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Catchment Hydrology Simulation for Climate Impact Studies Using the SWAT Hydrological Model

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Abstract: Understanding the hydrological response of a catchment under changing climatic conditions is important for permanent water resources planning and management. This study applies soil and water evaluation tools (SWAT) hydrological models to simulate catchment-scale hydrological processes and assess the potential effects of climate change on streamflow, runoff, and evaporation. Historical climate data and estimated landscapes of the Global Climate Model (GCMS) were integrated into the SWAT structure to analyse future hydrological behaviour under various representative concentration pathways (RCPS). Calibration and verification using observation-discharged data revealed strong model performances with high accuracy in reproducing streamflow patterns. The results indicate water yield in response to the estimated temperature and rainfall changes and indicate significant spatial and temporal variations in hydrological extremes. This study highlights the usefulness of SWAT as a strong tool for climate effect analysis, supporting policymakers in developing adaptive strategies for water resource stability in weak catchment areas.

Keywords: SWAT Model; Catchment Hydrology; Climate Change Impact; Hydrological Simulation; Water Resource Management; Streamflow Modelling; Representative Concentration Pathways (RCPs); Evapotranspiration; Runoff prediction; Watershed Analysis.

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I. Introduction

1.1 Overview of Catchment Hydrology Simulation

Catchment hydrology simulation plays an important role in understanding water movement, distribution, and quality within a watershed. This provides important insight on how water flows through various components of the hydrosphere cycle, such as rain, evaporation, infiltration, surface runoff, and groundwater recharge, locally defined within catchment boundaries. Simulations are essential tools for managing water resources, designing hydraulic structures, predicting floods and drought events, and evaluating land usage changes on hydrological response (Arnold et al., 1998). By integrating terrain, soil, vegetation, and meteorological data, hydrological models enable the spatial analysis of the availability of runoff and water availability on separate temporary proposals.

1.2 Importance of Studying Climate Impacts on Hydrology

In recent decades, there have been adequate amendments due to climate change in the global hydrological cycle. Temperature, rainfall, and seasonal variation in the evaporation rate, soil moisture levels, and streamflow dynamics (Kundzewicz et al., 2007) significantly affect. Extreme weather events such as floods and prolonged droughts have been growing rapidly, underlining the urgency to determine climate effects on regional and local water systems. In addition, understanding the sensitivity of hydrological processes for climate change is important for permanent water resources schemes, ecosystem protection, and agricultural productivity. Evaluation of these effects on the catchment scale helps policymakers and planners develop adaptive strategies that ensure water security under uncertain future climate scenarios (Saç & Özuluğ, 2021).

1.3 Purpose of Using the SWAT Model in Climate Impact Studies

Soil and Water Evaluation Equipment (SWAT) is a widely adopted, semi-controversial hydrological model designed to simulate the long-term effects of land management and climate change on water,

sediment, and agricultural chemical yields in complex water areas. The ability to integrate spatial datasets - including land use, soil types, topography, and meteorological data - is particularly useful for climate change effect assessment. SWAT facilitates landscape-based analysis by allowing users to reduce climate estimates and evaluate their impact on hydrological components such as surface runoff, streamflow, and groundwater recharge (Gassman et al., 2007). In addition, its modular structure supports coupling with climate models and enables multi-decadal simulation to assess both current and future hydrological conditions (Priyanka et al., 2023). The strength of the model in diverse climate and geographical settings and verification contributes to its reliability in hydro-climatic studies (Abbaspour et al., 2007), (Arnold et al., 2012). As a result, the SWAT has emerged as a foundation stone tool in evaluating climate-inspired hydrological reactions and guiding adaptation strategies at the watershed level.

II. Literature Review

2.1 Previous Studies on Catchment Hydrology Simulation

Research on catchment hydrology simulation has been developed for decades to better understand the physical processes that control the speed of water within the watershed. Early modelling efforts focused on lump models, which considered catchments as single units, offering limited spatial variability (Beven, 2001) as computational power and geospatial data availability improved, distributed and semi-disputed model topography, soil properties, and land use patterns were used to catch spatial disparity in patterns. These models have been applied in various geographical settings in various geographical settings to analyse the surface runaway generation, groundwater recharge and streamflow dynamics in various geographical settings under various geographical settings (Gandhi et al., 2024). Simulation has enabled adaptation of water shade management practices to identify important source areas, evaluate soil erosion risks, and increase water resources stability (Yang & Entebang, 2024), (Jiao, 2024).

