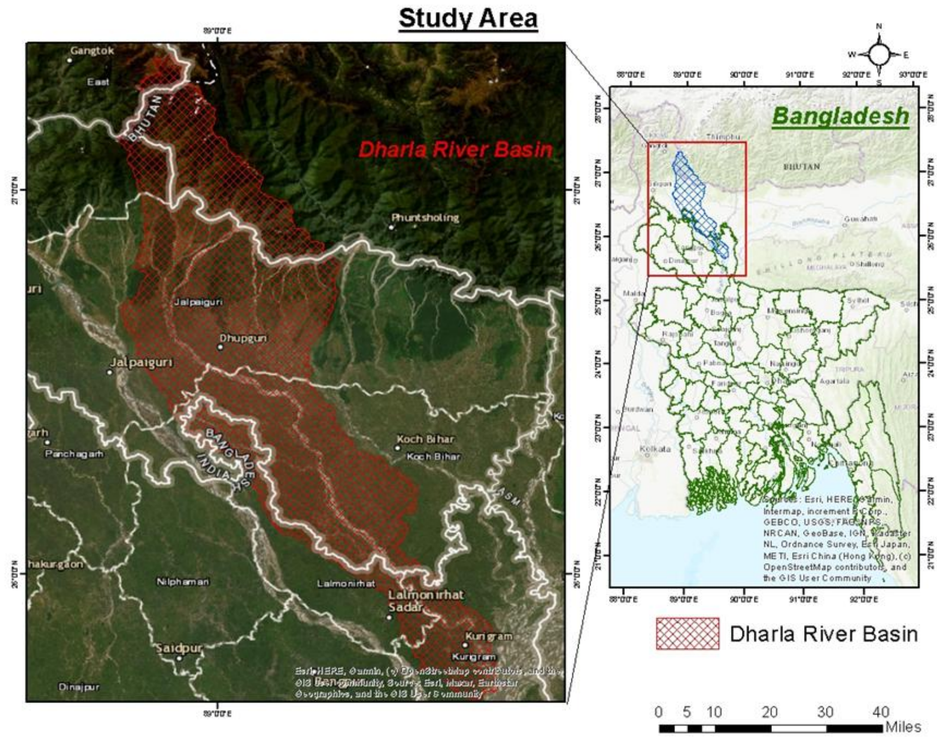

Figure 2.1: Study Area Map

2.2 Model Description

The Soil and Water Assessment Tool (SWAT) was employed to simulate hydrological processes in the Dharla River Basin. SWAT is a semi-distributed, process-based model that divides the watershed into multiple sub-basins, further subdivided into Hydrologic Response Units (HRUs) based on unique combinations of land use, soil, and slope. This spatial discretization allows the model to simulate water balance components such as surface runoff, infiltration, evapotranspiration, baseflow, and lateral flow independently for each HRU. Channel routing was performed using the Muskingum method, which accounts for transmission losses, evaporation, and baseflow contributions along the river network.
At the core of SWAT is the water balance equation, which integrates various hydrological fluxes to estimate daily soil moisture dynamics:

$$SWt = SW0 + \sum j = 1t\ (Rday - Qsurf - Ea - Wseep - Qgw) \quad (01)$$

Where:
- SW_t is the final soil water content (mm),
- SW_0 is the initial soil water content (mm),
- $R_{(day)}$ is daily precipitation (mm),
- $Q_{(surf)}$ is surface runoff (mm),
- E_a is evapotranspiration (mm),
- $W_{(seep)}$ is water percolating into the vadose zone (mm),
- $Q_{(gw)}$ is return flow from the shallow aquifer (mm).

This equation (01) provides the foundation for quantifying the water balance and simulating hydrological behavior across varying spatial and temporal scales. DEM, Soil and Land Use Data Preparation. ((Lamichhane et al., n.d.)

Hydrological modeling has become essential for assessing climate change impacts on river discharge, water resources, and extreme hydrological events. Among the widely used models, the Soil and Water Assessment Tool (SWAT) has gained significant recognition due to its capability to simulate hydrological processes under changing climate scenarios. SWAT operates on a semi-distributed approach, integrating climate, soil, land use, and topographic data to predict surface runoff, streamflow, sediment transport, and water quality. (Gassman et al., 2014).

