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Research Article

Development of a model to estimate groundwater recharge

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Abstract: Quantifying the spatial and temporal distribution of natural groundwater recharge is essential for effective groundwater modeling and sustainable resource management. This paper presents M-RechargeCal, a user-friendly software tool developed to estimate natural groundwater recharge using two widely adopted approaches: the Water Balance (WB) method and Water Table Fluctuation (WTF) method. In the WB approach, the catchment area is divided into seven land-use categories, each representing distinct recharge characteristics. The tool includes eighteen different reference Evapotranspiration (ET_0) estimation methods, accommodating varying levels of climatic input data availability. Additional required inputs include crop coefficients for major crops and Curve Numbers (CN) for specific land-use types. The WTF approach considers up to three aquifer layers with different specific yields (for unconfined aquifer) or storage coefficient (for confined aquifer). It also takes into account groundwater withdrawal (draft) and lateral water movement within or outside the aquifer system. M-RechargeCal is process-based and does not require calibration. Its performance was evaluated using six datasets from humid-subtropical environments, demonstrating reliable results (R^2 = 0.867, r = 0.93, RE= 10.6%, PMARE= 9.8, E_{NS} = 0.93). The model can be applied to defined hydrological or hydrogeological units such as watersheds, aquifers, or catchments, and can be used to assess the impacts of land-use/land-cover changes on hydrological components. However, it has not yet been tested in arid regions. M-RechargeCal provides modelers and planners with a practical, accessible tool for recharge estimation to support groundwater modeling and water resource planning. The software is available free of charge and can be downloaded from the author's institutional website or obtained by contacting the author via email.

Keywords: Groundwater recharge; Modelling; Software; Water balance; Aquifer; Specific yield

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Introduction

Groundwater recharge, also known as deep drainage or deep percolation, is a key hydrological process that replenish aquifer with water. Water primarily enters an aquifer from the Earth's surface through infiltration and percolation, driven mainly by natural events such as rainfall and snowmelt. Effective management of groundwater systems relies heavily on understanding and quantifying groundwater recharge, which plays a crucial role in many water resources studies aimed at assessing the dynamics of aquifer storage (Moeck et al. 2020; Ali, 2016). Therefore, accurate estimates of groundwater recharge are vital for research into groundwater volume estimation, contaminant transport modeling, irrigation planning, climate change impact assessment, saltwater intrusion in coastal aquifers, and rock weathering processes, among other topics.

However, according to Cartwrite et al. (2020), Rushton et al. (2020), Fu et al. (2019), Walker et al. (2019), Delottier et al. (2018), Crosbie et al. (2018), and Lanini and Caballero (2016), measuring groundwater recharge remains one of the fundamental challenges in hydrological research and assessment. The recharge process, which

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involves the downward movement of water into the saturated zone, is highly variable in both time and space and is influenced by numerous factors such as soil types, surface vegetation, rainfall patterns, topography, and underlying geology. Due to its complexity, groundwater recharge is widely recognized as one of the most challenging and uncertain components to estimate within a hydrological water balance framework (Akurugu et al. 2025).

Accurate evaluating groundwater recharge and understanding its temporal and spatial variability, is essential for multiple applications, including assessing groundwater resources, protecting water quality, managing streamflow and riparian ecosystems, recharging aquifers, simulating groundwater flow, and tracking the movement of contaminants. Numerous studies have demonstrated that such assessments are particularly important for supporting sustainable development experiencing rapid growth in agriculture, industry, and urbanization (Ali et al. 2022; Banimad et al. 2017).

Given the importance of groundwater recharge estimation, researchers have explored a wide range of approaches and strategies. These range from simple field-based techniques, such as seepage meters, to advanced numerical modeling and isotopic tracer methods, with the choice often depending on local physiography, climate conditions, available technology, and resources (Xu et al. 2024; Redda et al. 2024; Huang et al. 2023; Sun et al. 2023; Donmoyer et al. 2023; Mauricio et al. 2023; West et al. 2023; Irvine and Cartwright, 2022; Danielescu, 2022; Fauzia et al. 2021; Koch et al. 2019; Dandekar et al. 2018). Many researchers have emphasized the importance of combining different methods to enhance the reliability of recharge estimates (Ferede et al. 2020; King et al. 2017; Ali and Mubarak, 2017). However, such approaches often come with significant costs, labor demands, and equipment requirements, which can limit their practical applications, particularly in resource-constrained settings.

When accurate measurements of individual water balance components, especially runoff, are available, the Water Balance (WB) method is frequently used and can produce reasonable estimates of recharge (Halford and Mayer, 2000; Ali and Mubarak, 2017). Nonetheless, concerns about uncertainty in recharge estimation persist, as highlighted in several studies (Cartwright et al. 2020; Delottier et al. 2018; Lanini and Caballero, 2016). It is well-established that groundwater recharge is directly affected by climate and land use changes (Indhanu and Chub-Uppakarn, 2025; Naik et al. 2024; Li et al. 2024).

Existing models that simulate groundwater recharge, including simple water balance approaches (e.g. SMPR by Banimahd et al. 2017; Shama'a, 2023; Verma et al. 2023), one-dimensional models (e.g. HYDRUS-1D –Stafford et al. 2022; Tonkul et al. 2019), and Cumulative Rainfall Departure (CRD) model (Nekooei et al. 2020), often do not adequately consider the spatial variability of land use and soil type. For example, in WetSpass (Abdollah et al. 2012), the vegetation cover is assumed to remain constant throughout the simulation period, which rarely reflects actual conditions. In reality, seasonal crop cover often changes within four to five months following crop sowing or transplanting, and annual cycle of wet and dry seasons can significantly alter the distribution and composition of watershed vegetation. To achieve more accurate estimates, it is therefore critical to incorporate data on actual land-use patterns. Additionally, the online tool "Recharge Buddy" (Danielescu, 2022) estimates daily groundwater recharge, discharge, and aquifer storage changes based on water table elevations and specific yield, using a modified Water Table Fluctuation method. However, variably saturated subsurface models still face challenges in accurately predicting recharge due to complex storage dynamics at the capillary fringe (Gong et al. 2023).

While many methods for estimating recharge require expensive equipment and intensive fieldwork, they often fail to adequately account for temporal and geographical variability. Current models for assessing recharge distribution typically demand extensive data inputs, complex parameterization, and significant time investment for setup and calibration (Danielescu, 2022; Fauzia et al. 2021; Dandekar et al. 2018; Kambale et al. 2017; Banimahd et al. 2017). Several researchers have emphasized that reasonable estimates of recharge can be achieved by identifying and characterizing the specific flow mechanisms and hydrological processes at play in a given region (Cartwright et al. 2017; De Vries and Simmers, 2002; Rushton, 1988; Gee and Hillel, 1988).