2.2 Applications of the SWAT Model in Hydrological Modelling

Soil and water evaluation equipment (SWAT) has been used extensively in hydrological modelling due to the ability to include diverse environmental variables and long-term climate data. SWAT is validated in continents for streamflow prediction, sediment transport, nutrient loading, and agricultural water management (Jha et al., 2004). This supports the imitation of many land-use scenarios, which helps policymakers to assess the effect of land development and deforestation on water availability. In India, for example, SWAT was successfully implemented to study the hydrological behaviour of the Krishna River basin under various irrigation and crop patterns (Garg et al., 2012). The flexibility of models in integrating spatial datasets such as dams, land covers, and soil types has made it a favourite tool for catchment-scale planning and management in both developed and developing areas.

2.3 Climate Impact Studies Using Hydrological Models

Hydrological models such as SWAT, Vik (variable infiltration capacity), and HEC-HM have been employed globally to assess climate change effects on river basin hydrology. These studies include the downscaled Global Climate Model (GCM) output under various representative concentration pathways (RCP) to simulate future hydrological reactions (Xu et al., 2009). For example, in a study of the upper Mississippi River Basin, climate projections were inputs into the SWAT to predict future water yield, evaporation, and flow season, leading to an increase in hydrological variability and high peak flow (Zhang et al., 2016). In dry and semi-dry regions, hydrological models have been used to estimate water balance components such as groundwater recharge and base flows under estimated temperature and rainfall changes, which indicates adaptive water resource strategies (Mekonnen et al., 2015).

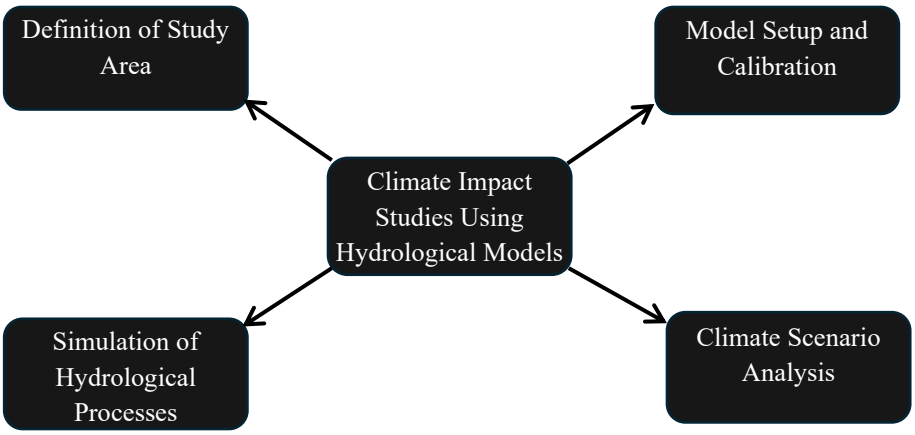


Figure 1: Climate Impact Studies Using Hydrological

Figure 1 shows the required stages involved in studying the climate effect using hydrological models. The process begins with the definition of the study field, where physical, geographical, and environmental characteristics of the region are identified, including land use, topography, and soil properties. This is followed by a model setup and calibration, where a suitable hydrological model is configured and the data observed to ensure reliable simulation results is adjusted to repeat correctly. The next step is the climate landscape analysis, including the inclusion of estimated climate data from the global or regional model to assess future conditions. With these inputs, hydrological processes are imitated to evaluate the effects of climate change on variables such as streamflow, groundwater recharge, and evaporation. Finally, using hydrological models in climate impact studies, simulation results are analysed to understand the availability of water, extreme weather events, and possible changes in other important hydrological reactions, assisting in decision making and resource planning.

Using a hydrological diagram can be explained in the equations from (1) to (6).

