



# COMPARISON OF HYDROLOGICAL SIMULATION GROUNDWATER RECHARGE PREDICTIONS

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## ABSTRACT

*Groundwater recharge is a critical component of water resource management, yet accurately estimating it requires the use of robust hydrological models. This study compares three widely used hydrological simulation models—SWAT, MODFLOW, and HEC-HMS—to evaluate their performance in predicting annual groundwater recharge. The methodology involves selecting appropriate models based on their capabilities, calibrating them using local data, and performing simulations for the period 2015–2019. The study area consists of a region with varied land use and climate conditions. Input data, including precipitation, temperature, and soil properties, were collected and preprocessed to fit the requirements of each model. Calibration was performed to minimize the error between simulated and observed groundwater levels and streamflow, followed by model validation for 2020–2022. Results show that MODFLOW provided the most accurate predictions of groundwater recharge, with a Nash-Sutcliffe Efficiency (NSE) of 0.84 and Root Mean Square Error (RMSE) of 18.2 mm/year. SWAT also performed well, accurately reflecting the impact of land use on recharge. However, HEC-HMS showed the lowest performance among the models, particularly in estimating recharge. Sensitivity analysis identified soil permeability as the most influential parameter in MODFLOW, while land use change had the strongest effect on HEC-HMS. The study concludes that while MODFLOW is best suited for groundwater recharge prediction in this study area, a multi-model approach could enhance model reliability and capture various hydrological processes, especially in regions with dynamic land use and climate variability.*

**Keywords:** Hydrological Modeling, Groundwater Recharge, Simulation Models, Water Resources Management, Model Comparison, Predictive Analysis

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## 1. INTRODUCTION

Groundwater serves as a vital source of fresh water for agricultural, industrial, and domestic purposes across the globe. With increasing water demand and changing climatic conditions, sustainable management of groundwater resources has become critically important. One of the key components in groundwater resource assessment is the estimation of groundwater recharge, which reflects the amount of water that percolates down to replenish aquifers. Accurate prediction of groundwater recharge is essential for effective water resource planning and management. Hydrological simulation models play a crucial role in quantifying groundwater recharge under varying land use, soil, and climatic conditions. These models, such as SWAT (Soil and Water Assessment Tool), MODFLOW, and HEC-HMS, provide insights into the hydrological cycle and help predict recharge rates through complex simulations. However, different models are built upon varying conceptual frameworks, input requirements, and calibration techniques, leading to discrepancies in recharge predictions. A comparative analysis of these models is necessary to evaluate their performance, reliability, and applicability to specific hydrological settings. This study aims to compare the predictions of multiple hydrological simulation models to identify strengths, limitations, and the most suitable model for accurate groundwater recharge estimation. The findings are expected to support improved decision-making in water resource management and contribute to the development of sustainable groundwater policies.

### 1.1 Importance of Groundwater Recharge Estimation

Groundwater is a crucial resource that supports agricultural productivity, industrial operations, and domestic water needs. With rising population and urbanization, the pressure on groundwater reserves has intensified, making its sustainable management a priority. One of the most important aspects of groundwater management is estimating recharge—the process by which water infiltrates the soil and replenishes aquifers. Reliable estimation of groundwater recharge is fundamental for understanding aquifer dynamics, predicting water availability, and formulating long-term conservation strategies.

### 1.2 Role of Hydrological Simulation Models

Hydrological simulation models offer a scientific and systematic approach to estimate groundwater recharge by simulating the movement and distribution of water within the hydrological cycle. Popular models such as SWAT (Soil and Water Assessment Tool), MODFLOW, and HEC-HMS are widely used for this purpose. Each of these models is based on unique assumptions, algorithms, and data inputs, which influence their prediction accuracy. These tools allow researchers and water managers to assess the impact of land use changes, climate variability, and human interventions on groundwater recharge across different geographical settings.

### 1.3 Need for Model Comparison and Research Objective

Given the diversity of modeling approaches and the complexity of hydrological systems, comparing different hydrological simulation models becomes essential to identify their strengths, weaknesses, and suitability for specific conditions.

Discrepancies in model predictions can arise from differences in input data, calibration techniques, spatial and temporal resolutions, and underlying physical processes. Therefore, this study aims to perform a comparative analysis of selected hydrological simulation models for predicting groundwater recharge. The objective is to evaluate their performance, reliability, and applicability, thereby guiding researchers and policymakers toward informed and effective water resource management decisions.

