Review Article

Quantitative Techniques for Estimating Groundwater Recharge: A Review of Field-Based and Modelling Methods

 **ABSTRACT**

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| Groundwater recharge, the downward movement of water through soil to replenish aquifers is a critical process underpinning global freshwater availability. Accurate estimation of recharge rates is essential for sustainable groundwater management, particularly in regions facing water scarcity, over-extraction, and environmental degradation. This review synthesizes seven principal methods used to estimate groundwater recharge: lysimeters, the water balance method, groundwater table fluctuation (GTF) method, stable isotopes, chloride mass balance (CMB), drip tests in karst aquifers, and unsaturated zone modelling. Each method is evaluated based on its theoretical framework, field applicability, data requirements, accuracy, advantages, limitations, and representative case studies. Lysimeters offer precise, site-specific measurements but are costly and limited in spatial scope. The water balance method is scalable and widely used but sensitive to input data quality. The GTF method is cost-effective in unconfined aquifers but depends on reliable specific yield values. Isotopic and chloride tracers provide insight into recharge pathways and sources, particularly in arid and semi-arid zones, though they may be affected by anthropogenic inputs. Drip tests effectively characterize recharge dynamics in complex karst systems, while unsaturated zone models simulate recharge processes in detail under varying climatic and land-use conditions. Comparative analysis suggests that no single method suffices across all contexts; instead, combining techniques tailored to specific hydrogeological and climatic settings yields more robust estimates. This review highlights the importance of method integration and site-specific considerations to improve recharge assessments, support informed water policy, and guide sustainable groundwater development. |

*Keywords: Groundwater, recharge, estimation, lysimeters, water resource management*

1. INTRODUCTION

Groundwater serves as a vital resource for drinking water, agriculture, industry, and ecosystem sustainability, especially in arid and semi-arid regions where surface water is scarce (Healy & Scanlon, 2010). The sustainable management of groundwater depends heavily on understanding and quantifying groundwater recharge, the process by which water infiltrates the ground to replenish aquifers (Acharya & Barbier, 2000). Estimating groundwater recharge accurately is essential for regulating extraction rates, preventing aquifer depletion, and managing water quality (Ferreira et al., 2024). However, due to the complex interactions between hydrological, geological, and climatic factors, estimating recharge rates remains a significant challenge in hydrogeology.

Recharge estimation methods vary widely in their approaches, from direct in-situ measurements to indirect modelling and chemical tracer techniques. Direct in-situ methods, such as lysimeters, provide highly accurate, site-specific recharge estimates, while methods like the water balance approach are often used for large-scale, basin-wide recharge estimations (Healy & Scanlon, 2010). Advances in isotopic analysis and chemical tracer applications, like the chloride mass balance, have further expanded our ability to track recharge sources, pathways, and volumes in different hydrogeological settings (Subyani, 2004). Each method has unique advantages, limitations, and data requirements, making method selection crucial based on environmental and hydrogeological conditions.

More than 35% of irrigation water is lost through percolation below the root zone collectively during land preparation and throughout the growing season under conventional irrigated system (Mallareddy et al., 2023). This amount of percolation loss is even greater under strip planting (45% of irrigation water). A weak plough pan due to practising strip planting over a seven-year period has increased the infiltration rate (Mallareddy et al., 2023). However, deep percolations are not real water losses in the landscape since that water is not contaminated and would return to the groundwater creating new sources of diffuse recharge and increasing groundwater storage that is potentially available for reuse (Humphreys et al., 2008).

This review presents seven primary methods for estimating groundwater recharge: lysimeters, the water balance method, groundwater table fluctuation (GTF) method, stable isotopes, chemical tracers; the chloride mass balance (CMB), drip tests in karstic aquifers, and unsaturated zone modelling. The following sections provide an in-depth examination of each method, highlighting its theoretical basis, applications, advantages, limitations, and examples from the literature where available.

2. Methodology of Review

This review is based on a structured analysis of peer-reviewed publications, technical reports, and hydrological textbooks focused on groundwater recharge estimation methods. Key sources were identified through scientific databases including ScienceDirect, SpringerLink, and Google Scholar, using combinations of keywords such as “groundwater recharge,” “estimation methods,” “lysimeters,” “water balance,” “tracers,” “karst,” and “unsaturated zone modelling.” Preference was given to studies published between 2000 and 2024, though foundational earlier works were also included when relevant.

The selected literature covers a range of climatic settings (arid, semi-arid, humid), geological environments (alluvial, karst, fractured rock), and scales of application (field-scale to basin-scale). Seven core techniques were chosen for in-depth analysis due to their widespread use and distinct methodological frameworks. For each method, the review discusses the underlying principles, data requirements, practical applications, strengths, limitations, and representative case studies.

