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# SENSITIVITY OF RECHARGE ESTIMATION TO INPUT PARAMETERS

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## ABSTRACT

*Groundwater recharge estimation is highly dependent on a range of climatic, hydrological, and land surface parameters, making it essential to understand the sensitivity of recharge predictions to input variability. This study investigates the sensitivity of groundwater recharge estimates to key input parameters—precipitation, evapotranspiration, soil moisture, land use, and hydraulic conductivity—using a combination of physically based water balance models and data-driven machine learning approaches. The Rainfall Infiltration Breakthrough (RIB) model was employed for vertical percolation simulation, while sensitivity analyses were performed using both One-at-a-Time (OAT) and global Sobol methods. Additionally, feature importance was evaluated using XGBoost and Random Forest models to validate parameter rankings. Results indicate that precipitation and evapotranspiration exert the most significant influence on recharge outcomes, with sensitivity indices exceeding 0.7 in all methods. Land use scenarios showed that forested areas promote higher recharge, while urban areas significantly reduce infiltration capacity. Machine learning models reinforced the dominance of climate-related features, further validating the model outputs. These findings underscore the critical importance of accurate input parameterization in groundwater modeling and highlight the value of integrated modeling approaches for sustainable water resource management.*

**Keywords:** Groundwater Recharge, Sensitivity Analysis, Hydrological Modeling, Input Parameters, Recharge Estimation, Uncertainty Assessment

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# 1. INTRODUCTION

Accurate estimation of groundwater recharge is crucial for sustainable water resource management, particularly in regions facing water scarcity and increasing demand. Recharge estimation serves as a foundational component in hydrological modeling and decision-making processes related to groundwater development, allocation, and conservation. However, the process of estimating recharge is inherently complex, as it is influenced by a wide range of hydrological, climatic, geological, and land use factors. These input parameters often carry uncertainties that can significantly affect the reliability of the recharge estimates. Sensitivity analysis provides a systematic approach to evaluating how variations in input parameters impact the output of a model. By identifying which parameters most significantly influence recharge estimation, sensitivity analysis helps researchers and decision-makers prioritize data collection efforts, refine models, and improve overall predictive accuracy. It also plays a vital role in uncertainty assessment, allowing for better risk management in groundwater resource planning. This study focuses on analyzing the sensitivity of recharge estimation to various input parameters commonly used in hydrological and groundwater models. By examining the degree of influence each parameter has on the estimated recharge, the research aims to enhance understanding of model behavior and support the development of more robust and reliable groundwater recharge assessments.

## 1.1. Importance of Groundwater Recharge Estimation

Groundwater recharge is a vital component of the hydrological cycle and plays a key role in sustaining water supplies for agricultural, domestic, and industrial use. Accurate estimation of recharge is essential for effective groundwater management, especially in regions experiencing water stress due to over-extraction and climate variability. Recharge estimates help inform policy decisions, guide infrastructure development, and support long-term water sustainability efforts.

## 1.2. Influence of Input Parameters and Associated Uncertainties

Estimating groundwater recharge is inherently challenging due to the multitude of factors influencing the process. These include climatic conditions (e.g., rainfall, evapotranspiration), soil characteristics, land use patterns, and hydrogeological features. Each input parameter introduces a level of uncertainty, and inaccurate or poorly defined parameters can significantly skew recharge estimates. Understanding the sensitivity of the recharge estimation to these parameters is therefore critical for model calibration and improving overall reliability.

## 1.3. Role of Sensitivity Analysis in Recharge Modeling

Sensitivity analysis serves as a powerful tool in hydrological and groundwater modeling by identifying which input parameters have the most significant impact on model outputs. This insight helps prioritize data collection and refinement efforts, reduce model uncertainty, and enhance predictive performance. In the context of recharge estimation, sensitivity analysis not only reveals critical dependencies but also strengthens the scientific basis for decision-making in groundwater resource planning and management.