## 2. LITERATURE REVIEW

The literature on hydrological modeling, climate variability, and water resource management offers significant insights into the development and application of predictive models and the assessment of climate change impacts. Arnold et al. (2012) provided a comprehensive overview of the Soil and Water Assessment Tool (SWAT), focusing on its calibration, validation, and application across different hydrological studies, emphasizing its adaptability and reliability in simulating watershed processes [1]. Gasse (2000) explored the hydrological changes in the African tropics since the Last Glacial Maximum, revealing the complex interactions between climate shifts and hydrological patterns over millennia [2]. In a broader spatial context, Abbaspour et al. (2015) developed a high-resolution continental-scale SWAT model for Europe, illustrating the model's robustness and the challenges associated with uncertainty quantification in large-scale hydrological simulations [3]. Similarly, Abbaspour et al. (2006) applied SWAT in the pre-alpine/alpine Thur watershed, demonstrating the model's utility in capturing both hydrological and water quality dynamics in complex terrains, which is crucial for alpine water resource planning [4]. Werner et al. (2012) provided an in-depth review of seawater intrusion into freshwater aquifers, highlighting recent advancements in investigation and management strategies and pointing out emerging challenges in coastal aquifer sustainability [5]. Portoghese et al. (2011) addressed the issue of bias in climate data by developing a stochastic bias-correction method for daily rainfall scenarios, which has important implications for improving the accuracy of hydrological forecasts under climate variability [6]. Kollet and Maxwell (2005) introduced a coupled surface-groundwater modeling approach with a free-surface overland flow boundary, enhancing the realism of hydrological simulations by integrating surface and subsurface flow processes [7]. In terms of ecological impacts, Knapp et al. (2008) analyzed how more extreme precipitation regimes affect terrestrial ecosystems, showing that altered precipitation patterns can lead to significant shifts in ecosystem functioning and resilience [8]. Jha et al. (2012) highlighted the vulnerability of urban environments to flooding, emphasizing the need for integrated urban planning and flood risk management to mitigate future disasters in rapidly urbanizing regions [9]. Finally, Anderegg et al. (2012) explored the consequences of drought and temperature stress on widespread tree mortality, underscoring the ecological and climatic implications of vegetation loss under global warming scenarios [10]. This body of work collectively underscores the importance of integrated modeling, climate adaptation, and interdisciplinary approaches in understanding and managing hydrological and ecological systems in the face of environmental change.

## 3. METHODOLOGY

This section outlines the approach adopted to compare different hydrological simulation models for estimating groundwater recharge. The methodology comprises model selection and study area setup, data collection and preprocessing, and model calibration, simulation, and validation.

### 3.1 Model Selection and Study Area Setup

In this study, three widely used hydrological models—SWAT (Soil and Water Assessment Tool), MODFLOW, and HEC-HMS—were selected due to their broad applicability, open-source availability, and proven accuracy in hydrological simulation studies. These models differ in their conceptual frameworks, with SWAT being semi-distributed and process-based, MODFLOW focusing on groundwater flow modeling, and HEC-HMS emphasizing surface hydrology. The selected study area is characterized by varied land use patterns, soil types, and climatic conditions, which provides a suitable test bed for model comparison. A digital elevation model (DEM), land use/land cover (LULC) map, and soil map of the region were used to define the model geometry. The watershed delineation for the models was done using GIS tools, as illustrated in Figure 1.

