Hydrological Assessment of Climate Change Impacts on the Upper Tassaoute Watershed, Morocco

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Abstract. The Tassaoute watershed, a significant tributary of the Oum Er-Rbia basin in central Morocco, is experiencing increasing water stress due to climate variability and declining precipitation trends. This study aims to assess the impacts of recent climatic changes on water resources in the watershed using the HBV (Hydrologiska Byråns Vattenbalansavdelning) conceptual hydrological model. Monthly meteorological and hydrological data were collected and used to calibrate and validate the HBV model, enabling simulation of runoff and the evaluation of the watershed's hydrological response to observed climate variability. The results highlight a noticeable reduction in streamflow and changes in seasonal water availability, which are closely linked to variations in rainfall and temperature patterns over recent decades. These findings underline the growing vulnerability of the Tassaoute watershed to climatic fluctuations and provide a scientific basis for improving water resource management in the region.
Keywords: Climate change, Water resources, HBV model, Morocco, Semi-arid regions.

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1 Introduction

Water scarcity is one of the most pressing challenges worldwide, threatening freshwater ecosystems, agricultural productivity, and human livelihoods [1]. Climate change is expected to intensify these pressures by altering precipitation patterns, increasing temperatures, and modifying hydrological cycles, resulting in notable shifts in the availability and distribution of water resources over time and space [2]. Both blue water (surface and groundwater) and green water (soil moisture derived from precipitation) are affected, posing particular risks for agriculture the sector with the highest global water demand [3–5]. Changes in temperature and rainfall patterns reduce soil moisture, increase crop water stress, and influence irrigation requirements, crop yields, and overall agricultural sustainability [6]. Green water, which represents the majority of crop water consumption, is especially vulnerable to these changes, affecting farmers' management decisions and crop choices under climate variability [4].

In Morocco, semi-arid conditions combined with population growth and expanding agricultural activities have placed additional pressure on water resources. Seasonal and regional water deficits are already prevalent, and climate projections indicate that reductions in rainfall, higher evapotranspiration, and altered river flow regimes are likely to worsen these shortages [7]. Agriculture, which consumes the majority of the country's freshwater, remains highly susceptible to these hydrological shifts [8]. Understanding the interaction between climate variability and water availability at both regional and local scales is therefore crucial for developing effective adaptation and management strategies.

The Upper Tassaoute Watershed, a key tributary of the Oum Er-Rbia basin, illustrates these challenges at a local scale. This semi-arid watershed supports essential agricultural activities and rural communities, yet is increasingly affected by seasonal rainfall variability, rising temperatures, and growing water [9]. Assessing the hydrological impacts of climate change in the watershed is essential to anticipate future water shortages, evaluate risks to agriculture and ecosystems, and guide sustainable water management strategies.

Hydrological modelling offers a practical approach to addressing these challenges. Among available tools, the HBV (Hydrologiska Byråns Vattenbalansavdelning) model has proven effective in simulating catchment hydrology, evaluating water balances, and supporting water resource management decisions [10]. Unlike fully distributed models that require intensive data, HBV is a semi-distributed conceptual model [11], making it well-suited for data-limited regions. In this study, the HBV model is applied to the Upper Tassaoute Watershed to analyze the hydrological response under observed conditions over recent decades. By examining the interactions between precipitation, temperature, and runoff at the monthly scale, this research aims to improve understanding of water availability dynamics and provide insights for sustainable management in a semi-arid Moroccan context.

2 Study area

The Tassaoute sub-basin, situated in central Morocco, is one of the most important tributaries of the Oum Er Rbia River (Fig 1) [12]. It originates in the High Atlas Mountains, where both snowmelt and rainfall play a crucial role in sustaining its hydrological regime. The basin exhibits significant altitudinal gradients, with mountainous upstream zones gradually transitioning to extensive agricultural plains downstream. These plains are among the most productive agricultural regions in Morocco, relying heavily on irrigation, particularly for cereals, fruit trees, and cash crops.