In areas such as faults, gravel-packed zones, stony regions, hills, and cracked soils, bypass flow can play a significant role in groundwater recharge. For example, in cracking soils, water can quickly infiltrate through large vertical pores that are initially air-filled, bypassing wetter or drier soil within the soil peds (Bronswijk, 1988; Oostindie and Bronswijk, 1992). In these conditions, bypass flow may be substantial when rainfall first begins and can decline as the fissures become saturated.

Accurately quantifying this process is crucial for realistic recharge estimation. Similarly, in watersheds with well-developed subsurface drainage systems, drainage discharge (Dr) can represent a significant portion of recharge outflow and must be subtracted from total recharge calculations. The net recharge in such areas is effectively the total recharge minus baseflow, which is particularly important in catchments with multiple streams or rivers. However, many existing models do not explicitly consider these factors.

In response to these limitations, the objective of this study is to introduce a straightforward yet physically based model named M-RechargeCal (short for "Multi-method Recharge Calculation"). This model combines two established estimation techniques: The Water Balance (WB) and Water Table Fluctuation (WTF) methods, and incorporates 18 different ET_0 calculation options. The M-RechargeCal model also considers water withdrawal (for domestic, irrigation, or industrial purposes), bypass flow through cracks, and drainage discharge. Additionally, it allows for the integration of actual, time-varying land-use data throughout the simulation period. By balancing methodological rigor with practical usability, the M-RechargeCal model aims to provide more accurate and realistic recharge estimates while remaining accessible to planners and researchers.

1 Materials and methods

1.1 Theory of Water balance method

According to the principle of mass balance, in a closed catchment system, the total inflow and outflow of water must be equal, i.e. $Q_{in} = Q_{out}$. A simplified form of water balance equation at catchment scale for a specific time period can be expressed as (Yin et al. 2011; Ali, 2017):

$$P + q_{in} = R_0 + R_e + ET_a + \Delta SM + q_{out} \quad (1)$$

Where: P = Precipitation (mm), q_{in} = any other inflow to the system, R_0= Surface runoff (mm), R_e = groundwater recharge (mm), ET_a = actual evapotranspiration (mm), q_{out} = any other outflow from the system, ΔSM= change in soil moisture (mm) for the specified time interval.

If the change in soil moisture is negligible, the equation can be rearranged to estimate groundwater recharge (R_e) as:

$$R_e = (P + q_{in}) - (R_0 + ET_a + q_{out}) \quad (2)$$

The runoff-recharge, bypass flow (or flow through cracks, included under q_{in}), and drainage discharge (included under q_{out}) are considered in the model. The model also provides the flexibility to include other miscellaneous or unknown inflow and outflow components (to or from the aquifer) in the input data.

(1) Actual Crop Evapotranspiration (ET_a) calculation

Traditionally, actual crop evapotranspiration (ET_a) is calculated as:

$$ET_a = (ET_0 \times K_c) \times K_s = ET_p \times K_s \quad (3)$$

Where: ET_0 is the reference crop evapotranspiration (mm), K_c is the crop coefficient, K_s is the soil moisture stress factor (or dryness factor), ET_p is the potential crop evapotranspiration. Based on the 'dryness (or water deficit)' and 'wetness (or water surplus)' condition, the ET_a is calculated as:

$$\begin{aligned} ET_a &= ET_p, \quad \text{If } P > ET_p \quad (\text{i.e. } K_s = 1) \\ &= P, \quad \text{If } P < ET_p \end{aligned} \quad (4)$$

Where: P is the rainfall, ET_p is the potential evapotranspiration (10 days calculation in the model).

(2) Runoff estimation

The USDA-SCS runoff equation (USDA-SCS, 1985) is expressed as:

$$R_0 = \frac{(P - 0.2S)^2}{P + 0.8S} \quad (5)$$

Where: R_0= runoff (mm), P = rainfall (mm), S= potential maximum retention after runoff begins (mm). The parameter (S) represents the potential retention capacity of the soil and may range from zero on smooth, impervious surface to very large values in highly permeable soils such as deep gravel.

For longer time steps (greater than an hour, such as daily or monthly) in runoff and recharge calculations, water losses due to evapotranspiration (ET) can significantly affect the water balance. In the M-RechargeCal model, a modified version of USDA-SCS method is used, which explicitly accounts for evapotranspiration losses (Ali et al. 2022; Ali, 2017):

$$R_0 = \frac{[(P - ETa) - 0.2S]^2}{(P - ETa) + 0.8S} \quad (6)$$

The 'S' value was calculated as (USDA-SCS 1985):

$$S = (1000/\text{CN}) - 10 \quad (7)$$

Where: CN is the curve number.

For non-homogeneous sub-area, the '*weighted average curve number*' or '*composite curve number*' can be calculated as:

$$CN_w = \frac{\sum_{i=1}^{i=n}(CN_i \times A_i)}{\sum_{i=1}^{i=n} A_i} \tag{8}$$

Where: CN_w is the composite curve number, i is the number of sub-area, CN_i is the curve number of the area A_i, and so on.

(3) Averaging rainfall

When multiple rain gauges are available within a catchment, the weighted average rainfall (P) can be calculated as:

$$P_{w.av} = \frac{\sum_{i=1}^{i=n}(P_i \times A_i)}{\sum_{i=1}^{i=n} A_i} \tag{9}$$

Where: P_i is the rainfall under area A_i.

(4) 'Runoff-recharge' estimation

'Runoff-recharge' refers to the portion of recharge that occurs from runoff areas, where water may continue to infiltrate into the subsurface for a significant period after rainfall has stopped. The 'runoff-recharge' (R_{rr}) is estimated as:

$$R_{rr} = \sum_{i=1}^{n} A_i \times r_{ri} \times t_i \tag{10}$$

Where: A_i is the area under section i, and r_{ri} is the 'runoff recharge rate' of the section i, and t is the time period for runoff recharge for the particular area A_i.

(5) Recharge from water-body

The quantity of recharge from the water-body can be quantified as:

$$Q_{wr} = \sum_{i=1}^{n} A_i \times r_{wi} \times t \tag{11}$$

Where: A_i is the area of water-body under section i, and r_{wi} is the 'percolation or recharge rate' of the section i, and t is the time period considered.