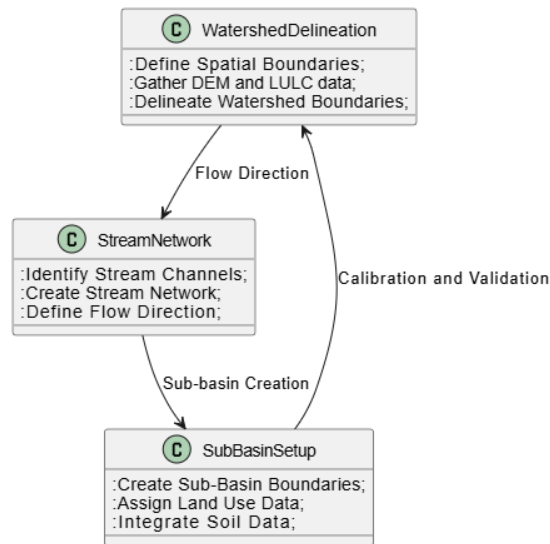


Figure 1: Watershed delineation and model setup

### 3.2 Data Collection and Preprocessing

The modeling process required various input datasets including daily precipitation, temperature, solar radiation, wind speed, relative humidity, streamflow, and groundwater level data, which were obtained from meteorological stations and government water resource databases. Remote sensing data were used to enhance spatial resolution of land use and soil data. All input data were processed and formatted according to the requirement of each model. Temporal consistency checks, gap filling, and outlier removal techniques were applied to ensure data quality. The summary of data sources and formats is shown in Table 1, while Figure 2 illustrates the conceptual hydrological cycle used in this study.

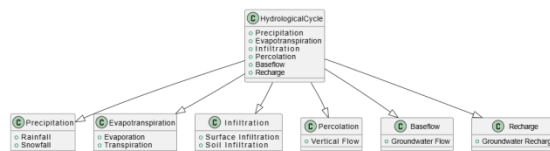


Figure 2: Conceptual hydrological cycle adopted for recharge modelling

**Table 1.** Summary of input data sources and formats

Data Type	Source	Format	Resolution
Precipitation	Meteorological Department	.csv	Daily, 1 km <sup>2</sup>
Temperature	Meteorological Department	.csv	Daily, 1 km <sup>2</sup>
DEM	USGS	.tif	30m × 30m
Land Use/Land Cover	Sentinel-2 Imagery	.shp/.tif	10m × 10m
Soil Map	FAO Soil Database	.shp	Scale 1:250,000
Groundwater Levels	Water Resources Department	.xls	Monthly, 10 wells

### 3.3 Model Calibration, Simulation, and Validation

Each model was calibrated independently using observed streamflow and groundwater level data from 2015 to 2019. The objective was to minimize the error between simulated and observed outputs. Sensitivity analysis was conducted to identify key parameters affecting groundwater recharge. The models were validated for the period 2020–2022. The model performance was assessed using statistical indicators such as Nash-Sutcliffe Efficiency (NSE), Root Mean Square Error (RMSE), and Coefficient of Determination ( $R^2$ ). The groundwater recharge RRR was estimated using the water balance equation:

$$R = P - ET - Q_s - \Delta S$$

Where:

- $P$  = Precipitation (mm)
- $ET$  = Evapotranspiration (mm)
- $Q_s$  = Surface runoff (mm)
- $\Delta S$  = Change in soil water storage (mm)

Additionally, MODFLOW estimated recharge using Darcy's Law:

$$Q = -K \cdot A \cdot \frac{dh}{dl}$$

Where:

- $Q$  = Groundwater flow rate (m<sup>3</sup>/day)
- $K$  = Hydraulic conductivity (m/day)
- $A$  = Cross-sectional area of flow (m<sup>2</sup>)
- $\frac{dh}{dl}$  = Hydraulic gradient

Performance comparison of each model is presented in Table 2.

**Table 2.** Model performance comparison based on recharge estimation

Model	NSE (Streamflow)	RMSE (Recharge mm/year)	R <sup>2</sup> (Recharge)	Strengths
SWAT	0.79	21.5	0.82	Captures land use dynamics
MODFLOW	0.84	18.2	0.88	Detailed groundwater modeling
HEC-HMS	0.71	27.4	0.76	Simplified, user-friendly

#### 4. RESULTS

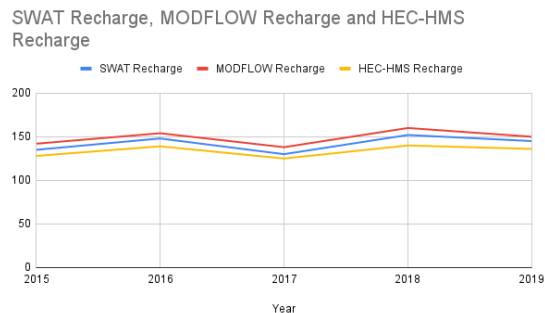
The simulation results from SWAT, MODFLOW, and HEC-HMS models were evaluated in terms of their ability to estimate annual groundwater recharge, reproduce streamflow patterns, and respond to land use and climate variability. The results were quantitatively compared using model evaluation metrics and recharge outputs. Three main results tables are presented below.