2.3 Data Collection and Processing

2.3.1 Digital Elevation Model (DEM)

A 30-meter resolution DEM was obtained from the USGS Earth Explorer platform. The tiles were mosaicked and projected to UTM Zone 45N using ArcGIS, and the basin boundary was delineated using the “Extract by Mask” tool. This DEM served as the foundation for stream network generation and watershed delineation.

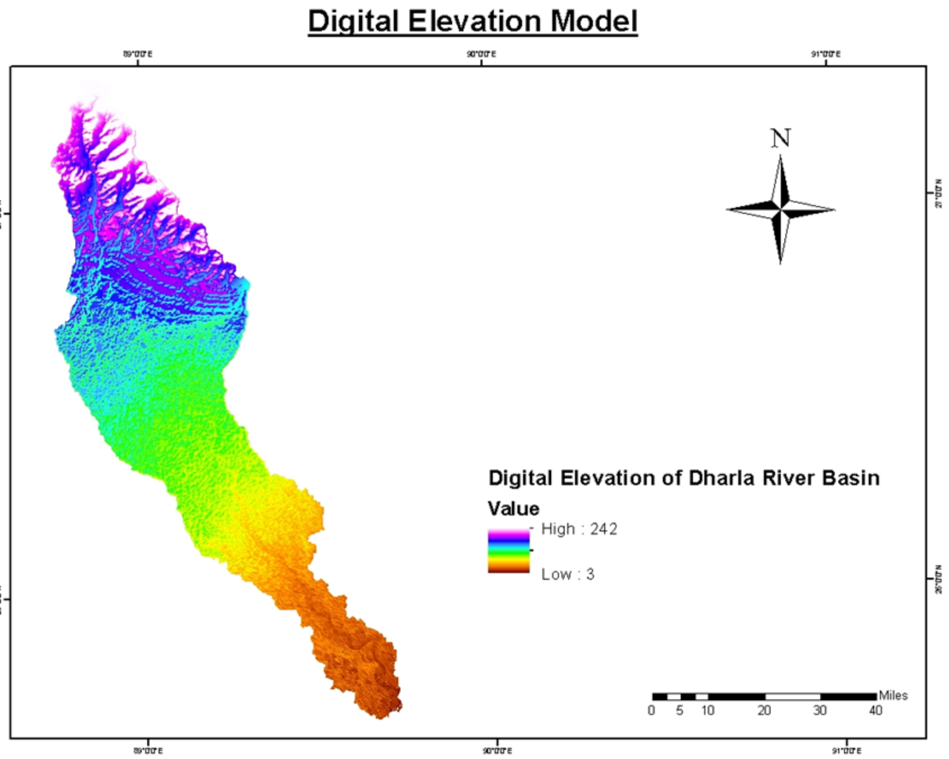

Figure 2.3.1: DEM of Dharla River Basin

2.3.2 Soil Data

Soil data were collected from the FAO global soil database and clipped to match the basin boundary. The soil attributes, including texture, hydraulic conductivity, and available water content, were processed to be compatible with SWAT input requirements. The data were projected to UTM Zone 45N and resampled to a 30 m grid resolution. The soil types were categorized based on SWAT classification codes, ensuring proper parameterization of infiltration, percolation, and soil moisture dynamics across the basin.