1.2 Theory of water-table fluctuation method

1.2.1 For unconfined aquifer

The Water-Table Fluctuation (WTF) method estimates groundwater recharge based on changes in the water-table level over time. For an unconfined aquifer, recharge (R) can be estimated as:

$$R = \Delta h \times S_y \tag{12}$$

Where: R = recharge occurring between times t_0 and t_j; Δh = change in water-table elevation during the specified time period; S_y= specific yield of the aquifer (dimensionless, or in percent).

In the M-RechargeCal model, additional factors such as water withdrawal (for drinking, irrigation or industrial purposes), and any other inflows (Q_{in}) or outflows (Q_{out}) within the aquifer system are also considered to refine the recharge estimate.

1.2.2 For confined aquifer, the WTF method uses the storage coefficient instead of specific yield

Recharge can be estimated as:

$$R = \Delta h \times S_c \tag{13}$$

Where: R = recharge occurring between times t_0 and t_j; Δh = difference in water table position during the given time period; S_c= Storage coefficient (dimensionless, or in percent).

1.2.3 Considerations and correction for water withdrawal and groundwater inflow-outflow

Today, in many parts of the world, groundwater is continuously extracted throughout the year for domestic, irrigation, drinking, fisheries and industrial uses (including small-scale industries). Failing to account for these withdrawals (drafts) would result in inaccurate recharge estimates. Additionally, other hydrological interactions, such as groundwater discharge as baseflow to rivers or streams during dry periods, or inflow from streams/rivers to the aquifer during high-flow stages, can significantly impact groundwater levels and must be considered.

To accurately quantify groundwater withdrawal, the start date, end date, pump discharge rate and daily operating hours for each pumping well must be specified. The total volume of groundwater pumped (Q_{pump}, m^3) for the period of interest can be calculated as:

$$Q_{pump} = \sum_{i=1}^{i=n}\sum_{t=1}^{t=m} q_i \times t \tag{14}$$

Where: Q_{pump} = Total groundwater volume pumped during the specified period (e.g. seasonal or annual) for the entire catchment (m^3); q_i= Discharge rate of pump 'i' (m^3/min) ; i= pump index, from 1 to n (total number of pumps in the catchment); m = Pump operation period (min); t = Time increment (minute), from 1 to m during the specified recharge period.

Considering all these factors, the adjusted recharge equation can be written as:

$$R = S_y * \left[\Delta h + \left(h_{pump} + h_{base}\right) - h_{gw-in}\right] \tag{15}$$

Where: h_{pump} = Pumping amount (mm depth) for domestic, irrigation, industry, etc. h_{base} = Discharge from groundwater as base-flow (mm); h_{gw-in} =

Inflow of water from stream/river to groundwater; S_y = specific yield (dimensionless, or in percent).

(1) Depth calculation

The depth of water withdrawn h_{pump} can be determined as:

$$h_{pump}(\text{mm}) = [Q_{pump}(\text{m}^3)/\text{Catchment area}(\text{Km}^2)] \times 10 \tag{16}$$

Then, the recharge rate (R_e) over the considered period (Δt) can be calculated as:

$$R_e = \frac{S_y \times [\Delta h + h_{pump} + h_{base} - h_{gw.in}]}{\Delta t} \tag{17}$$

Where: Δt is the time period considered.

(2) Considerations for multi-layer system

In many hydrogeological settings, the aquifer system may consist of multiple layers, each with different thickness and specific yields. To ensure accurate recharge estimates in such systems, it is essential to perform separate calculations for each layer, considering it unique specific yield and the elevations of lower and upper boundaries. In the M-RechargeCal model, provisions has been made to accommodate up to three (3) distinct layers within the same aquifer system.

(3) Complex situation of confined and unconfined aquifer

Complex scenarios can occur when an aquifer transitions between confined and unconfined conditions due to significant changes in the water table height, often caused by substantial groundwater withdrawal, or natural fluctuations. It this case, it is recommended that recharge calculations be performed separately for each section. This ensures that the significant variation in storage parameters is correctly reflected in recharge estimates.

(4) Unaccounted loss or gain

Following the approach highlighted by Danielescu (2022) in the soil water budget and irrigation scheduling model (SWIB), it is acknowledged that unaccounted losses or gains, often refereed to as budget errors, may occur in real-world recharge estimation. To address this, the M-Recahrge-Cal model includes an optional error term, which allows the users to input a reasonable estimate for unaccounted losses or gains (negative or positive). This helps balance the water budget and improves the reliability of the final recharge estimates.

1.3 About the model M-RechargeCal

The model M-RechargeCal (Multi-method Recharge Calculation) is a process-based hydrologic model designed to estimate natural groundwater recharge. It provides recharge estimates through two widely accepted approaches: The Water Balance (WB) and the Water-Table Fluctuation (WTF).

In the WB approach, the model operates on a 10-day calculation cycle. For the WTF method, the model is intended primarily for annual estimation; however, it can also produce seasonal estimation provided that both the rising and falling limbs of the water table are included.

M-RechargeCal is a conceptual, process-based rainfall-recharge model and offers the following key features:

(1) An intuitive input window for uploading and handling input data;

(2) A calculation module;

(3) An output screen for inspecting the results;

(4)The ability to download output files for further analysis.

In the WB approach, the M-RechargeCal model converts rainfall into runoff, evapotranspiration ET and recharge based on the characteristics of the watershed or catchment area and the available climatic data. To accurately represent spatial variations in land-use, the model currently allows up to seven sub-areas, each representing different land-use patterns or recharge categories. The size of these sub-areas can vary over time and should be provided as a percentage of the total catchment area (A).

In the WTF approach, the model can handle up to three distinct aquifer layers, each with its own depth and specific yield. As a process-based model, M-RechargeCal does not require calibration. However, the accuracy of the output fully depends on the reliability and correctness of the input data. Therefore, providing realistic and precise input values is essential to obtain credible results.

The model code is written in Python and is designed to run on Microsoft Windows. To make the tool user friendly, the Python engine is linked to a Graphical User Interface (GUI) developed in Java.

M-RechargeCal provides estimates of natural groundwater recharge. A schematic diagram of the model framework for the Water Balance component is shown in Fig. 1. After launching the main window (Fig. 2), the user should first select the estimation method eighter WB or WTF (Fig. 3). In the WB module, users upload the required input files for the catchment area and select the reference evapotranspiration ET_0 method from the 18 available options (Fig. 4).