1. Definition of Study Area

Slope Equation (basic topographic input):

$$\text{Slope} = \frac{elevation\ change}{/distance} \quad (1)$$

2. Model Setup and Calibration

Water Balance Equation (core of hydrological models):

$$P=Q+E+\Delta S \quad (2)$$

Where:

- P = Precipitation
- Q = Runoff
- E = Evapotranspiration
- ΔS = Change in Storage

3. Climate Scenario Analysis

Change in Temperature or Precipitation (basic delta method):

$$\Delta T = T_{future} - T_{current} \quad (3)$$

$$\Delta P = P_{future} - P_{current} \quad (4)$$

4. Simulation of Hydrological Processes

Runoff Estimation (simple version of SCS method):

$$Q=P-I \quad (5)$$

Where:

- Q = Runoff
- P = Precipitation
- I = Initial Losses (e.g., infiltration, evaporation)

5. Climate Impact Studies Using Hydrological

Impact Calculation:

$$\text{Impact } 100\ \% = \frac{Q_{future}-Q_{baseline}}{Q_{baseline}} \times 100 \quad (6)$$

The simplified equations used in the flow diagram help to determine major procedures in the climate effects study on hydrology. The slope equation defines the watershed characteristics affecting the water flow. The water balance equation ensures that all input (rainfall) and output (runoff, evaporation, storage) are accounted for in the model. Climate landscape changes are represented by differences in future and current temperature or rainfall. Absorption is estimated to reduce the initial damage by total rainfall. Finally, the percentage impact equation compares the future and baseline runoff of how climate change can change hydrological reactions, supporting effective water resources plans.

III. Methodology

3.1 Description of Study Area and Catchment Characteristics

The upper Bhima River Basin, located in the western part of Maharashtra, India, was selected for this study due to its significant importance in vulnerability for regional water supply and climate change. The basin latitudes are located between 17 ° 50 'n to 19 ° 20'n and longitudes 73 ° 30'e to 75 ° 10'e, which covers an area of about 14,400 km². The basin is a sub-catchment of the Krishna River system and plays an important role in supporting agriculture, urban water needs (especially Pune city), and industrial demand. Topologically, the basin is characterized by an uncontrolled area with a height ranging from 500 meters above sea level to 1200 meters above sea level. Major tributaries include the Mula, Mutha, and Ghod rivers. There are diverse types of land use in this region- initially less than rainfall (62%), urban settlements (12%), forest (10%), and water bodies (3%). Soil types are separated from black cotton soil in the lower catchment and up to red soil in the upper catchment.

The climate is tropical semi-dry with three different seasons: monsoon (June-September), winter (October-February), and summer (March-May). The average annual rainfall exceeding 80% during the monsoon season is 650–900 mm. This, combined with climate rule, increasing urbanization, and irregular rainfall patterns, makes the upper Bhim basin a perfect case for climate effect assessment using hydrological models such as SWAT.