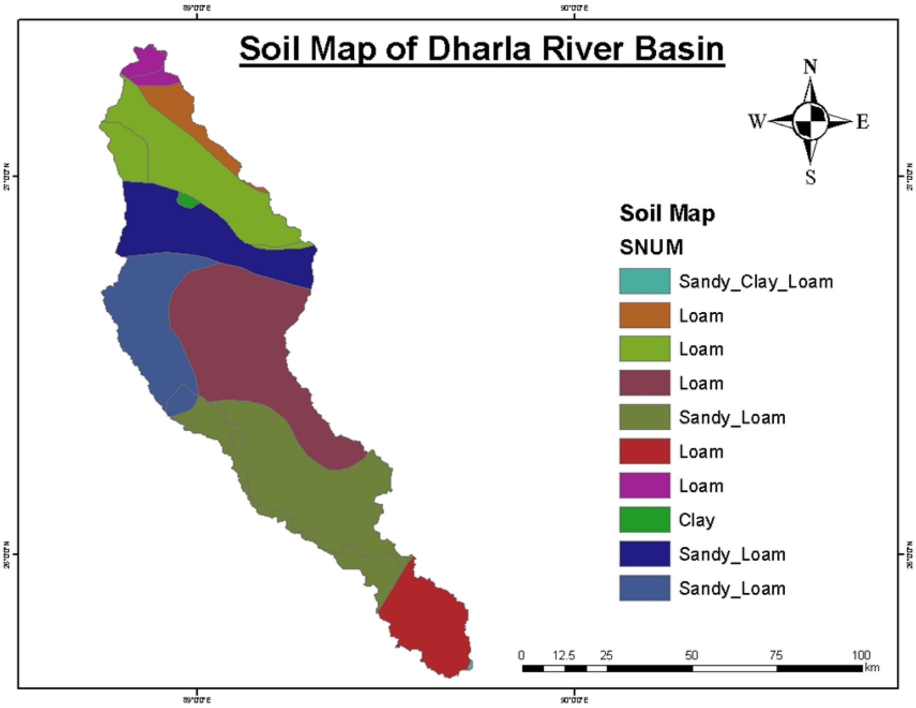

Figure 2.3.2: Soil Map of Dharla River Basin

2.3.3 Land Use and Land Cover (LULC) Map

Soil data were collected from the FAO global soil database and clipped to match the basin boundary. The soil attributes, including texture, hydraulic conductivity, and available water content, were processed to be compatible with SWAT input requirements.

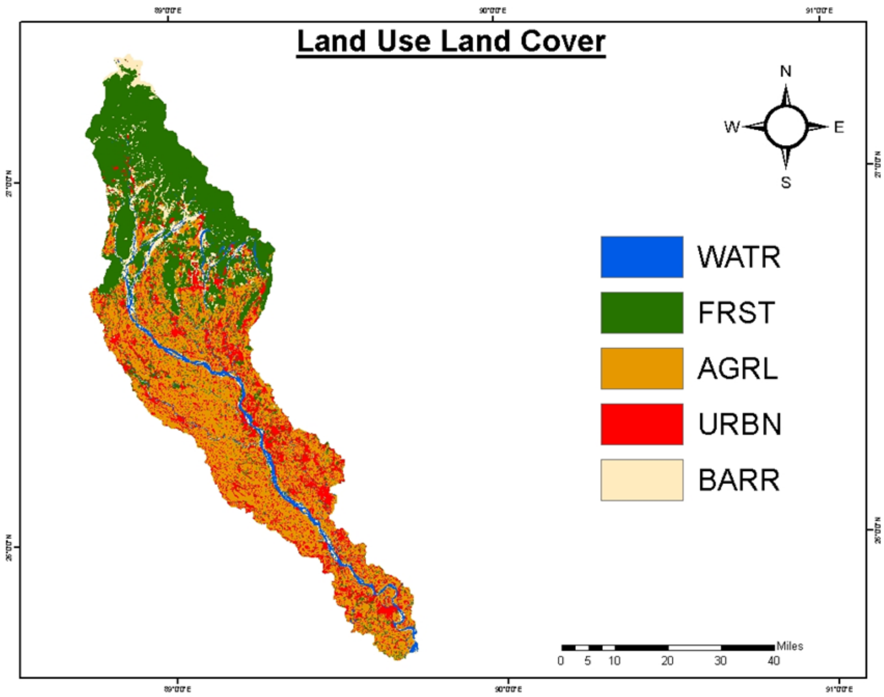

Figure 2.3.3: Land Use Map of Dharla River Basin

The data were projected to UTM Zone 45N and resampled to a 30 m grid resolution. The soil types were categorized based on SWAT classification codes, ensuring proper parameterization of infiltration, percolation, and soil moisture dynamics across the basin.

2.3.4 Climate Data Processing

Historical daily precipitation and temperature (maximum and minimum) data for the period 1999–2021 were collected from the Bangladesh Meteorological Department (BMD) for 3 nearby stations: Rangpur, Dinajpur, and Saidpur. Data quality checks were performed to ensure completeness and consistency; missing rainfall values were replaced with zeros, while missing temperature values were estimated through linear interpolation.