Despite its productivity, the basin faces mounting pressures from recurrent droughts, overexploitation of groundwater, and the broader impacts of climate variability, which collectively threaten both water availability and agricultural [13]. The combination of high socio-economic importance and climatic vulnerability makes the Tassaoute sub-basin a critical case study for assessing the impacts of climate change on water resources and informing sustainable water management strategies.

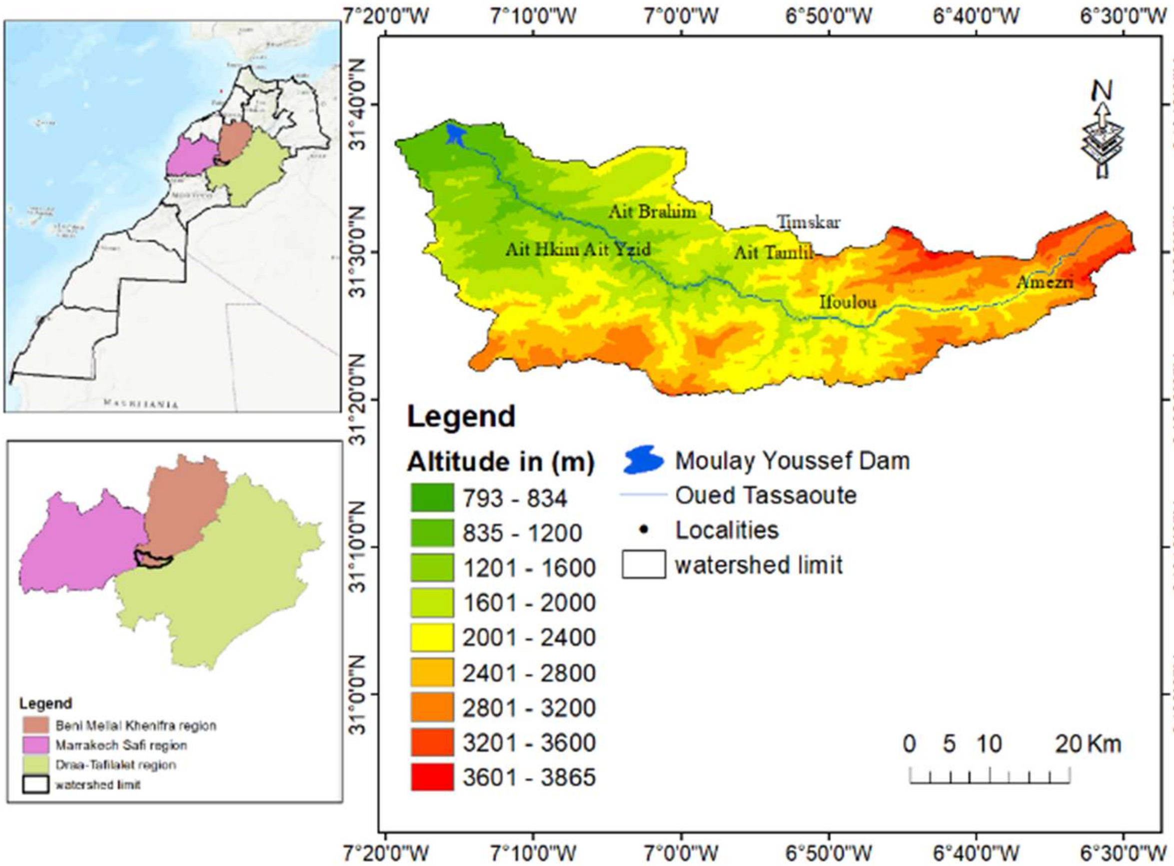

Fig. 1. Map of the location of the upper Tassaoute watershed

3 Methodology

The methodology of this study is designed to assess the hydrological response of the Tassaoute watershed using observed monthly data for precipitation, temperature, and runoff. The study follows a structured approach encompassing data collection, model setup, calibration and validation, and analysis of hydrological responses.