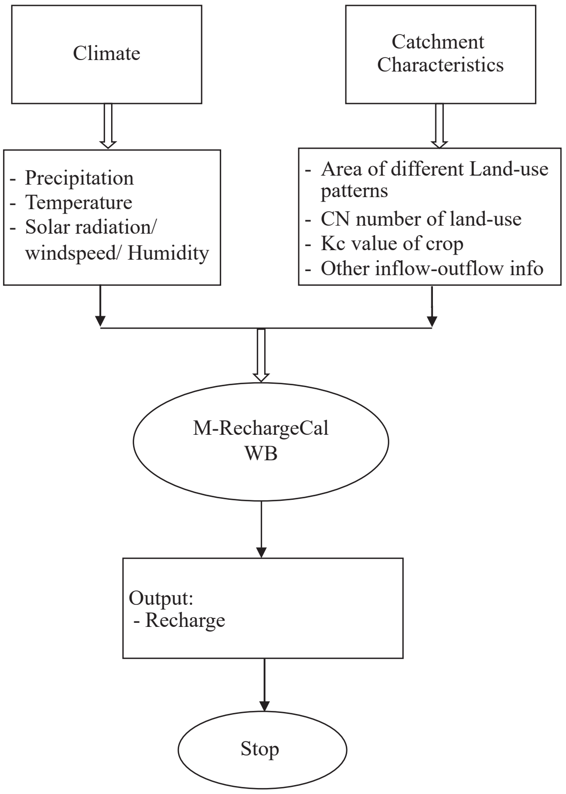

Fig. 1 Schematic diagram of the model framework for WB component

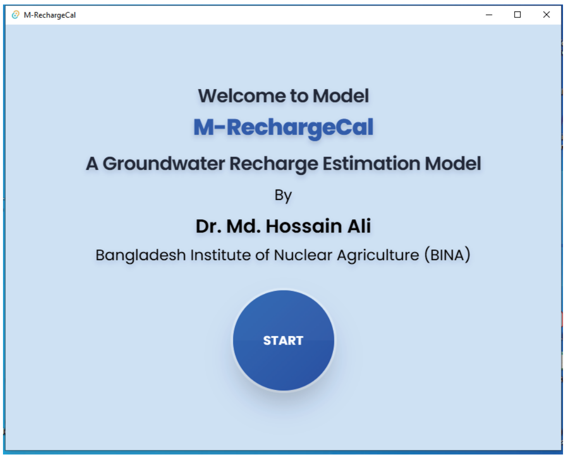

Fig. 2 View of the model sketch at starting phase

1.4 Detailed description

The reference evapotranspiration (ET_0) methods available in M-RechargeCal and their respective climatic data requirements are summarized in Table 1.

The WB model estimates groundwater recharge by combining land-use patterns, crop related and climatic information through a simple mass balance approach, calculated at a 10-day time step. The minimum required input data include precipitation, maximum and minimum air temperature,

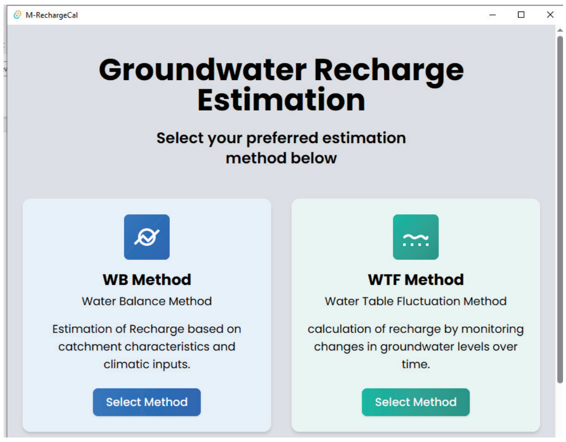

Fig. 3 Operational view of the model interface during method selection

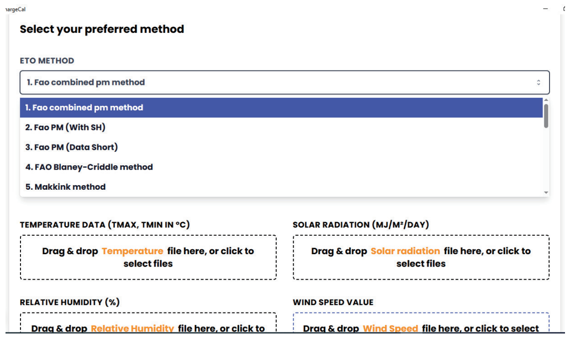

Fig. 4 View of the WB method interface during ET_0 selection phase

the area covered by each of the seven predefined land-use categories, curve numbers for each land-use type, and crop coefficient values for the cultivated crops or vegetations. All input data can be conveniently imported from an Excel (.xlsx) or .CSV file.

(1) Land-use pattern

In many parts of the world, land-use patterns vary throughout the year, especially the extent of water-bodies, cropland (area and type of crop), fallow or bare land, among others. To accurately capture these dynamic patterns, the model currently allows for up to seven sub-sections or sub-areas. These areas should be specified as percentages of the total catchment area, and can vary month-to-month based on local practices and conditions.

The land-use patterns defined in the model are as follows:

A1 = Crop-land (irrigated/rain-fed) (%);

A2 = Grass-land (%);

A3= Forest (%);

A4 = Bare land (%);

A5 = Very pervious area (gravel/sand), but not under crop-land (%);

Table 1 ET_0 methods included in M-RechargeCal and their required climatic input data

	Method	Reference	Climatic data required
1	FAO P-M (full data)	FAO 56 (Allen et al. 1998)	T_{max}, T_{min}, RH, WS, Rs
2	FAO P-M (with SH)	FAO 56 (Allen et al. 1998)	T_{max}, T_{min}, RH, WS, SH
3	FAO P-M (data-short)	FAO 56 (Allen et al. 1998)	T_{max}, T_{min}, RH
4	FAO B-C method	FAO 24 (Doorenbos and Pruitt, 1977)	T_{mean}
5	Makkink	Makkink (1957)	Rs
6	Hargreaves	Hargreaves and Samani (1985)	T_{max}, T_{min}
7	Hansen	Hansen (1984)	Rs
8	Turc	Turc (1961)	Rs
9	Prestley-Taylor method	Prestley & Taylor (1972)	Rs
10	Jensen-Haise	Jensen and Haise (1963)	Rs
11	Abtew	Abtew (1996)	Rs
12	de Bruin	de Bruin (1998)	Rs
13	Lobit et al.	Lobit et al. (2018)	T_{max}, T_{min}
14	Drooger and Allen	Drooger and Allen (2002)	T_{max}, T_{min}
15	Trajkovic	Trajkovic (2007)	T_{max}, T_{min}
16	Mintz and Walker	Mintz and Walker (1993)	T_{mean}
17	Smith and Stopp	Smith and Stopp (1978)	T_{mean}
18	ASCE method	Walter et al. (2000)	T_{max}, T_{min}, RH, WS, Rs

A6 = Water-body (%);

A7 = Absolute impervious area/Concrete/Urban area (%).