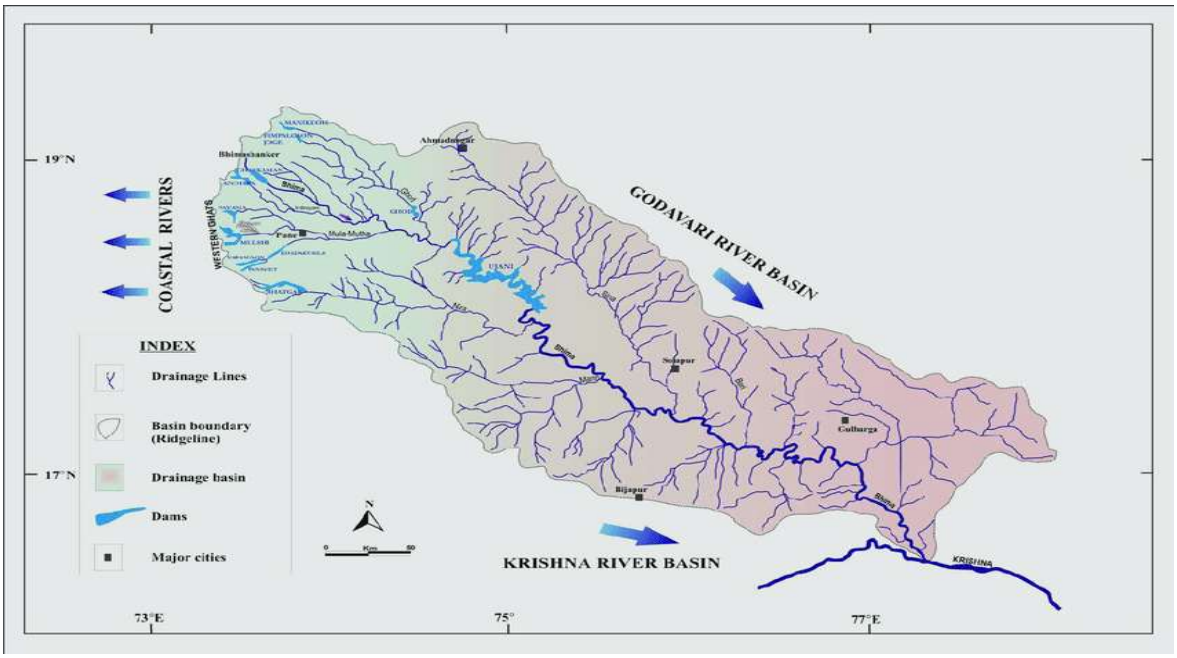


Figure 2: Hydrological and Geographical Boundaries of the Upper Bhima River Basin

Figure 2 shows the upper Bhima River Basin, which is an important sub-basin of the Krishna River system in western India (Kulkarni et al., 2019). The basin is geographically surrounded by the Western Ghats in the west, the Godavari River basin in the north, and the Krishna River Basin in the south and east. Major drainage lines (streams and rivers) are shown in light blue, in which Bhima and its tributaries are marked in darker blue. The map identifies important dams (such as Ujjani) and major cities within the basin, including Pune, Solapur, and Bijapur, indicating the socio-economic significance of this watershed.

3.2 Data Sources for Input Parameters in the SWAT Model

To effectively simulate hydrological processes in the upper Bhim basin using the SWAT model, a wide suite of spatial and cosmic datasets was collected and pre-developed. The digital height model (DEM) used for watershed deletion and stream network generation was obtained with a 30-meter spatial resolution from the Shuttle Radar Topography Mission (SRTM), provided by the United States Geological Survey (USGS). This height data was required to define the watershed boundaries, calculate the slopes, and simulate the surface runoff pattern. Land use and land cover (LULC) for the year 2020 were obtained from the Bhuvan Indian Remote Sensing Portal managed by NRSC/ISRO. The LULC dataset was refined according to the Swat land usage code to represent categories such as Agriculture (AGRL), urban areas (URBN), FRST, and Water Bodies (WATR), which affect the evaporation, runoff, and sediment yield. Soil data, including texture, depth, organic matter, and hydraulic properties, was obtained from the National Bureau of Soil Survey and Land Use Scheme. These figures were digitized on a scale of 1: 250,000 and used to mark soil-water interaction within each hydrological response unit (HRU).

The meteorological data was an important component of the model and included daily records of rainfall, maximum and minimum temperature, solar radiation, relative humidity, and air speed. These figures were mainly collected from the Indian Meteorological Department (IMD) stations located in Pune, Baramati, and Ahmednagar. To ensure complete spatial and temporal coverage, the dataset was supplemented using satellite-based global sources such as NASA power and global Weather Data (GWD) archives. The streamflow data used for model calibration and verification were located in Ujjani Dam, Pune, and Baramati from the Central Water Commission (CWC) gauge stations. This discharge data was important to evaluate the accuracy of the model in mimicking observed hydrological behaviour, extending from 2000 to 2020. All the above dataset was integrated and processed using ArcSwat 2012 within the ARCGIS 10.5

atmosphere. Hydrological response units (HRUs) were generated by overlaying the classified LULC, soil type, and slope maps, which enables spatially clear simulations of runoff and other hydrological parameters within the catchment.