3.1 Data Collection and Preprocessing

Monthly precipitation, temperature, and streamflow data were collected from meteorological and hydrological stations located within and around the Tassaoute watershed. Data quality checks were conducted to identify and correct missing values and outliers. Monthly time series were constructed to ensure consistent temporal alignment for all variables. Potential evapotranspiration (PET) was estimated using the Thornthwaite method, which is suitable for monthly datasets and uses mean monthly temperature and latitude to compute the energy available for evapotranspiration.

3.2 HBV Model Configuration for Monthly Data

The HBV model is a conceptual rainfall–runoff model that simulates the hydrological processes of a watershed through a series of storage compartments and [14]. When using monthly data, the model structure remains the same, but time steps are aggregated to the monthly scale. The main components of the HBV model applied in this study are:
Snow Module: In the headwaters of the watershed, snow accumulation and melt are considered. Monthly precipitation is partitioned into rainfall and snowfall based on temperature thresholds, and snowmelt is calculated using a degree-month factor adapted from the original degree-day approach.
Soil Moisture Module: Monthly precipitation infiltrates into a conceptual soil storage compartment. Water in the soil layer is partially lost through evapotranspiration (based on PET) and contributes to percolation and runoff generation.
Runoff Generation Module: Water exceeding the soil storage capacity is partitioned into quick flow (direct runoff) and baseflow (delayed subsurface flow) through conceptual reservoirs.
Routing Module: Simulated flows are routed to the watershed outlet, producing monthly discharge values comparable to observed data.

3.3 Model Calibration and Validation

Calibration was performed using observed monthly discharge data over a defined calibration period (1990–2021). Key parameters including soil moisture capacity, runoff coefficients, baseflow recession constants, and snowmelt degree-month factor were adjusted iteratively to maximize agreement between simulated and observed runoff.
Model performance was evaluated using:
Nash-Sutcliffe Efficiency (NSE): Measures the fit between simulated and observed flows.
Coefficient of Determination (R^2): Assesses the proportion of variance explained by the model.
Percent Bias (PBIAS): Quantifies average under- or overestimation of simulated discharge.
Validation was conducted on an independent period (2005–2021) to ensure robustness of the model and prevent overfitting.

3.4 Sensitivity Analysis

A sensitivity analysis was performed to identify which model parameters most strongly influence simulated monthly discharge. This step provides insight into the dominant hydrological processes of the watershed and highlights critical parameters for future data collection or model [15].

3.5 Analysis of Hydrological Response

After calibration and validation, the model simulated monthly streamflow, soil moisture dynamics, snow storage, and runoff components. Seasonal and interannual variations were analyzed to understand the watershed's response to observed climate variability. The analysis also focused on identifying periods of water surplus and deficit, which is crucial for water resource management in agricultural and domestic sectors.

4 Results

The calibration of the HBV model against observed discharge produced satisfactory results at the monthly scale. The optimized parameter set led to an overall Nash–Sutcliffe Efficiency (NSE) of 0.811, a coefficient of determination (R^2) of 0.812, and a Root Mean Square Error (RMSE) of 3.48 mm/day. These indices suggest that the model is able to capture the variability of observed streamflow with good accuracy, consistent with commonly accepted thresholds in hydrological modelling where NSE > 0.65 is considered acceptable.
Figure 2 presents the comparison between observed and simulated flows. The hydrograph shows that the HBV model successfully reproduced the seasonal dynamics of the catchment, including the timing of rising and recession periods as well as the magnitude of peak discharge events in many years. The model also represented the low-flow periods reasonably well, reflecting its ability to simulate water balance processes in semi-arid conditions.
However, the year-by-year analysis revealed significant variability in performance. In certain years, such as 1991, 1993, 2009, 2014, and 2015, NSE values exceeded 0.90, with R^2 values above 0.94, indicating excellent agreement between simulated and observed discharge. In contrast, in years such as 1998, 2000, 2001, 2004, and 2018, NSE values dropped below 0.30, and even became negative in 2001, reflecting a weak ability to simulate runoff during those periods. These differences suggest that while the HBV model is robust under average and wet conditions, its performance is less consistent during extreme hydrological years (fig 3).