(2) Time step (for Water Balance and recharge calculation)

Danielescu (2022) highlighted that the delay between precipitation events and actual response in soil moisture or downstream runoff, as well as the presence of snowfall, snowpack, and snowmelt during colder months, can introduce errors in daily surface runoff (R_0) calculations. Conversely, Howard and Lloyd (1979) demonstrated that water budget analyses using accounting periods longer than 10 days may also result in significant inaccuracies.

Considering these factors, and for practical simplicity, the M-RechargeCal model calculates R_0 and other WB components using a 10-day time window.

1.5 Modeling approach

1.5.1 Water Balance (WB) method

In the water balance method, groundwater recharge is estimated by systematically accounting for all water inputs and outputs within a hydrological system, typically at the land surface. In this model, the temporal resolution adopted is ten (10) days. The available rainfall is partitioned into evapotranspiration (ET), runoff, and deep percolation (recharge), based on climatic, soil and vegetation factors.

For climatic influences, reference evapotranspiration (ET_0) is first calculated. Depending on the crop type and its growth stage, ET_0 is then converted to actual evapotranspiration (ET_a). Runoff is estimated from rainfall using a modified USDA-SCS curve number method, which accounts for soil characteristics, vegetation cover, and slope. Recharge is subsequently calculated using the water budget method. Additionally, the model provides options to include water withdrawal, bypass or crack-flow, and other forms of inflow or outflow in the system (as specified by the user) to determine the net recharge more accurately.

1.5.2 Water-Table Fluctuation (WTF) method

The WTF approach models recharge based on the principle that an increase in the water-table elevation within an aquifer is primarily due to the addition of recharge within the hydrologic boundary. By computing the net water-level rise over a yearly period (or at least a seasonal period that captures both the rising and falling limbs) and using the aquifer's specific yield, the total recharge can be estimated. Similar to the WB method, the model also allows for the consideration of other inflow and outflow components, as provided by user, to refine the recharge estimate.

1.6 Sensitivity analysis

In groundwater modeling, sensitivity analysis is a critical technique for evaluating how variations in input parameters affect model outputs. Essentially, it investigates the degree to which different input variables influence the final result. This process helps identify the parameters that most significantly affect model performance, guiding more efficient data collection, model refinements, and uncertainty analysis.

The location used for testing the sensitivity of the model parameters, along with the characteristic of the climatic data and other relevant details, are described below. The ten-day cumulative totals of reference evapotranspiration ET_0, rainfall, and the 10-day average air temperature for Mymensingh location (for the year 2022), which were used in the sensitivity analysis, are shown in Fig. 5. For this analysis, data corresponding to a specific ten-day period (the 10^{th} out of 36 periods in the year) were selected for each parameter.

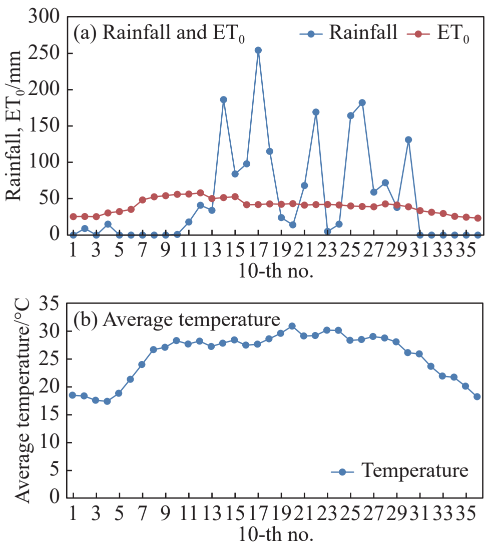

Fig. 5 Patterns of (a) rainfall and ET_0, and (b) average temperature throughout the year 2022 at Mymensingh

We run the model repeatedly by varying the values of different parameters (ET_0, P, Kc, CN) (Table 2) by 10%, 20% and 30% from their base values, and recorded the resulting recharge outputs. The percentage change in output was compared against the percentage change in input values to identify the most sensitive parameters.

2 Model evaluation

The results of the model "M-RechargeCal" were compared with field estimates of recharge obtained through previous studies (Ali et al. 2022; Ali, 2017), with recharge values derived from tracer techniques and water level fluctuation method.

2.1 Description of the test sites

The model was evaluated at three different sites using multiple estimation methods. The study locations are depicted in Fig. 6. These sites were selected to represent a range of climatological, hydrogeological and watershed characteristics. Table 3 provides a summary of the key characteristics of each site. Additionally, Table 4 outlines the years during which the studies were conducted at each location along with the corresponding recharge estimation methods employed.

Hydrogeological characteristics and aquifer type

A brief outline of the hydrogeological characteristics and aquifer type are described below.

(1) Nachol

The geological log of the study area is presented in Fig. 7. The uppermost 80 feet from the ground surface consists primarily of clay. The vertical profile of the subsurface lithology shows stratification, with layers of clay, silty clay, very fine sand and fine sand in the upper section. Below this, the profile transitions to medium coarse sand, coarse sand and mixtures thereof. The saturated thickness of the unconfined aquifer in this area was measured to be approximately 25 meters (82 feet).