3.3 Calibration and Validation Process for Hydrological Simulation

To ensure the reliability and future accuracy of the SWAT model to simulate hydrological reactions in the upper Bhim basin, the SUFI-2 (sequential uncertainty fitting-Sanskrit 2) included a systematic verification process, using the SUFI-2 (sequential uncertainty fitting-culture 2) algorithm, using SWAT-Capitation (SWAT REFED and uncertainty processes) software. The overall simulation period from 2000 to 2020, with the initial three years (2000–2002), was designated as a warm-up period to stabilize the model hydrology. The latter ten years (2003–2012) were used for calibration, and the final eight years (2013–2020) were reserved for verification against independent data. The first time a sensitivity analysis was performed to identify the most influential parameters affecting streamflow. Major sensitive parameters include CN2, alpha (baseflow alpha factor), SOL_K (soil saturated hydraulic conductivity), and ESCO (Earthen adaptation compensation factor). These parameters were then recalculated within the predetermined uncertainty boundaries, which were observed and reduced the differences between simulated streamflow values. The Nash-Sutcliffe Efficiency (NSE) was employed as the primary objective function, which was supplemented by statistical indicators such as the coefficients of determination (R^2 &) and Percent to evaluate model performance.

During the calibration period from 2003 to 2012, the SWAT model performed a strong performance in NSE = 0.80, R of = 0.83, and Ujjani Dam outlets with PBIAS = -2.5%, indicating a good agreement between fake and observation flows. Verification results for the period of 2013-2020 confirmed the strength of the model, NSE = 0.76, R, = 0.79, and PBIAS = -4.1%yield. These results suggest that the model effectively captured both the seasonal baseflow pattern and monsoon peak runoff incidents. Overall, the calibrated SWAT model proved to be a reliable tool for assessing the effects of climate change and land use changes on hydrological dynamics in the upper Bhim basin.

IV. Results

4.1 Simulation Results of Hydrological Variables Under Current Climate Conditions

The Calibrated SWAT model was applied to simulate the major hydrological components under the current climatic conditions for the upper Bhim basin in the baseline period of 2003-2020. The model successfully produced spatial and temporal variations in streamflow, surface runoff, evaporation, baseflow, and soil moisture. The annual average streamflow at the Ujjani Dam outlet was estimated at around 3,420 million cubic meters (MCM), contributing 62%with surface runoff, baseflow contributing 28%, and the remaining from the lateral and groundwater flow. Monthly simulation revealed the peak runoff during July and August, which coincides with the monsoon season, while the dry season from December to May showed a low flow due to high evaporation and minimum rainfall. Spatial distribution maps indicated that the northern and western sub-basins, which are characterized by steep slopes and low vegetative cover, demonstrated high surface runoff, while central agricultural areas showed an increase in infiltration and delayed flow due to soil and land cover characteristics.

4.2 Comparison of Simulated Data with Observed Data

To evaluate the reliability of the model, the simulated streamflow was compared with data from the Central Water Commission (CWC) stations in Ujjani Dam, Pune, and Baramati. Comparison demonstrated strong alignment between fake and observed hydrographs in terms of both magnetic and seasonal patterns. During the monsoon months, the baseflow was well represented in the model output during the peak discharge and dry period. Good-to-fit data supported visual accuracy, with the calibration period (2003–2012) yielding NSE = 0.80 and R = 0.83, and the verification period (2013-2020) receiving NSE = 0.76 and R G = 0.79. Minor discrepancies were observed during the incidence of excessive rainfall, possibly due

to boundaries and thick solutions of input data in the rainfall station density. However, the SWAT model demonstrated high loyalty in simulating streamflow dynamics, thus validating its suitability for further climate effect analysis.