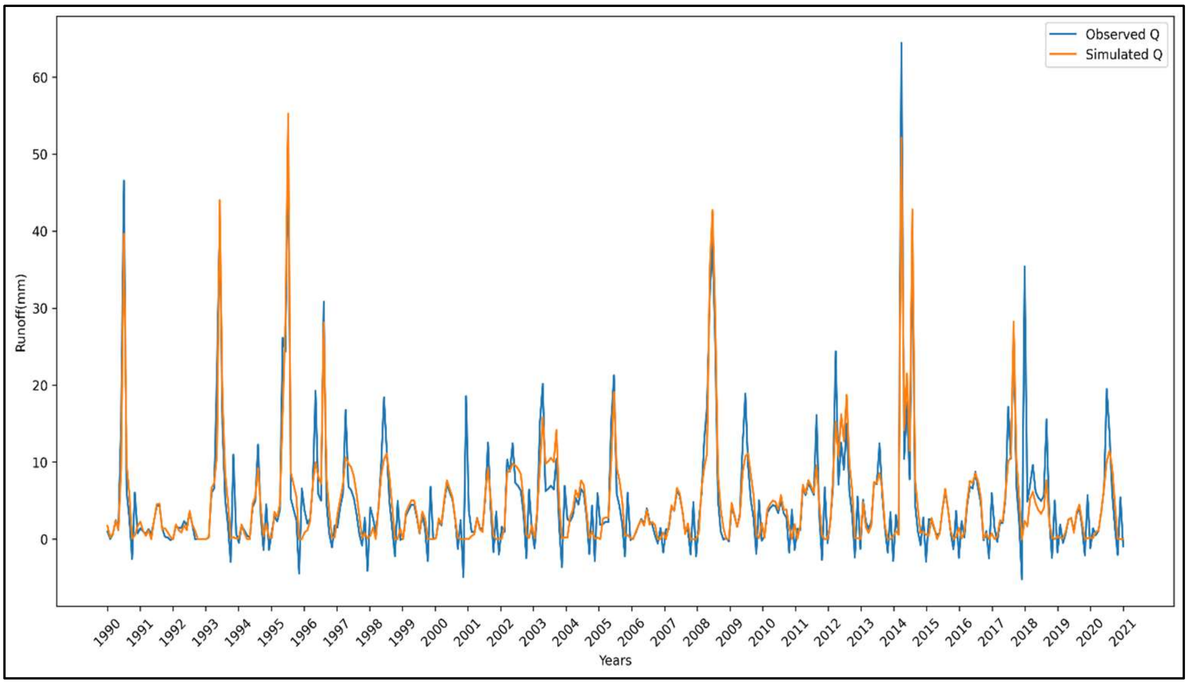

Fig. 2. Simulation of monthly average runoff of the Tassaoute upstream watershed [1990 - 2021]

In addition to calibration performance, a parameter sensitivity analysis was conducted to investigate the influence of each parameter on model efficiency. The analysis was performed by varying individual parameters across their feasible ranges while keeping others fixed at their optimized values, and computing the resulting NSE for each simulation.
The results indicate that the most sensitive parameters are FC (field capacity), BETA (soil moisture nonlinearity), and k0 (fast runoff coefficient) (fig 4). Variations in these parameters caused the largest changes in NSE, highlighting their dominant role in controlling runoff generation and soil moisture dynamics. LP (limit for potential evapotranspiration) and UZL (threshold for upper zone runoff) also showed moderate sensitivity, indicating their relevance to evapotranspiration processes and quick flow response. In contrast, k1 and k2, which

control slower runoff components, exhibited relatively minor influence on overall model performance.