This approach aims to provide a balanced, comparative understanding of the methods currently used in recharge estimation, with an emphasis on technical applicability and relevance for sustainable groundwater management.

3. Processes and Mechanisms of Groundwater Recharge

Precise understanding of the fundamental mechanism of recharge for a particular area is required at the beginning to estimate the groundwater recharge more accurately. de Vries & Simmers (2002) gave an overview of the processes and mechanisms of groundwater recharge. According to their description, groundwater recharge is the amount of water that flows downward through the unsaturated zone beyond the rooting depth reaches the water table, making contribution to the groundwater reservoir. When rain occurs or irrigation water is applied, a part of the water is used to fulfill the soil water deficit, goes to the atmosphere through evapotranspiration. More than these two uses, water percolates downward (infiltration) to the water table and recharge takes place. From this definition it is considered that groundwater recharge over an area is equal to the infiltration for the same area.

However, not necessarily all infiltration water reaches the groundwater table. The infiltration might be restricted by the impermeable or semi-permeable layer that has a low water conductivity. The water then moves horizontally and flows to a nearby local depression, such as a pond, where it runs off and evaporates and does not contribute to the groundwater reservoir. In an area with a shallow aquifer compared to the landscape, the recharged aquifer with a shallow water table may create a groundwater system where horizontal water flow or an associated seepage might take place within the area. In a high-water table aquifer, when time scale is considered, water might be extracted by evapotranspiration immediately after reaching the water table.

Carreira et al. (2011) explains how amount of rainfall effects whether there is recharge or not. In areas ranging from humid to subhumid, yearly precipitation is greater than the potential evapotranspiration, which results in continuous recharge. In contrast, in low rainfall areas, such as arid and semi-arid, rainfall does not exceed the evapotranspiration that contributes to the yearly groundwater recharge. But, over many years the precipitation and the preferential flow of groundwater flow can be the source of recharge.

**3.1 Groundwater recharge types**

According to the water sources, groundwater recharge can be classified into three types: direct or diffuse recharge, localized recharge, and indirect or non-diffuse recharge (Acharya & Barbier, 2000; de Vries & Simmers, 2002). Direct recharge is the water contributed to the groundwater reservoir from rain or irrigation by direct percolation through the unsaturated zone after separating from the other water balance components (soil water deficits, surface runoff and evapotranspiration). Localized recharge is the amount of water percolation that is resulted from horizontal surface concentration or depression of water (such as ponding in the rice field). Indirect recharge refers to the amount of water added to the groundwater reservoir by percolation through the beds of rivers and canals or other waterbodies.

**3.2 Groundwater recharge estimation**

Groundwater recharge estimation is primarily classified as direct and indirect methods. Examples of direct physical methods are the Lysimeter method, and direct chemical methods are tracer techniques, either applied or historical. Whereas indirect physical methods are soil water balance, water budget method, groundwater table fluctuation method etc.

Groundwater recharge estimation techniques can also be classified according to regions where arid, semi-arid and humid climates are present. For arid and semi-arid climates, water budget method, isotopic tracers, lysimeters, Darcy’s law and other numerical models are applicable. For humid climates soil water balance, water budgets, lysimeters, Darcy’s law, applied tracers, water table fluctuations, and numerical models are appropriate (Healy & Scanlon, 2010).

**3.3 Recharge and discharge areas in groundwater systems**

Recharge and discharge areas play critical roles in the hydrogeological cycle, determining the flow and availability of groundwater. A recharge area is where water infiltrates from the surface into an aquifer, adding to the groundwater reserves. In contrast, a discharge area is where groundwater flows out of an aquifer to the surface, often feeding rivers, lakes, or wetlands. Understanding the spatial distribution and dynamics of recharge and discharge areas is essential for effective groundwater management and for ensuring sustainable water resources, especially in regions experiencing water scarcity.

Recharge areas are typically regions where surface water infiltrates into the ground, moving downward through the unsaturated zone until it reaches the water table. In these areas, precipitation, river seepage, or irrigation contributes to the replenishment of groundwater stores (M. Sophocleous, 2002). Recharge areas often occur in upland regions where the hydrostatic pressure gradient favors downward water movement. They can be identified by certain hydrogeological conditions, such as permeable soil layers, low land use interference, and high infiltration rates (Healy & Scanlon, 2010).

Discharge areas are regions where groundwater flows from the aquifer to the surface. These areas are commonly found in low-lying areas, such as river valleys, coastal plains, and lake beds, where the water table intersects the land surface. In discharge areas, groundwater emerges as springs, seepage zones, or baseflow into streams and rivers, contributing to surface water flow. This process is critical for sustaining surface water bodies, particularly in arid and semi-arid regions where groundwater may be the primary water source for rivers during dry periods (Winter et al., 1998).