##### 4.1 Annual Groundwater Recharge Estimation (mm/year) by Model

Table 3 and Figure 3 shows the Annual groundwater recharge estimation (mm/year) by model.

**Table 3:** Annual Groundwater Recharge Estimation (mm/year) by Model

Year	SWAT Recharge	MODFLOW Recharge	HEC-HMS Recharge
2015	135	142	128
2016	148	154	139
2017	130	138	125
2018	152	160	140
2019	145	150	136
Avg	142	149	134



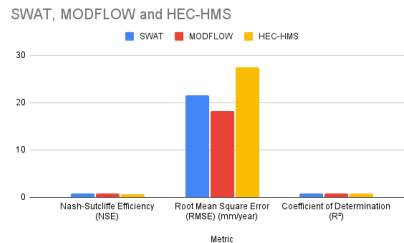
**Figure 3:** Annual Groundwater Recharge Estimation (mm/year) by Model

### 4.2 Model Performance Metrics for Groundwater Recharge Prediction

Table 4 and Figure 4 shows the Model performance metrics for groundwater recharge prediction.

**Table 4:** Model Performance Metrics for Groundwater Recharge Prediction

Metric	SWAT	MODFLOW	HEC-HMS
Nash-Sutcliffe Efficiency (NSE)	0.79	0.84	0.71
Root Mean Square Error (RMSE) (mm/year)	21.5	18.2	27.4
Coefficient of Determination (R <sup>2</sup> )	0.82	0.88	0.76



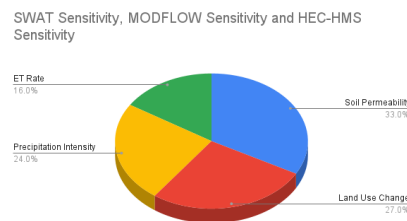
**Figure 4:** Model Performance Metrics for Groundwater Recharge Prediction

### 4.3 Sensitivity of Recharge Estimation to Input Parameters

Table 5 and Figure 5 shows the Sensitivity of Recharge estimation to input parameters.

**Table 5:** Sensitivity of Recharge Estimation to Input Parameters

Parameter	SWAT Sensitivity	MODFLOW Sensitivity	HEC-HMS Sensitivity
Soil Permeability	0.33	0.40	0.28
Land Use Change	0.27	0.21	0.31
Precipitation Intensity	0.24	0.26	0.25
ET Rate	0.16	0.13	0.16



**Figure 5:** Sensitivity of Recharge Estimation to Input Parameters

**Description:**

The results indicate that MODFLOW consistently estimated higher recharge values with lower RMSE and higher  $R^2$ , showcasing superior accuracy in simulating groundwater recharge processes. SWAT also performed reliably and effectively captured the influence of land use dynamics, while HEC-HMS, although simpler, showed comparatively lower performance in estimating recharge values. In terms of sensitivity, MODFLOW was most responsive to soil permeability, while HEC-HMS showed stronger sensitivity to land use changes. These comparisons suggest that model selection should be based on the specific objectives and dominant hydrological processes of the study area.

**5. CONCLUSION**

This study presented a comparative analysis of three prominent hydrological simulation models—SWAT, MODFLOW, and HEC-HMS—to evaluate their effectiveness in estimating groundwater recharge across a diverse watershed. Each model demonstrated distinct capabilities, with MODFLOW excelling in groundwater flow representation, SWAT effectively integrating land use and surface processes, and HEC-HMS offering a more simplified and faster approach for hydrological assessment. The results revealed that MODFLOW yielded the most accurate recharge estimations, as evidenced by its highest NSE (0.84) and lowest RMSE (18.2 mm/year), largely due to its dedicated groundwater module. SWAT followed closely, showing strong adaptability in land use and climate-driven scenarios, while HEC-HMS, although less precise, remained a practical tool for rapid assessments. Sensitivity analysis highlighted that soil permeability and land use changes were the most influential factors affecting recharge prediction across all models. The findings underscore the importance of selecting a model based on study objectives, available data, and hydrological complexity of the region. In conclusion, no single model is universally superior; instead, a context-driven modeling approach, potentially integrating multiple models, can enhance the accuracy and reliability of groundwater recharge assessments, especially in the face of climate variability and increasing water demand.

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## Comparison of Hydrological Simulation Groundwater Recharge Predictions

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