These findings confirm that soil moisture storage capacity and runoff generation parameters are critical for accurately representing the hydrological behavior of the catchment, and thus should receive particular attention during calibration.

Table 1 summarizes the HBV model parameters used in this study, including their physically meaningful ranges, initial guess values for calibration, and the final optimized values obtained through the NSE-based optimization. The initial values were selected based on previous studies and hydrological reasoning, while the calibrated values were derived using the L-BFGS-B optimization algorithm. Notably, the final calibration resulted in significant adjustments to parameters controlling soil moisture storage (FC) and runoff generation (k1, k2), which aligns with their high sensitivity identified in the parameter analysis.

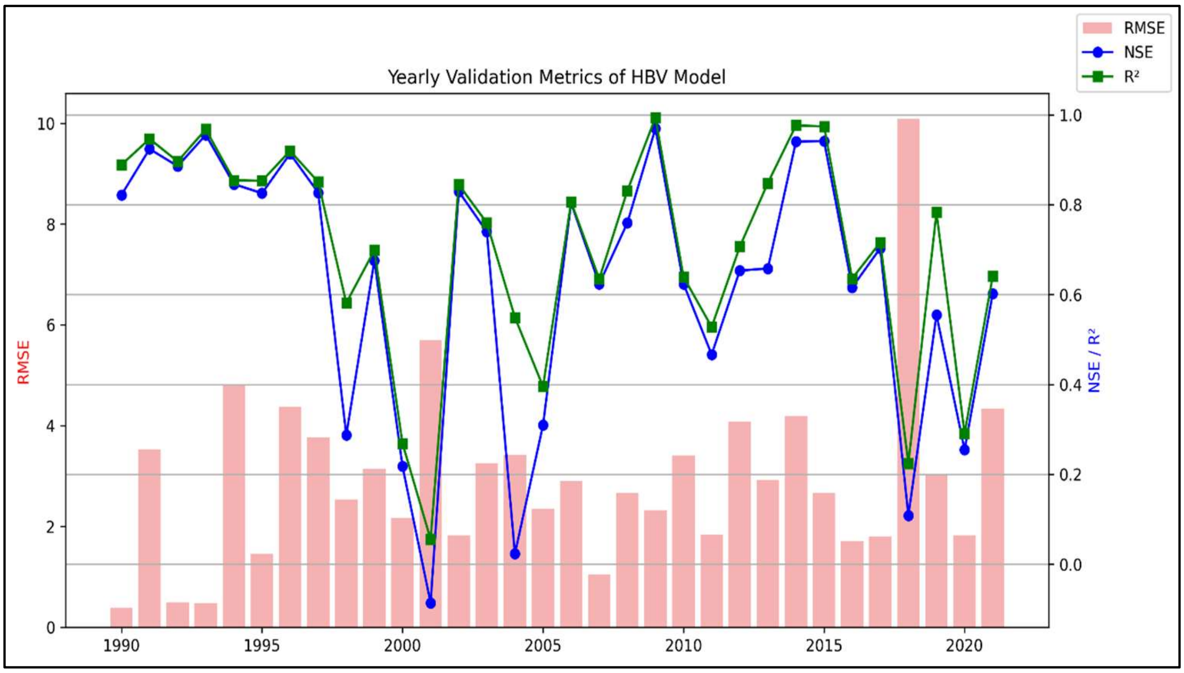

Fig. 3. Annual Validation Metrics (RMSE, NSE, R^2) of the HBV Hydrological Model, 1990–2021