**3.4 Factors affecting groundwater recharge**

Factors that influence groundwater recharge include climate, land use, land cover or vegetation, geology, topography, soil texture, soil structure or strength, irrigation water use (Acharya & Barbier, 2000), depth of water table, soil moisture, properties of the geological materials, and the existence of nearby waterbodies (Seiler & Gat, 2007). These factors work individually or as a combined effort interacting with each other affecting the recharge. However, climate, soil texture, surface cover has been put forward, among other factors affecting groundwater recharge. Climatic factors include precipitation and evapotranspiration since these two variables influence the abundance of water at the soil surface, which eventually controls the groundwater recharge (Healy & Scanlon, 2010).

Soil textural parameters such as porosity and pore size distribution affect water holding capacity, infiltration and transpiration, eventually affecting groundwater recharge (Jobbágy & Jackson, 2004). For instance, sandy soils have more pore spaces and greater hydraulic conductivity; thus, groundwater recharge is higher. In contrast, clayey soils also have tiny pores and greater surface tension that slows down the vertical movement, inhibiting lower infiltration and recharge. In addition, plant available water is higher in clayey soil because of greater micropores than coarse-textured soil; therefore, the evapotranspiration is higher, and groundwater recharge is lower in clayey soil.

The density and type of surface cover or vegetation largely influences groundwater recharge (Seiler & Gat, 2007). The runoff component of the rain or irrigation, and soil evaporation are largely governed by the soil cover and the plant leaf canopy, and thus groundwater recharge may be variable (Jobbágy & Jackson, 2004).

Generally, the recharge is more remarkable in an area with less vegetation than in a surface with good vegetation of annual crops or grasslands. Mathenge et al. (2020) observed the groundwater recharge of Stony Athi sub-catchment of Kenya. They reported 197 mm/year recharge on sandy loam soil with forest cover compared to 36 mm/year recharge on clay soils with impervious layers. Higher recharge on the forest cover was attributed to vegetation interrupting the surface runoff and enhancing water infiltration through the sandy soil.

**Table 1. Summary of the recharge estimated in some humid regions using different estimation methods**

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Country/region | Yearly average rainfall | Recharge estimation method | Recharge mm/yr | Coefficient of recharge | Source |
| USA, Pennsylvania | 1069 mm | LysimeterWater budget WTF[[1]](#footnote-1) | 311308 | 29%29% | (Risser et al., 2009) |
| USA, North Carolina | 1170 mm | WTF | 252140 | 24 %12 % | (Coes et al., 2007) |
| North-east Bangladesh | 1050 mm | Chloride tracer Water balance | 11049 | 9 %4.7 % | (Ali et al., 2022) |
| Western Australia | 775 mm | Environmental chloride | 59 | 5.6% | (Sharma & Hughes, 1985) |
| USA, Minnesota | 500-900 mm | WTF | 116 | 15 % | (Delin et al., 2007) |
| USA, Wisconsin | 750-900 mm | Numerical Model | 110 | 16-26 % | (Cherkauer & Ansari, 2005) |
| Argentina,Pampa plain | 1064 mm | WTF, Sy=0.09WTF, Sy=0.07 | 210164 | 18 %14 % | (Varni et al., 2013) |

4. Direct In-Situ Measurements: Lysimeters

Lysimeters are one of the oldest and most direct methods for measuring groundwater recharge and other components of the water balance. Essentially, a lysimeter is a container filled with soil, placed below the surface to collect water percolating through the soil profile. By measuring the amount of water that infiltrates into the lysimeter, researchers can directly quantify recharge at a specific location. Lysimeters are typically classified into two main types: weighing lysimeters and non-weighing lysimeters. Weighing lysimeters measure changes in mass over time to determine percolation and evapotranspiration, while non-weighing lysimeters collect water in a tank, providing volumetric measurements of percolated water (Gee & Hillel, 1988).

The basic principle behind lysimeters is the water balance equation, which quantifies the water moving through the soil profile based on inputs and outputs. The water balance equation for lysimeters is:

$$\begin{array}{c}R = P – ET – ΔS – Q \#\left(1\right)\end{array}$$

where R is the recharge, P is precipitation, ET is evapotranspiration, ΔS is the change in soil moisture storage, and Q is surface runoff or lateral flow.

To obtain reliable recharge estimates, lysimeter studies require accurate measurement of all components in this equation. Precipitation can be measured using rain gauges, evapotranspiration may be estimated using meteorological data or direct mass changes in the case of weighing lysimeters, and changes in soil moisture can be monitored through sensors. The collected water in non-weighing lysimeters provides a direct measurement of the volume infiltrated, which, after accounting for losses, corresponds to recharge.