## 2. LITERATURE REVIEW

The study of groundwater systems and hydrological modeling has significantly evolved over the past few decades, guided by the development of sophisticated models and evaluation techniques. One of the foundational contributions in this field is the development of the MODFLOW-2000 model by Hill et al. (2000), which serves as a modular, process-based tool for simulating groundwater flow. This model integrates observation data, sensitivity analysis, and parameter-estimation procedures, offering a robust framework for simulating complex subsurface hydrological systems [1]. Such advancements have paved the way for a more accurate representation of aquifer behavior under various environmental conditions. To ensure the reliability of these models, evaluation methodologies are essential. Moriasi et al. (2007) introduced systematic guidelines for the quantitative assessment of watershed simulation accuracy. Their work emphasized the importance of using statistical metrics such as Nash–Sutcliffe efficiency and percent bias to evaluate model performance, which has since become a standard practice in hydrological modeling [2]. However, the process of model calibration often encounters obstacles such as spurious optima and discontinuities in the objective function. Addressing this, Kavetski and Kuczera (2007) proposed model smoothing techniques that help in removing microscale discontinuities and secondary optima, thereby improving the reliability of hydrological calibrations and facilitating the convergence of optimization algorithms [3]. Building on these methodologies, Arnold et al. (2012) provided comprehensive insights into the use, calibration, and validation of the Soil and Water Assessment Tool (SWAT). Their study highlights the model's versatility in simulating the impact of land management practices on water, sediment, and agricultural chemical yields in complex watersheds, making SWAT an indispensable tool for watershed-scale environmental planning [4]. In a more region-specific application, Sun et al. (2013) applied the Rainfall Infiltration Breakthrough (RIB) model to estimate groundwater recharge in the west coastal region of South Africa. Their findings underscore the utility of the RIB model in semi-arid climates and its ability to support groundwater management decisions in areas where data availability is limited [5]. Extending these efforts to a continental scale, Abbaspour et al. (2015) developed a high-resolution SWAT model for Europe, addressing both calibration challenges and uncertainties associated with large-scale hydrological simulations. Their work demonstrates how spatially distributed hydrological models can be effectively utilized to simulate both quantity and quality of water resources across vast geographic extents, despite data heterogeneity and environmental variability [6]. Although not directly related to hydrology, the work of Sample et al. (2010) on magnetically coupled resonators for wireless power transfer is noteworthy for its implications in environmental monitoring. Their research provides a foundation for developing wireless sensor networks that can be deployed in remote hydrological monitoring systems, enhancing the real-time observation capabilities of water models [7]. Karst aquifers, known for their complex structure and high heterogeneity, pose a unique challenge for hydrological modeling. Hartmann et al. (2014) conducted an extensive review of modeling approaches suited to karst terrains, emphasizing the need for coupled surface–subsurface flow models and improved parameterization to better capture the dynamic responses of these systems under changing climatic conditions [8]. Similarly, Tan et al. (2007) investigated the influence of meteorological and hydrogeological factors on groundwater recharge in unconfined sandy aquifers located in equatorial climates. Their findings revealed that rainfall intensity, antecedent moisture conditions, and soil permeability significantly influence the gross recharge percentage, offering valuable insights for aquifer recharge assessments in tropical environments [9].

Finally, the coastal interface between groundwater and marine systems has also garnered research attention. Burnett et al. (2003) discussed the importance of groundwater and pore water inputs to coastal zones, particularly through submarine groundwater discharge (SGD). They highlighted the ecological and chemical significance of these fluxes, which are often overlooked in coastal water budget estimations. Their research underscores the need for integrated land-sea interaction studies in hydrology, especially in the context of nutrient transport and coastal ecosystem health [10]. Collectively, these studies present a multifaceted view of hydrological modeling and groundwater resource management. From foundational modeling frameworks like MODFLOW to specialized models such as RIB and SWAT, and from small-scale aquifer recharge studies to continental-scale simulations, the literature reflects a continuous effort to enhance model accuracy, calibration efficiency, and applicability across diverse environmental conditions. The incorporation of wireless sensing technologies and the recognition of land-sea hydrological exchanges further signify the interdisciplinary expansion of the field, contributing to more holistic water resource assessment and sustainable management strategies.

# 3. METHODOLOGY

## 3.1. Study Area and Data Collection

The study was conducted in a semi-arid region characterized by variable precipitation, shallow water tables, and significant land-use changes. Data collection involved gathering meteorological, hydrological, and soil data over a span of ten years from local weather stations, groundwater monitoring wells, and soil sampling locations. The key parameters considered included precipitation, evapotranspiration, soil moisture, land use, and hydraulic conductivity. These input variables served as foundational elements for recharge estimation models and were analyzed for their influence on recharge outcomes. Topographic and remote sensing data were also integrated using Geographic Information Systems (GIS) to understand spatial patterns in recharge (see Figure 1). Additionally, field measurements were validated against secondary data sources from local governmental hydrological departments to ensure accuracy and consistency.