Table 2 Tested variables, conditions, and their base values for sensitivity analysis

	Variable	Conditions	Base-value for testing sensitivity
1	ET_0	P< ET_p	ET_0 = 20 mm
		P> ET_p	ET_0 = 20 mm
2	P (*P= 41 mm, ET_p=58 mm*)	P< ET_p	P= 41 mm
	P (*P= 84 mm, ET_p=58 mm*)	P> ET_p	P= 84 mm
	P(*P= 186 mm, ET_p= 56.65 mm*)	P> ET_p	P= 186 mm
3	CN	P> ET_p	CN = 60
4	Kc	P< ET_p	Kc=0.9
		P> ET_p	Kc=0.9

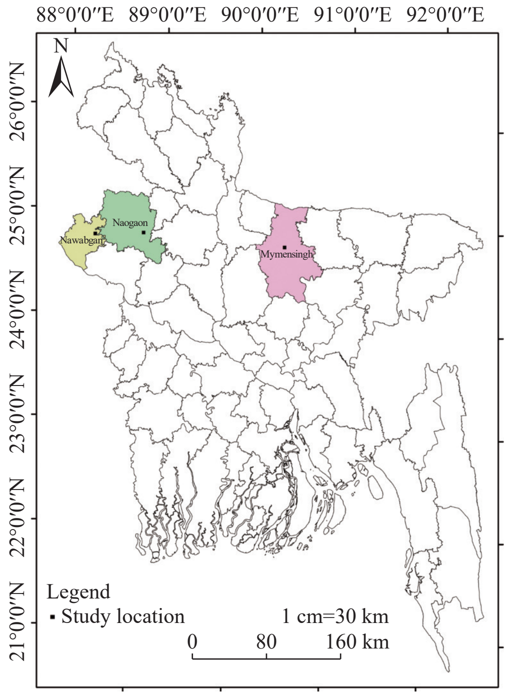

Fig. 6 Map of Bangladesh showing the study locations

(2) Niamatpur

Subsurface Lithology

The first 90 feet from ground surface consists of hard clay, followed by 10 feet of clay mixed with very fine sand. The vertical profile of the subsurface lithology shows stratification with clay, silty clay, very fine sand and fine sand in the upper section. Beneath this, the layers consist of medium coarse sand, coarse sand and their mixtures. The geological log of study area is presented in Fig. 8. The saturated thickness of the unconfined aquifer was at 19.51 meters (64 feet).

(3) Mymensingh

The site is located within the Ganges Alluvial Plain. The topography across most of the area is predominantly plat. Surface soils are alluvial, ranging from sandy loam to clay loam, with a deep underlying clay profile. The subsurface aquifers consist of alluvial deposits characterized by a heterogeneous mix of fine sands, coarse sands, and gravels. Hydraulic conductivity in this region varies between 5 m^3/m^2/day to 10 m^3/m^2/day (Mojid, 1994). The confined aquifer is located at an approximately depth of 79.25 meters (260 feet).

2.2 Model performance indicators

Evaluating model performance requires the use of both statistical criteria and graphical analysis. Addiscott and Whitmore (1987) emphasized that relying on a single metric to quantify the discrepancy between model outputs and observed data can be misleading; instead, using multiple evaluation methods together provides a more comprehensive assessment of how closely model estimates align with actual measurements. According to Loague and Green (1991), a model is considered a reliable representation of reality only if it can predict

Table 3 Characteristics of the test sites

Sl. No	Test site	Latitude deg.N	Longitude deg.E	Elevation (above m.s.l.) /m	Yearly rainfall (2022) /mm	Monthly average temperature /°C
1	Mymensingh	24.73	90.4	16	1,874	18.1–29.8
2	Nachol (*ChapaiNawabgonj district*)	24.73	88.42	46	1,387	18–36
3	Niamatpur (*Naogaon district*)	24.80	88.94	27	1,395	17.8–35.9

Table 4 Year-wise location and method of recharge estimation

Sl. No	Test site and year	Method of recharge determination	Reference
1	Nachol, 2018	Tracer technique	Ali et al. (2022)
2	Nachol, 2019	Tracer technique	Ali et al. (2022)
3	Niamatpur, 2019	Tracer technique	Ali et al. (2022)
4	Niamatpur, 2019	Water-table fluctuation	Ali et al. (2022)
5	Mymensingh, 2015	Tracer technique	Ali (2017)
6	Mymensingh, 2016	Tracer technique	Ali (2017)

* Note:
a) The data used for No.1-2 were taken from Table 2 and Table 3 of Ali et al. (2022).
b) The data used for No.3 were from Table 5 of Ali et al. (2022).
c) The data used for No.4 were from Table 6 of Ali et al. (2022).
d) The data used for No.5-6 were taken from Table 1 of Ali et al. (2017).

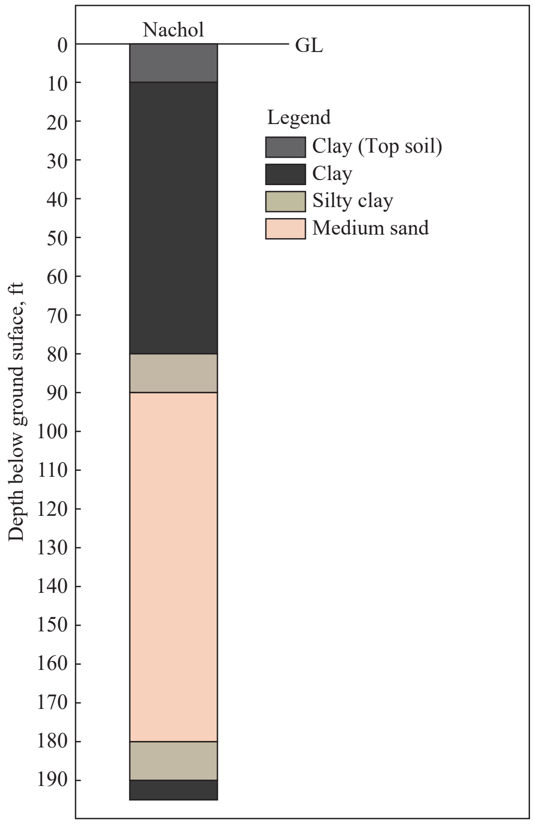

Fig. 7 Geological log of the study site, Nachol

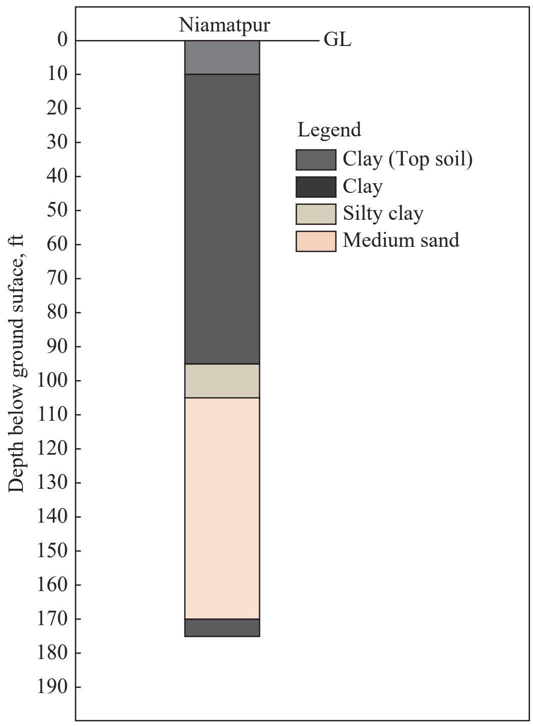

Fig. 8 Geological log of the study area, Niamatpur

observable phenomenon with acceptable accuracy and precision.