To enhance spatial representation and capture transboundary influences, additional precipitation data were extracted from Indian Meteorological Department (IMD) gridded NetCDF datasets for Jalpaiguri, Alipurduar, and Cooch Behar. For the upper catchment in Bhutan, rainfall data were obtained from the IMD grid cell centered at 27°N and 89.30°E, representing the contributing highland region. All datasets were processed, cleaned, and converted into SWAT-compatible formats with corresponding climate station lookup tables containing location and elevation information.

Among the BMD stations, Rangpur was selected as the representative source for temperature input. The integration of multi-source climate data provided a spatially distributed and quality-controlled dataset, ensuring reliable representation of rainfall and temperature variability across the transboundary Dharla River Basin.

Through this multi-source climate dataset integration, the model was equipped with a more spatially comprehensive and quality-controlled climate input to better represent precipitation variability and temperature influences across the transboundary Dharla Basin.((Teutschbein et al., 2012)

Table 2.1: Climate Data Lookup

ID	NAME	LAT (DEGREE)	LONG (DEGREE)	ELEVATION (METER)
1	Rangpur	25.73	89.23	34
2	Dinajpur	25.627	88.64	34
3	Sydpur	25.78	88.90	43
4	Jalpaiguri	26.5	88.75	75
5	Coochbehar	26.32	88.45	45
6	Alipurduar	26.48	89.53	80
7	Bhutan	27	89.30	300

2.4 SWAT Model Setup

The hydrological model of the Dharla River Basin was developed using QSWAT, an extension of the Soil and Water Assessment Tool (SWAT) within QGIS, designed for simulating watershed-scale hydrological responses to land use, soil, and climate variability. The Digital Elevation Model (DEM) served as the base for watershed delineation, with the outlet positioned near the Kurigram BWDB station. The delineation process resulted in three sub-basins representing the basin's hydrological structure.

Hydrologic Response Units (HRUs) were defined using land use, soil, and slope data, where thresholds of 5%, 10%, and 10% were applied to exclude minor classes. Land use and soil data were reclassified to match SWAT codes, and slope classes were derived from the DEM. Historical climate data (precipitation and temperature) were integrated via the climate station editor, ensuring appropriate linkage between sub-basins and weather stations.

The simulation was run for 1999–2021, with a five-year warm-up period to stabilize hydrological conditions. QSWAT automatically generated weather generator files, HRU definitions, and configuration tables. This model setup served as the baseline simulation, forming the basis for calibration, validation, and future discharge projections under varying climate scenarios.

2.5 Model Calibration and Validation

The SWAT model was calibrated and validated using observed monthly discharge data recorded at the Kurigram station. The historical dataset covered the period from 2004 to 2021. Calibration was performed from 2004 to 2015, while validation was carried out from 2016 to 2021. Observed daily discharge data obtained from the Bangladesh Water Development Board (BWDB) were processed into monthly averages to match the temporal resolution of the SWAT output.

The calibration process was conducted using the SWAT-CUP software, applying the SUFI-2 (Sequential Uncertainty Fitting Version 2) algorithm. Fourteen hydrologically sensitive parameters were selected based on sensitivity analysis and previous literature. The performance of the calibrated model was evaluated using key statistical indicators including the coefficient of determination (R^2), Nash–Sutcliffe Efficiency (NSE), Percent Bias (PBIAS), Kling–Gupta Efficiency (KGE), p-factor, and r-factor.

3. RESULT AND DISCUSSION

3.1 Model Simulation Output

The model simulation of the Dharla River Basin performed using the calibrated SWAT model for the period 1999–2021, produced monthly streamflow at the basin outlet near Kurigram. The simulated discharge pattern (Figure-3.1) reflects the strong monsoon-driven hydrology of the basin, with pronounced seasonal variations. Peak flows typically occur between June and September, corresponding to the southwest monsoon rainfall, while low flows dominate during the dry season (December to April).