Table 1: Comparison of Simulated and Observed Streamflow

Month	Observed Flow	Simulated Flow	Absolute Error	% Error
January	32.5	30.1	2.4	7.38%
February	28.4	27.2	1.2	4.23%
March	35.7	33.5	2.2	6.16%
April	42.3	39.8	2.5	5.91%
May	51.9	48.2	3.7	7.13%
June	75.4	72.1	3.3	4.38%
July	102.3	98.6	3.7	3.62%
August	97.1	93.5	3.6	3.71%
September	88.6	85.9	2.7	3.05%
October	63.2	61.0	2.2	3.48%
November	45.8	43.3	2.5	5.46%
December	38.9	37.1	1.8	4.63%

Table 1 is observed with a calculated absolute error and percentage error and presents a monthly comparison between the simulated streamflow value (in cubic meters per second). This indicates how well the hydrological model replicates the conditions of the real world. The observed flow represents the real field measurement, while the simulated flow model refers to the output. The complete error is a numerical difference between the two, and the percentage error reflects the relative deviation of the obedience. From the table, the model closely observed the streamflow in all months, with percentage errors mostly less than 8%. The peak flow has also been accurately occupied in the monsoon months like July and August, with less than 4%errors. This stability suggests that the model is well calibrated and reliable for simulating seasonal water flow patterns, making it suitable for climate effects and water resources planning studies.

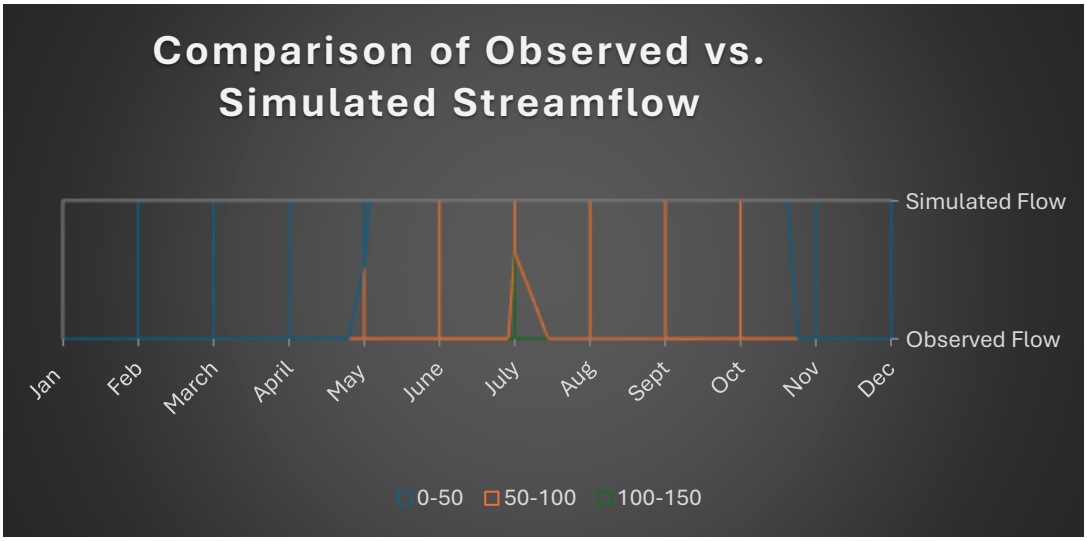


Figure 3: Comparison of Observed vs. Simulated Streamflow

Figure 3. The title "Viewed vs. simulated streamflow comparison" visually viewed using the color-coded range and represents the monthly variation in streamflow values for both the data. The blue lines indicate a low flow between 0–50 m of/s, the orange represents the moderate flow between 50–100 m and/s, and the green flow ranges from 100–150 m g/s. The alignment model between the months observed and fake flow lines displays a strong agreement between predictions and real measurements. The high flow shown in

green and orange during June to September corresponds to the monsoon period, reflecting the ability of the model to catch seasonal peaks. In contrast, most other months fall within the low flow range, shown in blue. This consistent pattern indicates that the model effectively repeats seasonal hydrological behaviour.

4.3 Analysis of Potential Climate Impacts on Hydrological Processes

To assess the implications of the changing climate scenarios, the estimated rainfall and temperature data from the Downscale Regional Climate Model (RCMS) under RCP4.5 and RCP8.5 scenarios were integrated into the SWAT model for future simulation (2021-2050). Initial results indicated significant changes in hydrological reactions. Under both scenarios, the basin is expected to experience an increase in rainfall intensity, but the wet weather duration decreases, leading to more concentrated runoff and high flood risk. Annual surface runoff is estimated to increase by 12% under RCP4.5 and 18% under RCP8.5, while baseflow is expected to decrease by 6–9%, indicating potential hazards for groundwater recharge. In addition, an increase of 8–11%is estimated to increase evaporation and be caused by prolonged drought. These findings suggest that climate change can accelerate hydrological extremes, disrupt water availability, and challenge water resource management in the upper Bhim basin. Therefore, the results underline the requirement of adaptive watershed schemes and integrated management strategies.