The developed model was tested with the datasets described previously. Comparisons between observed and simulated outputs were conducted graphically. Additionally, several statistical and model efficiency indicators were calculated to assess overall model performance, including Mean Bias, Mean Absolute Error (MAE), Root Mean Square Error (RMSE), Relative Error (RE), Coefficient of Determination (R^2), Pearson Correlation Coefficient (r), Nash and Sutcliffe Efficiency (E_{NS}), and Percent Mean Relative Absolute Error (PMRAE) (Ali and Abustan, 2014).

2.3 Model performance

The recharge rates (mm/year) obtained from the test sites and the corresponding model output (based on the Water Balance approach) are presented in Fig. 9. To further evaluate model accuracy and reliability, the values of key statistical indicators and model efficiency metrics for the yearly recharge estimates are summarized in Table 5.

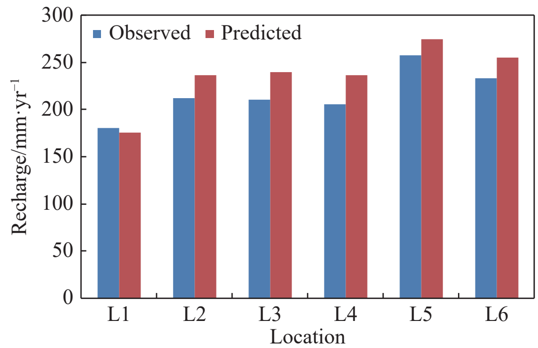

Fig. 9 Observed versus model-predicted groundwater recharge

The error indicators, such as Mean bias, MAE, RMSE, RE and PARMSE, were found to be low, while the Pearson correlation coefficient, R^2 and Coefficient of Nash and Sutcliffe efficiency exhibited high values. Low values of MAE, RMSE, RE, PMAMSE, combined with high values of r, R^2 and E_{NS}, indicate that the model performs well across different conditions. According to the rating criteria proposed by Ali and Abustan (2014), a PMARE value between 5 and 10 corresponds to a 'very good' model. Therefore the performance of the model M-RechargeCal model can be considered very good.

2.4 Sensitivity of the input parameters

The percentage change in the output (recharge, Re) resulting from various percentage changes in input variables is summarized in Table 6.

Table 5 Performance indicators of the M-RechargeCal model

Sl.	Indicators (unit)	Typical range	Obtained value (for yearly recharge, mm)
1	Mean bias (mm)	–∞ to + ∞ (perfect: 0)	19.6
2	Mean absolute bias or error (MAE) (mm)	0 to ∞ (perfect: 0)	21.3
3	RMSE (mm)	0 to ∞ (perfect: 0)	23.0
4	RE (%)	–∞ to + ∞ (perfect: 0)	10.6
5	PMARE (Percent Mean Absolute Relative Error)	0 to ∞ (perfect: 0)	9.8
6	Pearson's correlation coefficient (r)	–1 to +1 (perfect: 1)	0.93
7	R^2	0 to 1 (perfect: 1)	0.867
8	Coefficient of Nash and Sutcliffe efficiency (E_{NS})	–∞ to 1 (perfect: 1)	0.93

Table 6 Summary of tested variables, conditions, and their percent variation under different changes in input parameters

Sl no.	Variable	Condition	Percent change in recharge under the percent change of input by			Incremental change in recharge (%) (for 10% change in input)
			10%	20%	30%	
1	ET_0	ET_p>P (positive change in ET_0)	0	0	0	0
	ET_0 *(P=41 mm)*	ET_p <P (positive change)	−14.6	−12.2	−9.6	2–3
	ET_0 *(P=41 mm)*	ET_p <P (negative change)	18.9	20.8	22.7	1–2
	ET_0 *(P=84 mm, ET_0=52.75, ET_p=58.03)*	ET_p <P (positive change)	−18	−40	−66 (*ET_p* close to *P*)	22–26
	ET_0 *(P=84 mm)*	ET_p <P (positive change)	16	30	42	12–14
	ET_0 *(P=186 mm)*	ET_p <P (positive change)	−1.6	−3.3	−5.1	1.7–1.8
2	P	P< ET_p	0	0	0	0
	P *(P= 84 mm)*	P> ET_p (positive change)	29.3	33.8	37.8	3–4
	P *(P= 84 mm)*	P> ET_p (negative change)	17.3	8.9	0 (P=ET_p)	–9
	P *(P= 186 mm)*	P> ET_p (positive change)	3.9	7.4	10.2	–3
	P *(P= 186 mm)*	P> ET_p (negative change)	−5.0	−11.1	−19.2	6–8
3	CN (a) P=84 mm, ET_p=58	P>ET_p (positive change)	−7	−16	−27	9–11
		P>ET_p (negative change)	4.6	7.5	8.3	1–2
	CN (b) P=186mm, ET_p=58	P>ET_p (positive change)	−17	−33	−49	16–17
		P>ET_p (negative change)	18	36	55	18–19
4	K_c	P<ET_p	0	0	0	0
		P>ET_p (P=186, ET_p=60.25)	−1.1	−2.1	−3.2	1–1.1

Groundwater recharge has a complex relationship with multiple factors including rainfall amount (P), atmospheric crop-water demand (i.e. reference evapotranspiration ET_0), crop type and growth stage (crop coefficient, K_c), soil type (which affects drainability) and land-cover or vegetation type (expressed by the curve number, CN), among others (Eq. 18, Ali, 2016). In the water balance approach, recharge is governed by Eq. (2), as cited here. Multiple factors jointly determine the recharge rate; however, for sensitivity analysis, the effect of varying a single parameter under a dominant limiting condition was studied.

$$R = f(S, T, V, P, CA, Gs, DWT, ET..) \tag{18}$$

Where: f = Function; S = Soil factor; T = Topographical factor; V = Vegetation factor; P = Precipitation *or* Rainfall factor; CA = storage capacity of the aquifer; Gs = Subsurface geological factor; DWT = Depth to water-table; ET = Climatic Evapotranspiration (ET) demand.