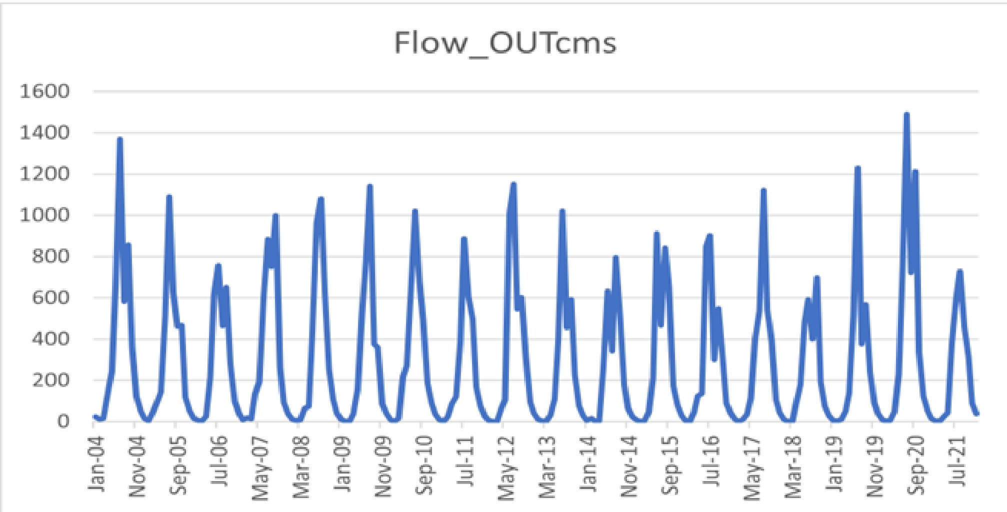

Figure 3.1: SWAT Model Simulation

The simulation results exhibit distinct annual flow cycles, where the magnitude of discharge fluctuates from less than 100 m³/s in dry months to above 1200–1500 m³/s during peak monsoon events. This cyclical pattern highlights the basin's sensitivity to seasonal rainfall variability and the dominant influence of monsoon precipitation on surface runoff generation. The simulated flow trends also indicate occasional inter-annual variability, which may be linked to the regional climatic anomalies and transboundary rainfall variations across Bhutan and India.

Overall, the simulated hydrograph confirms that the model successfully captures the temporal dynamics of the Dharla River, reproducing the expected seasonal flow regime and variability consistent with field observations.

3.2 Model Calibration and Validation

The SWAT model for the Dharla River Basin was calibrated for the period 2004–2015 and validated for 2016–2021 using observed monthly discharge data from the Kurigram station. Fourteen hydrologically sensitive parameters, identified through prior sensitivity analysis and literature review, were optimized using the SUFI-2 algorithm within SWAT-CUP. Key performance metrics including Nash–Sutcliffe Efficiency (NSE), coefficient of determination (R^2), Percent Bias (PBIAS), Kling–Gupta Efficiency (KGE), p-factor, and r-factor were used to evaluate the model's performance.

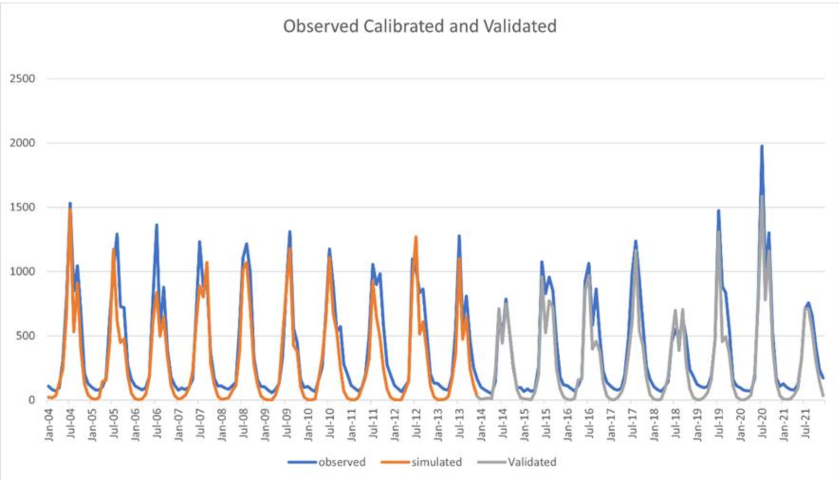

Figure 3.2: Observed Calibrated and Validated

During the calibration period, the model exhibited strong agreement with observed data, achieving R^2 = 0.92, NSE = 0.85, PBIAS = +24.9%, KGE = 0.73, p-factor = 0.89, and r-factor = 0.80. The high R^2 and NSE values indicate that the model successfully reproduced the observed streamflow dynamics, capturing both the timing and magnitude of flows. The positive PBIAS value (+24.9%) suggests a slight overestimation of discharge, which is within an acceptable range for hydrological modelling in tropical river basins (Pandey et al., 2018). The KGE value of 0.73 further confirms the model's ability to reproduce the variability, bias, and correlation structure of observed flows, while p-factor and r-factor values demonstrate satisfactory uncertainty performance.