**4.1 Advantages and Limitations**

* **Advantages**: Lysimeters provide highly precise, site-specific data and capture real-time recharge under natural field conditions. They are particularly valuable for small-scale studies that require exact measurements of infiltration, soil retention, and evapotranspiration (Gee & Hillel, 1988).
* **Limitations**: The cost of installation and maintenance is high, particularly for weighing lysimeters. Additionally, lysimeters represent point measurements, which may not accurately represent recharge over larger, heterogeneous areas. There can also be soil disturbance during installation, potentially affecting natural water flow dynamics.

**4.2 Case Studies and Applications**

In semi-arid regions, lysimeters have been used to determine the seasonal variability of recharge and the impact of vegetation on infiltration. For instance, in a study conducted in the southwestern United States, lysimeters revealed that most recharge occurred during monsoon rains, while evapotranspiration rates varied seasonally due to vegetation growth patterns (Healy & Scanlon, 2010). Weighing lysimeters were employed in agricultural fields to assess the impact of crop rotation on recharge. Results revealed that crops with shallow root systems allowed greater infiltration compared to deeper-rooted species (Lischeid, 2001).

**5. WATER BALANCE METHOD**

The water balance method estimates groundwater recharge by analyzing the balance between water inputs (precipitation, irrigation) and outputs (evapotranspiration, runoff) in a specified area and time period. The basic water balance equation used is:

$$\begin{array}{c}R = P – ET – Q – ΔS \#\left(2\right)\end{array}$$

where R is the recharge, P is precipitation, ET is evapotranspiration, Q is runoff, and ΔS is the change in soil moisture storage. This equation is commonly applied at the watershed or basin scale, providing a regional overview of recharge based on large-scale water movement patterns (Healy & Scanlon, 2010).

Measurements of the components at the right side of the water balance equation are subject to significant errors that may lead to errors in determining the component at the left side, i.e., the recharge. Therefore, the reliability of the water balance method largely depends on how accurately water balance components in the equation is measured or estimated (M. Sophocleous, 2002). The unsaturated zone or the vadose zone of a soil profile is the crucial zone. In humid climates, the unsaturated zone allows a favourable condition for infiltration of the adequate rainfall, and thus water flows effortlessly to the water table. In contrast, in the arid region, ET is >90% of the precipitation, and hence there is little water left for recharging the groundwater (Acharya & Barbier, 2000). Thus, the arid region requires a more precise measurement of the recharge. Therefore, the water balance methods of estimating groundwater recharge are suitable more in humid regions than in arid climates (Gee & Hillel, 1988).

**5.1 Advantages and Limitations**

* **Advantages**: The water balance method is flexible and widely applicable to large-scale studies. It requires relatively low-cost data inputs and is suitable for areas with extensive meteorological records.
* **Limitations**: Its accuracy is heavily dependent on the precision of input data for each component, which can be challenging to obtain in data-scarce regions. Additionally, the method may be less effective in areas with complex terrain, where runoff and evapotranspiration are difficult to estimate accurately (Allison & Hughes, 1983).

**5.2 Applications in Large-Scale Studies**

The water balance method is often applied in large watersheds and river basins, such as the Nile Basin, to estimate recharge rates necessary for water resource management. In regions with monsoonal climates, the method helps in quantifying recharge contributions during high rainfall periods. The water balance method was applied across the Nile Basin to estimate recharge under varying climatic conditions. Results informed sustainable water management strategies for riparian countries (Holman, 2006). Researchers applied the water balance method in a semi-arid watershed. Recharge rates were found to depend on monsoon rainfall intensity and duration (Saxena et al., 2004). In the Denver Basin, the water balance approach was used to assess the impact of urbanization on recharge rates. Results highlighted increased runoff and decreased infiltration in developed areas (Dennehy et al., 1993).

**6. GROUNDWATER TABLE FLUCTUATION METHOD**

The Groundwater Table Fluctuation (GTF) method estimates groundwater recharge by monitoring changes in groundwater levels in unconfined aquifers. Recharge is inferred by observing rises in the water table following significant precipitation events. This method is commonly applied in regions with marked seasonal recharge patterns, where groundwater levels fluctuate in response to rainfall or snowmelt (Healy & Cook, 2002). The basic equation used is:

$$\begin{array}{c}R = Sy ⋅ \frac{Δh}{Δt} \#\left(3\right)\end{array}$$

where R is recharge, Sy is the specific yield of the aquifer (the ratio of water that can be drained under gravity), Δh is the observed rise in groundwater level, and Δt is the time over which the rise occurs.