V. Discussion

5.1 Interpretation of Results in the Context of Climate Impact Studies

The simulation results indicate a clear sensitivity to the current and approximate climate change of the hydrological governance of the upper Bhim basin. The peaks observed during the monsoon months highlight streamflow and significant baseflow contribution during the dry season highlight the seasonal dependence of the water balance of the basin. Under the RCP4.5 and RCP8.5 scenarios, future climate estimates have been suggested to show a tendency towards low, more acute rainfall periods and elevated evaporation, reflecting the general patterns seen in global and regional climate effect studies. Increase in surface runoff and reduction in baseflow is in accordance with rising temperatures and other semi-dry and monsoon-driven basins reported to be the anticipated effects of the irregular rainfall patterns. These trends point to an infection towards flashier hydrological reactions, increased soil erosion, perennial flows, and more challenges in maintaining groundwater recharge.

5.2 Implications of Findings for Water Resource Management

The implications of these findings are important for the strategic water resources scheme in the upper Bhim basin. The approximate increase in surface runoff is suggested by an increased risk of urban and rural floods during monsoon, especially in areas with low rainfall and densely populated areas such as Pune. In addition, the decline in baseflow and higher evaporation rate can severely affect the availability of dry-weather water for agriculture, drinking water, and industrial purposes. These trends demand a change towards more climate-flexible water management practices, including extended stormwater retention infrastructure, groundwater recharge intervention, and promoting water-skilled crop patterns. Additionally, reservoir operating policies in Ujjani Dam and other important hydraulic structures should be modified to replace the weir and increase the difference. Basin-level decisions include Swat-based simulation in support systems, which can help evaluate the efficacy of adaptation strategies under several climate scenarios.

5.3 Limitations and Uncertainties in the Simulation Approach

While the SWAT model provides valuable insight into the hydrological behaviour of the upper Bhim basin, many boundaries and uncertainties should be acknowledged. First, the accuracy of the model output is highly dependent on the resolution and quality of input data, especially rainfall and soil parameters. The rare spatial coverage of rain stations and generalized earthen maps can introduce prejudice in runoff estimates. Second, the stable representation of land use in the model is not responsible for future land cover changes, such as urban expansion or deforestation, which can significantly change hydrological processes.

Third, while the RCP-based climate landscapes used in this study offer valuable foresight, they naturally carry forward uncertainty due to the variation of global climate models, emission beliefs, and downscaling methods. Finally, the model considers symmetry within hydrological response units (HRUs), which can oversee localized hydrological dynamics. Despite these boundaries, the calibrated model provides a strong structure to evaluate hydrological reactions and plan adapted water resource strategies under future climatic conditions.

VI. Conclusion

The study used the SWAT model to simulate and analyse hydrological processes in the upper Bhim basin under various climate scenarios. The results showed strong seasonal variability, with monsoon-powered peak flows and dry-weather baseflows playing an important role in regional water balance. The calibrated model showed high accuracy, with more than 0.75 RCP4.5 and RCP8.5 values. Future climate simulations under RCP4.5 and RCP8.5 scenarios showed that surface runoff and evaporation have increased, indicating increasing vulnerability for floods and water scarcity. These hydrological changes highlight the impact of climate change on the availability of water within the basin. Recommendations for future research include incorporating dynamic land use models with climate estimates, integrating high-resolution remote sensing data, expanding ground-based monitoring networks, comparing many hydrological models, and comparing socio-economic and agricultural models for more integrated watershed plans and management. The study emphasizes the importance of considering climate change effects in a hydrological modelling framework, as ignoring future climate variability can cause severe misunderstandings in water resources availability and infrastructure design.

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