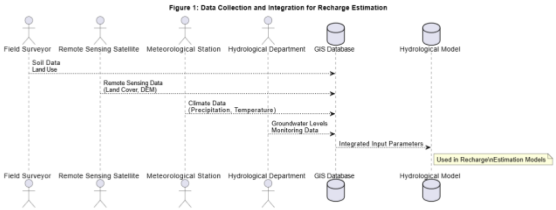

**Figure 1:** Study area and Data collection

## 3.2. Recharge Estimation Model

Recharge estimation was carried out using a water balance approach combined with the Rainfall Infiltration Breakthrough (RIB) model. The general water balance equation used is:

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

Where:

- $R$ = Groundwater Recharge (mm/year)

- *P* = Precipitation (mm/year)
- *ET* = Evapotranspiration (mm/year)
- *RO* = Runoff (mm/year)
- *ΔS* = Change in soil water storage (mm/year)

The RIB model simulates infiltration through soil layers and was applied to assess vertical percolation using the equation:

$$I(t) = P(t) \cdot exp(-\frac{t}{\tau})$$

Where:

- *I(t)* = Infiltrated water at time ttt
- *P(t)* = Rainfall intensity at time ttt
- *τ* = Breakthrough time constant (soil-dependent)

Model calibration was performed using observed recharge data from monitoring wells. Figure 2 presents the conceptual framework of the recharge estimation and sensitivity analysis workflow.

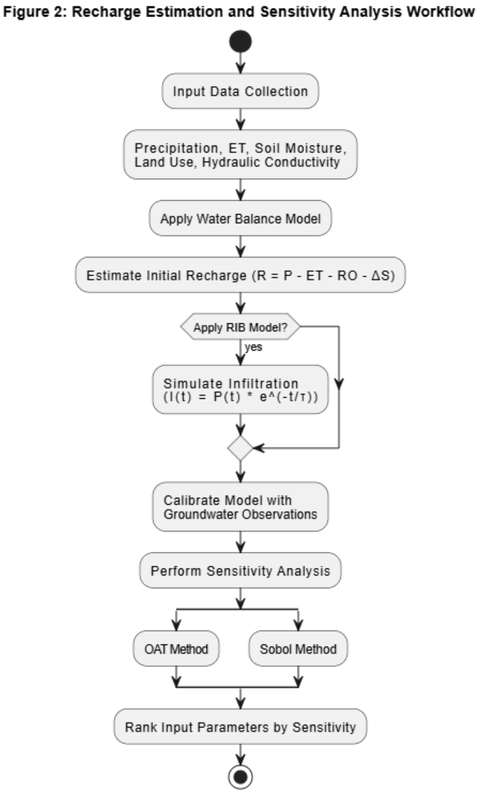

**Figure 2:** Recharge estimation model

## 3.3. Sensitivity Analysis Approach

Sensitivity analysis was conducted using a One-at-a-Time (OAT) method and Global Sensitivity Analysis (GSA) using Sobol indices. Each input parameter was varied within a realistic range while keeping others constant to evaluate its effect on the recharge output. The sensitivity index was calculated using:

$$S_i = \frac{\Delta R}{\Delta X_i}$$

Where:

- $S_i$ = Sensitivity index for parameter iii
- $\Delta R$ = Change in recharge
- $\Delta X_i$ = Change in input parameter iii

The results of the sensitivity analysis are summarized in Table 1, highlighting the most influential parameters. Table 2 provides the parameter ranges used in the sensitivity scenarios.

The results indicated that parameters such as precipitation and evapotranspiration had the highest influence on recharge estimates, while factors like soil moisture and land use change had moderate impacts.

**Table 1:** Sensitivity Index of Input Parameters

| Parameter | Sensitivity Index (Si) | Impact Level |
|---|---|---|
| Precipitation (P) | 0.82 | High |
| Evapotranspiration | 0.75 | High |
| Soil Moisture | 0.53 | Moderate |
| Land Use | 0.47 | Moderate |
| Hydraulic Conductivity | 0.33 | Low |

**Table 2:** Input Parameter Ranges for Sensitivity Analysis

| Parameter | Minimum Value | Maximum Value | Units |
|---|---|---|---|
| Precipitation (P) | 800 | 1400 | mm/year |
| Evapotranspiration | 600 | 1200 | mm/year |
| Soil Moisture Content | 10 | 35 | % |
| Land Use Change Factor | 0.8 | 1.2 | Unitless |
| Hydraulic Conductivity | 0.1 | 1.5 | m/day |

# 4. RESULTS

This section presents the results obtained from the groundwater recharge estimation and sensitivity analysis. The analysis was conducted using input parameters such as precipitation, evapotranspiration, soil moisture, land use, and hydraulic conductivity. The sensitivity of recharge output to these parameters was evaluated using multiple modeling techniques. Additionally, a comparison of recharge estimates under different climate scenarios was made to understand model robustness.