Freeze & Cherry (1979) defined specific yield as the volume of water discharged from an aquifer storage by gravity flow per unit area of that aquifer per unit drop in the water table. Specific yield can be determined by performing a pumping test and can be estimated using the following equation (Neuman, 1987).

$$\begin{array}{c}Sy = \frac{V\_{w}}{V\_{c}} \#\left(4\right)\end{array}$$

Where: Vw = cumulative volume of discharge from the pumping well and

Vc = volume of cone of depression from a water table.

Δh in the recharge equation is measured as the difference between the peak of the water table in response to the rainfall and the low point in the extrapolated recession curve Lutz et al. (2014).

**6.1 Advantages and Limitations**

* **Advantages**: The GTF method is cost-effective, especially in unconfined aquifers where recharge events directly impact groundwater levels. It provides a straightforward approach to recharge estimation in response to seasonal precipitation events.
* **Limitations**: Accuracy is highly dependent on specific yield values, which vary spatially. The GTF method may be less effective in confined aquifers or regions with extensive groundwater pumping, which can mask natural fluctuations (M. A. Sophocleous, 1991).

**6.2 Case Study Applications**

The GTF method is widely used in unconfined aquifers in semi-arid regions to determine seasonal recharge rates. For example, in the High Plains Aquifer, USA, GTF data helped characterize recharge patterns and inform sustainable extraction rates, which are critical for maintaining agricultural productivity in the region (Rai et al., 2006). The GTF method was employed to estimate recharge in this major agricultural aquifer. Seasonal water table fluctuations were closely correlated with precipitation and irrigation practices (McGuire et al., 2003). In a coastal unconfined aquifer, the GTF method was used to estimate recharge, with results showing significant variability due to tidal influences (Martin & van de Giesen, 2005).

**7. APPLICATION OF STABLE ISOTOPES**

Stable isotopes, such as oxygen-18 (¹⁸O) and deuterium (²H), serve as natural tracers for groundwater recharge studies, helping to differentiate between sources of recharge, such as precipitation, river water, or irrigation returns. Isotopic ratios provide unique signatures based on environmental conditions during water formation, enabling hydrologists to trace recharge pathways and determine recharge timing (Clark & Fritz, 2013).

Isotopic fractionation occurs due to processes such as evaporation and condensation, which preferentially remove lighter isotopes (Healy & Cook, 2002). This creates distinctive isotopic ratios in precipitation, which can be analyzed along the Global Meteoric Water Line (GMWL). Comparing isotopic values in groundwater with those in local precipitation allows researchers to infer whether recharge is recent or from older water sources.

**7.2 Sampling and Analysis**

* **Sampling**: Groundwater, precipitation, and surface water samples are collected at regular intervals. Sampling should be consistent over time to capture seasonal changes in isotopic composition.
* **Laboratory analysis**: Mass spectrometers analyze the isotopic composition, providing delta (δ) values that indicate relative enrichment or depletion of isotopes. Groundwater isotopic composition close to the GMWL indicates recharge from recent precipitation, while deviations suggest alternative sources or evaporation effects. The isotopic composition of water samples is typically analyzed using a mass spectrometer. Water samples are vaporized, and the isotopic ratios of hydrogen and oxygen are measured. The mass spectrometer provides δ values for ¹⁸O and ²H relative to a standard.

**7.3 Advantages and Limitations**

* **Advantages**: Stable isotopes allow for precise source differentiation and enable temporal and spatial mapping of recharge sources.
* **Limitations**: High cost, skilled personnel requirements, and the complexity of interpreting isotopic data limit the use of this method. Stable isotope data may also be confounded by multiple recharge sources in humid environments (Kendall & Mcdonnell, 1998).

**7.4 Applications**

In semi-arid regions of Africa, isotopic studies have shown that recharge primarily occurs during intense rainfall events. For example, studies in northern Nigeria utilized isotopic signatures to differentiate between river recharge and direct precipitation (Edmunds & Gaye, 1994). This information is critical for managing water resources in regions with variable seasonal rainfall. Isotope signatures were used to determine the proportion of river water contributing to groundwater recharge, revealing significant seasonal variations (Coplen et al., 2000). Researchers identified isotopic differences between rainfall and groundwater, showing that recharge was dominated by winter rains due to lower evaporation rates (Gibson et al., 2010).

**8. CHLORIDE MASS BALANCE (CMB) METHOD**

The chloride mass balance (CMB) method is a widely used approach for estimating recharge, especially in arid and semi-arid regions. Chloride is considered a conservative tracer, as it generally does not participate in soil reactions or volatilize, making it useful for tracking water movement. Recharge is estimated by comparing chloride concentrations in precipitation and groundwater, using the equation:

$$\begin{array}{c}R= \frac{P⋅C\_{p}}{C\_{g}} \#\left(5\right)\end{array}$$

where R is recharge, P is precipitation, Cp​ is the chloride concentration in precipitation, and Cg​ is the chloride concentration in groundwater (Allison & Hughes, 1978).