Table 3.1: Climate Data Lookup

Metric	Value	Interpretation
PBIAS	**+24.9%**	**Acceptable**
NSE	**0.85**	**Good**
R^2	**0.92**	**Very good**
KGE	**0.73**	**Good**
p-factor	**0.89**	**Good**
r-factor	**0.80**	**Acceptable**

Validation results for 2016–2021 showed consistent model performance, confirming the robustness and predictive capability of the calibrated parameters. The model accurately simulated seasonal and inter-annual variations in streamflow, including both high-flow and low-flow periods. Figure X illustrates the time series comparison of observed and simulated monthly discharge, highlighting the close alignment throughout the study period. The model was particularly effective in capturing the monsoon peaks, which are critical for flood risk assessment and water resources planning in the Dharla Basin.

3.3 Discussion

The successful calibration and validation of the SWAT model using historical climate data and observed discharge from the Kurigram station demonstrate the reliability of the model for simulating hydrological responses in the Dharla River Basin. The statistical performance indicators $R^2 = 0.92$, NSE = 0.85, and PBIAS = 24.9 indicate excellent agreement between simulated and observed discharge data. These values suggest that the model accurately captures the seasonal flow patterns, peak flows, and baseflows, which are critical for reliable future projections.

The relatively high p-factor (0.84) and moderate r-factor (0.63) further support the model's capability to envelop most observed data within the simulation uncertainty band. The calibration process, which included the adjustment of 14 sensitive hydrological parameters using the SUFI-2 algorithm in SWAT-CUP, allowed the model to simulate streamflow dynamics with a high degree of precision.

In summary, the SWAT model exhibited strong predictive accuracy and reliability, making it a strong tool for projecting future discharge under changing climate conditions. The careful calibration, supported by quantitative performance evaluation and uncertainty analysis, reinforces the credibility of the simulation results and their suitability for decision-making in the context of transboundary water management.

4. CONCLUSIONS

This study successfully developed a robust hydrological model of the Dharla River Basin using the SWAT model integrated with QSWAT and QGIS, providing a detailed understanding of the basin's hydrological processes. The model was rigorously calibrated for 2004–2015 and validated for 2016–2021 using observed discharge at the Kurigram station, with performance metrics of $R^2 = 0.92$, NSE = 0.85, PBIAS = +24.9%, KGE = 0.73, p-factor = 0.89, and r-factor = 0.80, demonstrating very good agreement between simulated and observed monthly streamflow. The results indicate that the model accurately reproduces both seasonal and inter-annual variations, including monsoon peak flows and low-flow periods, which are critical for water resources planning and flood risk assessment in the basin.

Sensitivity analysis identified fourteen key hydrological parameters, including CN2, ALPHA_BF, GW_DELAY, GWQMN, and CH_K2, which significantly influence model outputs. This emphasizes the importance of proper parameter selection and calibration to ensure reliable hydrological predictions. The slight overestimation of flow (PBIAS = +24.9%) is within acceptable limits and can be addressed in future studies through improved spatial datasets, enhanced land use classification, and better representation of groundwater-surface water interactions.

The outcomes of this research provide a strong foundation for future hydrological studies in the Dharla River Basin. The calibrated model can be directly applied to assess the impacts of climate change under various RCP scenarios, enabling researchers to quantify potential changes in discharge, flood frequency, and seasonal variability. Additionally, the model framework can be expanded to study sediment transport, water quality, and watershed management scenarios, making it a versatile tool for comprehensive basin management and planning.

By establishing a validated and reliable modelling framework, this study paves the way for future investigations into climate resilience, transboundary water management, and sustainable utilization of the Dharla River Basin. Policymakers and water resource managers can use the findings to inform flood mitigation strategies, optimize water allocation, and plan for climate adaptation measures, ensuring the basin's sustainable management in the face of changing hydrological patterns.

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AI USE DECLARATION

A portion of the text in this manuscript was refined using AI-based language assistance tools to improve grammar, clarity, and organization. All technical content, analyses, interpretations, and conclusions are entirely the authors' original work. The authors have thoroughly reviewed and verified the accuracy, relevance, and integrity of the final manuscript.

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