Table 1. HBV Model Parameters — Initial, Range, and Calibrated Values

Parameter	Description	Range	Initial Value	Calibrated Value
FC	Field capacity (mm)	200 – 600	300	200.00
BETA	Soil moisture nonlinearity exponent	1 – 4	2.0	2.00
k0	Fast runoff coefficient	0.10 – 0.60	0.30	0.3020
k1	Intermediate runoff coefficient	0.01 – 0.20	0.05	0.0218
k2	Slow runoff coefficient	0.01 – 0.15	0.05	0.0218
Kp	Percolation coefficient	0.01 – 0.30	0.10	0.0123
UZL	Threshold for upper zone runoff (mm)	5 – 25	10.0	10.00
LP	Limit for actual evapotranspiration	0.30 – 1.00	0.60	1.00

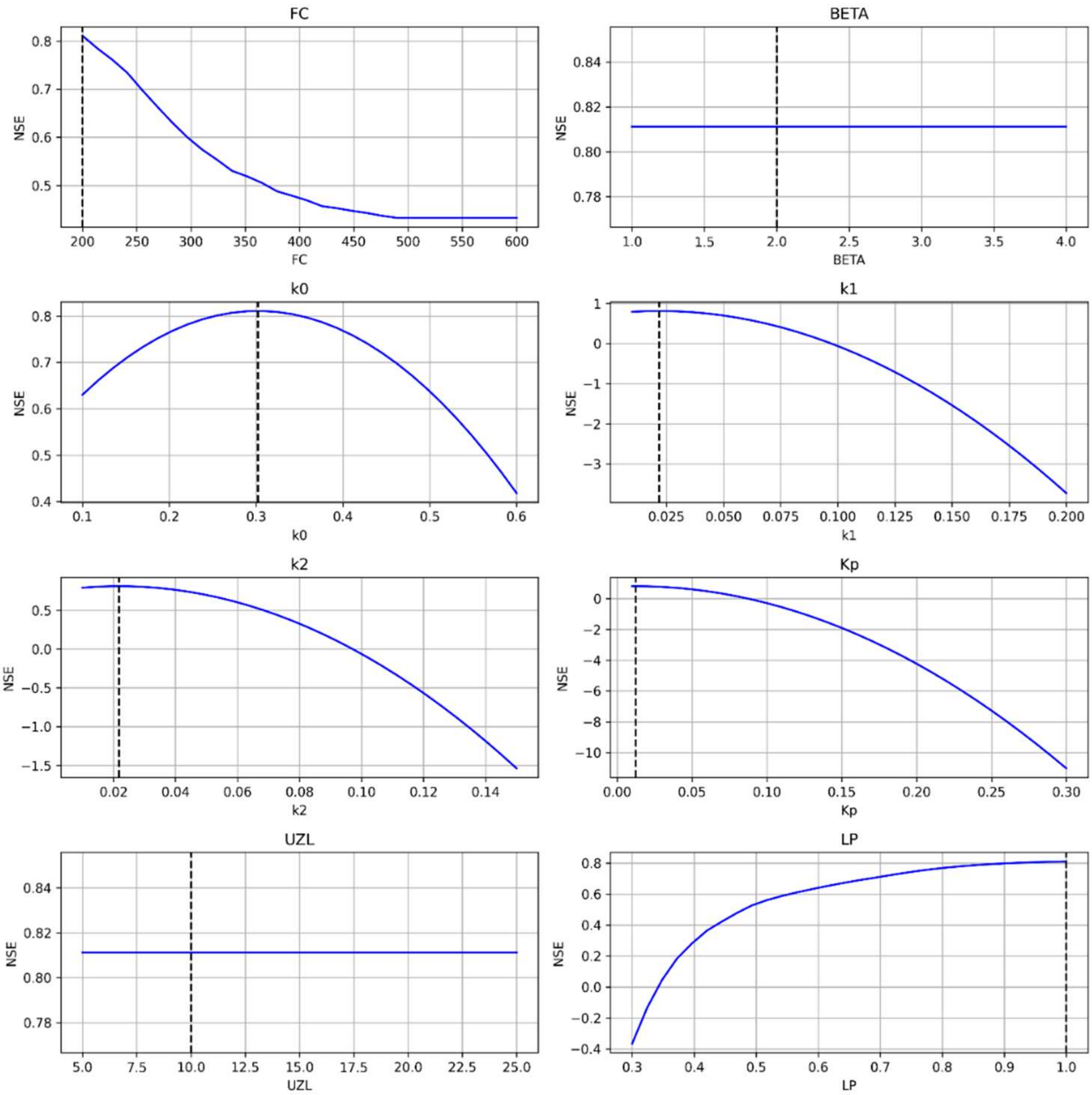

Fig. 4. Sensitivity of the model to changes in parameter values based on the NSE. The dashed lines indicate the optimal parameter values obtained after validation.

5 Discussion

The results confirm that the HBV model is suitable for simulating streamflow in the study catchment, providing a robust overall performance (NSE and R^2 above 0.80). This finding aligns with previous applications of HBV in semi-arid and Mediterranean-type environments, where the model has been shown to capture seasonal water balance dynamics with relatively simple parameterization.

The strong performance during years such as 1991, 1993, and 2009 indicates that the model structure adequately represents the dominant rainfall–runoff mechanisms when hydrometeorological conditions follow typical seasonal patterns. Under these circumstances, the calibrated parameters reproduced both the timing and magnitude of flows with limited deviation from observations.

By contrast, weaker performance in years such as 2000, 2001, and 2018 highlights the limitations of the model. These years were characterized by unusual hydro-climatic conditions, such as severe droughts or irregular rainfall, which are difficult to represent at a monthly scale. Conceptual lumped models such as HBV may oversimplify processes related

to soil moisture variability, quick runoff generation, and groundwater recharge, especially when input data lack high temporal resolution. Moreover, catchment heterogeneity in land use, topography, and soil characteristics is not explicitly considered, which may further explain the discrepancies in dry or highly variable years.