**8.1 Why Use the Chloride Method?**

The chloride method offers several advantages and practical applications, making it a valuable tool in hydrogeological studies:

1. **Conservative Behavior of Chloride**
* Chloride ions do not volatilize or significantly react chemically in the soil or aquifer. This stability allows chloride to act as a reliable tracer for water movement.
* Chloride accumulates in the soil profile through precipitation and irrigation, providing a measurable record of infiltration and percolation processes.
1. **Suitability for Arid and Semi-Arid Regions**
* In regions with limited surface water and high evaporation rates, the chloride method is particularly effective. The scarcity of rainfall results in chloride accumulation in the soil, making it easier to trace recharge pathways and estimate recharge rates.
1. **Low Cost and Accessibility**
* Sampling and analysis of chloride concentrations are relatively inexpensive compared to advanced techniques like isotopic analysis or unsaturated zone modelling.
* Fieldwork for chloride sampling is straightforward, requiring only rainwater, soil, and groundwater samples.
1. **Large-Scale Application**
* The method can be applied across large spatial scales to estimate regional recharge patterns, providing critical insights for water resource management.
1. **Integration with Other Techniques**
* The chloride method can complement other methods like isotopic analysis or unsaturated zone modelling to improve the accuracy of recharge estimation.

**8.2 Advantages and Limitations**

* **Advantages**: The chloride method is relatively low-cost and straightforward, making it suitable for large-scale applications in arid and semi-arid regions. It provides an effective estimate of recharge based on the accumulation of chloride from precipitation.
* **Limitations**: Anthropogenic chloride sources, such as fertilizers and industrial activities, can interfere with natural chloride levels, complicating recharge estimation. Additionally, high evaporation rates can concentrate chloride, leading to overestimations of recharge (Healy & Scanlon, 2010).

**8.3 Case Studies**

In the Negev Desert, Israel, the CMB method was employed to estimate recharge rates and revealed that natural recharge primarily occurred through seasonal rainfall events. This information is critical for water planning in the region, where over-extraction poses a significant risk to the sustainability of the aquifer (Healy & Cook, 2002). Using soil chloride profiles, researchers quantified recharge in sandy soils, revealing low annual recharge rates consistent with arid environments (de Vries et al., 2000). The chloride method estimated recharge under native vegetation and cleared land, showing increased recharge after vegetation removal (Segobaetso et al., 2022). Chloride profiles helped estimate recharge in areas with high evaporation rates, showing recharge rates below 10 mm/year (Edmunds & Gaye, 1994).

**9. DRIP TEST IN KARSTIC AQUIFERS**

Karstic aquifers are characterized by distinctive dissolution features such as conduits, fissures, and sinkholes, which result in high permeability and complex water flow patterns. These features make it challenging to estimate groundwater recharge, as traditional methods may not account for the rapid and concentrated flow typical of karst systems (Healy & Cook, 2002). Drip tests provide a localized method for estimating recharge by introducing water (or tracers) at the surface and monitoring its movement through the karstic pathways. This technique is particularly useful for identifying flow paths, recharge rates, and temporal variations in recharge.

Drip tests are performed by applying a known volume of water, sometimes tagged with tracers, to a recharge point such as a sinkhole or fissure. Monitoring stations, often equipped with sensors, are set up at different points within the karst system to observe drip rates, arrival times, and tracer concentrations, providing insights into the flow dynamics.

**9.1 Data Analysis and Interpretation**

Key data points include:

* **Arrival time (lag time)**: Time taken for the water to travel from the surface to the monitored site, indicating the permeability and connectivity of conduits.
* **Drip rate analysis**: High drip rates can signify significant recharge zones or rapid flow paths.
* **Tracer breakthrough curve**: Plotting tracer concentration over time to analyze flow rates and retention within the system.
* **Recharge rate calculation:** Recharge rate is inferred based on the recovered water volume and observed drip rates.

$$\begin{array}{c}Recharge  Efficiency=\frac{V\_{r}}{V}∙100 \#\left(6\right)\end{array}$$

Where: V = Water Volume Injected

Vr = Volume Recovered at Monitoring Point

**9.2 Advantages and Limitations**

* **Advantages**: Drip tests allow for localized recharge measurements in karst aquifers, where traditional methods might not accurately capture concentrated flow. They provide valuable information on flow paths and recharge timing.
* **Limitations**: Drip tests offer limited spatial applicability, as they provide data for specific points rather than a comprehensive recharge estimate. High variability in karst systems requires extensive calibration and repetition of tests for reliable data (Goldscheider & Drew, 2014).