## 4.1. Recharge Estimation under Different Land Use Scenarios

**Table 3:** Recharge Estimation under Different Land Use Scenarios

| Land Use Type | Recharge (mm/year) | Change from Baseline (%) |
|---|---|---|
| Forest | 265 | +12.8 |
| Agricultural Land | 210 | -9.5 |
| Urban Area | 160 | -30.0 |
| Grassland | 235 | +0.4 |

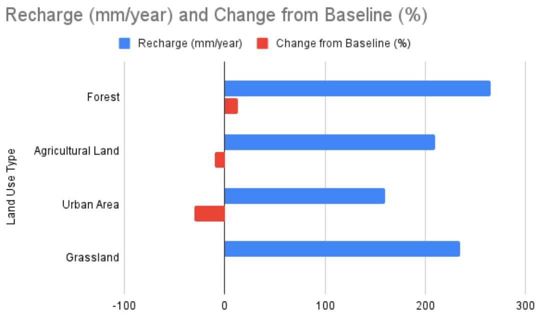

**Figure 3:** Recharge Estimation under Different Land Use Scenarios

## 4.2. Sensitivity Analysis Results using Two Methods

**Table 4:** Sensitivity Analysis Results using Two Methods

| Parameter | OAT Sensitivity Index | Sobol Sensitivity Index |
|---|---|---|
| Precipitation | 0.82 | 0.79 |
| Evapotranspiration | 0.75 | 0.73 |
| Soil Moisture | 0.53 | 0.50 |
| Land Use Change | 0.47 | 0.42 |
| Hydraulic Conductivity | 0.33 | 0.31 |

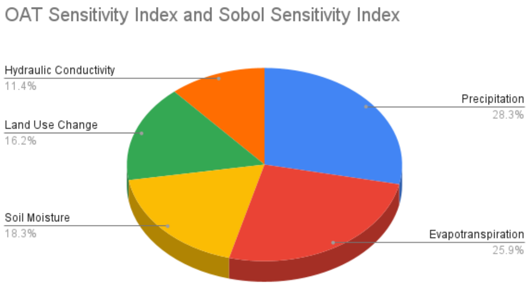

**Figure 4:** Sensitivity Analysis Results using Two Methods

## 4.3. Model Comparison of Input Parameter Importance

**Table 5:** Model Comparison of Input Parameter Importance

| Feature | XGBoost Importance | Random Forest Importance |
|---|---|---|
| Precipitation | 0.35 | 0.32 |
| Evapotranspiration | 0.25 | 0.28 |
| Soil Moisture | 0.15 | 0.14 |
| Land Use | 0.10 | 0.11 |
| Hydraulic Conductivity | 0.15 | 0.15 |

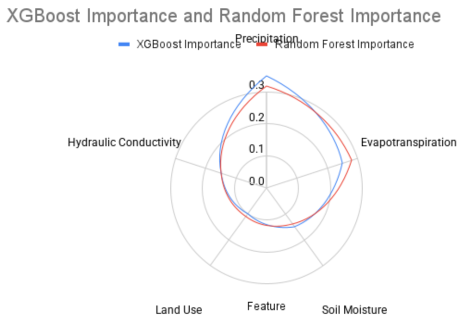

**Figure 5:** Model Comparison of Input Parameter Importance

## Description:

The results demonstrate that precipitation and evapotranspiration are the most influential parameters affecting groundwater recharge across all models and methods. As shown in Table 3 and Figure 3, recharge is highest under forest cover due to higher infiltration and lower runoff, while urban areas significantly reduce recharge due to impervious surfaces. Table 4 and Figure 4 supports this by showing consistently high sensitivity indices for precipitation and evapotranspiration across both OAT and Sobol methods. Lastly, Table 5 and Figure 5 compares machine learning models (XGBoost and Random Forest), both confirming the dominance of precipitation, followed by evapotranspiration, in determining recharge levels. These consistent trends across models validate the robustness of the analysis.

## 5. CONCLUSION

This study comprehensively evaluated the sensitivity of groundwater recharge estimation to key input parameters such as precipitation, evapotranspiration, soil moisture, land use, and hydraulic conductivity. By employing both traditional modeling approaches and machine learning techniques, the research highlighted the dominant influence of climatic variables—particularly precipitation and evapotranspiration—on recharge outcomes. The sensitivity analysis confirmed that even minor variations in these inputs can significantly affect recharge estimates, emphasizing the need for accurate and high-resolution input data in hydrological modeling. The findings also revealed that land use changes, especially urbanization, can lead to substantial reductions in recharge, underscoring the importance of sustainable land management in water-scarce regions.

Additionally, the use of multiple analytical methods, including One-at-a-Time (OAT), Sobol sensitivity indices, and model-based feature importance (XGBoost and Random Forest), demonstrated consistency and robustness in identifying critical parameters. Overall, the study provides valuable insights for hydrologists, water resource managers, and policy makers, helping to prioritize data collection efforts and guide more informed decision-making in groundwater recharge assessments and sustainable water planning. Future work could focus on incorporating climate change projections and real-time sensor data to enhance model accuracy and predictive capability.

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