In WB form,

$$R_e = (P + q_{in}) - (R_0 + ET_a + q_{out}) \tag{19}$$

(1) ET_0

The response of recharge to changes in ET_0

depends on the relationship between rainfall (P) and potential evapotranspiration. The impact of ET_0 on recharge is generally negligible when $P<ET_p$, but becomes more pronounced when $P>ET_p$. This is because the available water (rainfall) is first used to satisfy atmospheric demand, then contributes to surface runoff (as shown in Eq.2), and only the remaining portion contributes to recharge. When rainfall is high (e.g. 186 mm), the sensitivity of recharge to ET_0 variation is minimal (approximately 1.7% for a 10% change in ET_0) because there is sufficient water to fully meet the ET_0.

Depending on the chosen ET_0 estimation method, either solar radiation or air temperature is typically the most sensitive climatic variable influencing the calculation of ET_0, and consequently, the estimated recharge. Additionally, the appropriate use of coefficient value, required in several ET_0 methods, such as the FAO B-C method, is also crucial for determining accurate ET_0 values.

(2) Rainfall

Similar to response observed for ET_0, when rainfall (P) is less than or equal to the potential evapotransipiration (ET_p), increases in rainfall (P) have little effect on recharge. Beyond this point, recharge increases proportionally with higher rainfall amounts. However, when the difference between P and ET_p is large, additional rainfall has a diminishing effect on recharge because sufficient water is already available for potential recharge, so further increases do not significantly contribute to it.

(3) Curve Number (CN)

The Curve Number (CN) represents runoff potential, with higher values indicating greater runoff. For example, CN=100 indicates and impervious surface, while CN=60 represents moderate runoff potential. When the CN value increases from 60, the recharge rate decreases, and this change closely matches the rate of change in the input. Conversely, when the CN value decreases from 60, the output (recharge) changes more slowly, indicating reduced sensitivity. At higher rainfall amounts (e.g. 186 mm instead of 84 mm), sensitivity increases in both positive and negative directions because more water becomes available for recharge.

(4) Crop coefficient (Kc)

The crop coefficient (Kc) reflects the evapotranspiration (ET) potential, with higher values indicating greater ET demand. When $P<ET_p$, changes in Kc have minimal effect on recharge because there is not enough water available to meet the ET demand. When $P>ET_p$, increasing Kc by 10% to 30% results in a slight reduction in recharge (approximately 1.1%–3.2%), indicating low sensitivity.

Based on the percentage change in recharge, the CN appears to be the most sensitive parameter, with the largest incremental change (approximately 18%–19%). ET_0 is also sensitive when the difference between P and ET_p is small. The sensitivity of rainfall decreases as its value increases. Among all tested paramters, Kc shows the least sensitivity, with only about a 1%–3% effect on recharge.

3 Discussions

3.1 Limitations of the model M-RechargeCal

Models for estimating groundwater recharge are essential for sustainable water resources management because they provide more accurate estimates of how quickly aquifers are replenished. Such models help researchers, engineers, and policymakers understand the dynamics of groundwater systems, particularly in regions where water scarcity poses significant challenges. These models provide valuable information on how changes in the environmental conditions and human activities affect groundwater levels by taking into account factors such as rainfall, soil composition, land use, and aquifer characteristics. This knowledge is crucial for designing measures to prevent over-extraction, guarantee a sustainable long-term water supply, and meet domestic, agricultural, and industrial water demands.

Furthermore, recharge estimating models play a crucial role in climate change adaption efforts because they help forecast the potential future impacts of land-use and climatic changes, such as shifts in temperature and precipitation patterns, on groundwater resources. Despite its significance, groundwater recharge remains challenging to quantify and is still considered one of the most unpredictable components of the hydrological cycle. To address the need for practical and applicable recharge estimation, the M-RechargeCal model was developed to strike an effective balance between complexity and accuracy. While the author recognizes that more sophisticated and rigorous methods exist for simulating hydrological processes, these approaches are often impractical for many applications due to their high demands for data, resources, and specialized personnel.

The M-RechargeCal model is designed to

provide a physically based, preliminary estimate of annual recharge that can be used for (1) generating recharge inputs for groundwater flow models, (2) defining general spatial patterns and the degree of spatial variability of recharge across a region.

The six case studies previously presented demonstrate that M-RechargeCal produces reasonably accurate estimates of annual recharge. However, it is important to recognize the model's limitations. It has not been tested in Wetland areas, desert or Mediterranean climates, regions with freezing ground, or gravel-pack zones.

The model is primarily intended for application at small watershed scales. While the WB method computes water balance and recharge at a 10-day time step, ensuring more accurate soil–water balance, runoff estimation, it does not explicitly consider the depth to the water table in its calculation.

Additionally, although the model allows users to apply a correction factor for recharge limits, it cannot explicitly handle recharge rejection processes, such as those caused by frozen or saturated ground, which remains a key limitation.

3.2 Scope of the model/other utilities

The M-RechargeCal model can be applied in various ways, including:

(1) Studying the impact of land-use and land-cover changes on hydrological components such as recharge, runoff, and evapotranspiration (ET).

(2) Assessing the effects of climate change on hydrological processes.

(3) Utilizing land-use and land-cover data derived from GIS or remote sensing techniques as input (in terms of percentage for each category), enabling more accurate estimate of hydrological components.

4 Conclusion

M-RechargeCal is a software tool developed to estimate natural groundwater recharge using two approaches: The Water Balance (WB) method and the Water Table Fluctuation (WTF) method. The WB method divides the catchment into seven land-use categories and applies 18 reference evapotranspiration methods along with crop coefficients and curve numbers to estimate recharge. The WTF method considers up to three aquifer layers with different specific yields and accounts for water withdrawal and groundwater inflow/outflow.

As a process-based model, M-RechargeCal requires no calibration and depends on the accuracy of input data. It was tested with six datasets from humid subtropical regions, showing strong performance with statistical indicators of R^2 = 0.85, Pearson's r = 0.93, RE = 10.6%, PMARE = 9.8%, and E_{NS}= 0.93. These results demonstrate that the model is a reliable tool for estimating groundwater recharge in water resource planning.

M-RechargeCal strikes a good balance between simplicity and accuracy, making it practical and accessible for groundwater modelers. Its outputs can guide and inform annual water management plans to promote sustainable groundwater use. Furthermore, the model is useful for hydrogeologists and regional planners to evaluate potential impacts of land use changes, urbanization, and climate change on groundwater recharge patterns and rates.

Although developed in Bangladesh, M-RechargeCal is suitable for use in other humid and temperate regions, providing accurate annual and regional groundwater recharge estimates consistent with field observations. The software is free for personal and educational purposes, provided proper citation is given.

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