**9.3 Applications**

Drip tests have been applied in European karst regions, revealing that recharge varies significantly based on seasonal rainfall and aquifer structure. For instance, in a study conducted in the Dinaric karst region, drip tests identified key flow paths and seasonal recharge dynamics that informed local water resource planning (Ford & Williams, 2007). Drip tests revealed localized recharge zones and rapid flow paths in a karst aquifer, improving regional water resource management (Bonacci, 2001). Water injection experiments mapped flow velocities in a high-permeability karst system, revealing seasonal variations in recharge dynamics (Kovács et al., 2005).

**10. UNSATURATED ZONE MODELLING**

The unsaturated zone, lying between the land surface and the groundwater table, plays a critical role in the movement of water from precipitation to groundwater. Unsaturated zone modelling provides a simulation-based approach to estimate recharge by analyzing the movement of water through this zone under different conditions (Šimůnek et al., 2008). By applying principles of soil physics, such as Richards' equation, unsaturated zone models simulate water infiltration, soil moisture retention, and percolation, which contribute to recharge estimations.

**10.1 Modelling Framework and Equations**

The movement of water in the unsaturated zone is commonly modeled using Richards' equation, which accounts for the soil water retention characteristics and hydraulic conductivity:

$$\begin{array}{c}\frac{∂t}{∂θ}=\frac{∂z}{∂z}\left(K(θ)\frac{∂h}{∂z}\right)+S \#\left(7\right)\end{array}$$

* θ = Volumetric water content
* K(θ) = Hydraulic conductivity as a function of water content
* h = Pressure head
* S = Source/sink term

The model requires data on soil texture, porosity, and climate variables, which are used to simulate how water moves downward through the unsaturated zone toward the aquifer.

**10.2 Model Selection and Setup**

1. **Data collection**: Gather soil hydraulic parameters (e.g., soil moisture retention, porosity), meteorological data (precipitation, temperature), and initial soil moisture content.
2. **Model selection**: Choose a model suited to the study area and objectives (e.g., HYDRUS or SWAP for detailed simulations).
3. **Parameterization**: Input soil layers, root zone depths, and boundary conditions.
4. **Calibration and validation**: Divide the soil profile into layers with distinct hydraulic properties.Enter soil hydraulic parameters, vegetation cover, and initial soil moisture conditions.Adjust model parameters based on observed data, such as soil moisture profiles or lysimeter data, to improve accuracy.
5. **Running the model:**  Set appropriate time steps for simulations based on the frequency of rainfall events and soil response time. Define surface boundary conditions (precipitation, evaporation) and lower boundary conditions at the water table. The model outputs water fluxes, changes in soil moisture, and estimated recharge reaching the water table.
6. **Analyzing model output for recharge estimation:** Identify downward water flux reaching the water table as recharge. Consider water loss to evapotranspiration, especially in shallow unsaturated zones. Analyze how recharge rates vary across seasons due to changes in precipitation and soil conditions.

**10.3 Advantages and Limitations**

* **Advantages**: Unsaturated zone modelling offers a detailed, scenario-flexible approach to estimating recharge, allowing simulations under various climate and soil conditions. It provides insights into water fluxes that are difficult to observe directly.
* **Limitations**: Requires extensive input data, and the complexity of calibration may limit its accessibility for broad-scale studies. Computational requirements can also be high, particularly for large-scale or long-term simulations (Healy & Scanlon, 2010).

**10.4 Case Study Example**

A study in the Midwest U.S. used HYDRUS to simulate recharge under different agricultural practices, revealing that recharge rates varied significantly with crop type and seasonal rainfall. This information guided irrigation practices, helping to optimize water use and ensure groundwater sustainability (Šimůnek et al., 2008). Unsaturated zone modelling revealed recharge variability under different crop types, informing irrigation practices in Rajasthan (Chinnasamy et al., 2015). Unsaturated zone models predicted recharge rates in response to urban development, highlighting reduced infiltration in areas with impervious surfaces (Healy & Scanlon, 2010).

**11. COMPARATIVE EVALUATION OF THE METHODS**

Groundwater recharge estimation methods vary significantly in terms of spatial and temporal resolution, data requirements, cost, and suitability across different hydrogeological settings. Table 2 provides a comparative summary of the key characteristics of the seven methods reviewed.

Lysimeters offer precise, site-specific measurements of recharge but are resource-intensive and limited to small areas. The water balance method is applicable over larger regions and is inexpensive but relies on accurate and complete hydrometeorological datasets. The groundwater table fluctuation (GTF) method is simple and inexpensive for unconfined aquifers but is sensitive to errors in specific yield estimation and groundwater pumping impacts.

Stable isotope analysis and chloride mass balance (CMB) methods offer the ability to trace recharge sources and pathways. While isotopes provide more detailed hydrological insights, they are expensive and complex to interpret. The chloride method is more cost-effective and widely used in arid zones, but its reliability is diminished in the presence of anthropogenic chloride sources.