The parameter sensitivity analysis provides further insight into the internal functioning of the model and its limitations. The high sensitivity of FC, BETA, and k0 suggests that soil moisture storage and fast runoff generation processes are the primary drivers of hydrological response in this catchment. This emphasizes the importance of accurately estimating soil-related parameters and rainfall partitioning when applying HBV in semi-arid environments. Conversely, the relatively low sensitivity of k1 and k2 indicates that slower baseflow components play a smaller role in shaping discharge dynamics at the monthly scale.
Despite these limitations, the HBV model demonstrates strong potential as a decision-support tool. Its ability to reproduce long-term hydrological behavior with relatively simple input requirements makes it appropriate for regions where detailed data are limited. For climate change impact studies, this reliability is particularly important, as it ensures that the model can be applied with confidence to assess future hydrological responses under different climate scenarios.
Future work could improve model performance by testing the use of monthly input data instead of monthly averages, which would better capture short-term rainfall–runoff dynamics. Additionally, adopting multi-objective calibration strategies may help balance the simulation of high flows, low flows, and overall water balance. Incorporating more detailed evapotranspiration estimation methods or semi-distributed structures could also enhance the representation of catchment processes.

6 Conclusion

The HBV model proved to be an effective tool for simulating streamflow in the study catchment using monthly precipitation, temperature, and evapotranspiration data. Overall performance metrics (NSE = 0.811, R^2 = 0.812, RMSE = 3.48 mm/day) indicate that the model reliably reproduces observed flow dynamics, capturing both seasonal variability and baseflow trends. Year-by-year validation revealed some variability, with the model performing exceptionally well in certain years and less accurately during extreme hydrological conditions, highlighting the influence of data resolution and catchment heterogeneity.
Despite these limitations, the HBV model offers a robust framework for hydrological assessment and can be confidently applied to future climate change impact studies. Future improvements, such as higher temporal resolution inputs, multi-objective calibration, or refined evapotranspiration representation, could further enhance model accuracy, particularly during extreme events. Overall, this study demonstrates the value of HBV for understanding water resources in semi-arid catchments and supports its use for sustainable water management and climate adaptation planning.

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