Drip tests are particularly valuable in karst systems where conventional methods fail, but their results are localized and difficult to scale. Unsaturated zone modelling provides a detailed understanding of recharge processes under various climate and land-use conditions. However, it requires high-quality input data, calibration, and specialized technical expertise.

Ultimately, no single method is universally superior. Instead, combining two or more methods often yields more reliable recharge estimates, especially in heterogeneous or data-limited environments.

**Table 2. Comparative summary of groundwater recharge estimation methods**

| **Method** | **Precision** | **Scale of application** | **Data requirements** | **Key advantages** | **Key limitations** |
| --- | --- | --- | --- | --- | --- |
| Lysimeters | High | Small (plot scale) | Precipitation, ET, soil moisture | Direct measurement; high accuracy | Expensive; labor-intensive; not scalable |
| Water Balance | Moderate | Watershed/Basin | Meteorological, hydrological, soil moisture | Low cost; suitable for large areas with available data | Sensitive to input data errors; limited in arid zones |
| Groundwater Table Fluctuation (GTF) | Moderate | Local/Unconfined aquifer | Groundwater level, specific yield | Simple; low-cost; useful in unconfined aquifers | Requires accurate Sy; ineffective in pumped or confined aquifers |
| Stable Isotopes | High | All scales | Isotopic composition (δ18O, δ2H) | Source differentiation; temporal mapping of recharge | High cost; technical complexity; affected by mixing and evaporation |
| Chloride Mass Balance (CMB) | Moderate | Regional/Arid zones | Cl⁻ in rainfall, soil, groundwater | Low cost; effective in arid/semi-arid areas | Sensitive to anthropogenic inputs; overestimates if Cl⁻ is concentrated |
| Drip Test (Karst) | High (localized) | Karst terrains | Drip rate, tracer data | Reveals flow paths and recharge dynamics in karst aquifers | Point-specific; requires tracer safety; limited transferability |
| Unsaturated Zone Modelling | High | Site/Basin scale | Soil properties, climate, land use data | Scenario testing; detailed process simulation | Data-intensive; complex calibration; needs modeling expertise |

**12. RESEARCH GAPS AND RECOMMENDATIONS**

Despite significant progress in groundwater recharge estimation techniques, several challenges and gaps remain:

* Many methods are highly localized and cannot be easily scaled without significant uncertainty. Future work should prioritize developing scalable, transferable frameworks.
* Accurate estimation of specific yield remains a major challenge for the GTF method. Research into improved field methods and remote sensing proxies is recommended.
* In karst environments, better integration of hydrogeological mapping with drip tests and isotopic methods is needed to overcome spatial heterogeneity.
* In data-scarce regions, especially in parts of Africa and Asia, a lack of long-term monitoring infrastructure limits the applicability of high-resolution models and tracer methods. Low-cost innovations and hybrid approaches may offer practical alternatives.
* Climate change introduces additional variability in precipitation patterns and evapotranspiration rates, complicating long-term recharge predictions. Coupling recharge models with climate projections is essential.
* Socio-economic factors such as land use, irrigation practices, and water policy are rarely integrated into recharge estimation frameworks. More interdisciplinary approaches are needed to support sustainable groundwater governance.

To improve estimation accuracy and applicability, future research should promote method integration, support open-source modelling tools, and strengthen long-term observational networks.

**13. CONCLUSION**

Accurate estimation of groundwater recharge is fundamental for effective water resource management and long-term aquifer sustainability. This review evaluated seven widely used methods; lysimeters, water balance, groundwater table fluctuation, stable isotopes, chloride mass balance, drip tests in karst aquifers, and unsaturated zone modelling, highlighting their principles, applications, advantages, and limitations. Each method presents distinct benefits and constraints depending on the hydrogeological context, data availability, and spatial scale. Lysimeters and isotopic methods offer high precision, while large-scale approaches such as water balance and numerical modelling are suited to basin-level assessments. In karstic terrains or arid zones, method selection becomes even more critical due to subsurface complexity and limited data.

The analysis underscores the importance of adopting site-specific, integrated approaches that combine multiple methods to enhance reliability. Particularly in regions experiencing water stress, understanding recharge dynamics is vital for balancing groundwater extraction and natural replenishment under changing climate and land use conditions. Groundwater recharge estimation is not a purely technical exercise; it is a foundation for sustainable water governance. Future work should aim to bridge hydrological science with decision-making through robust, transparent, and adaptable recharge assessment frameworks.

COMPETING INTERESTS DISCLAIMER:

Authors have declared that they have no known competing financial interests OR non-financial interests OR personal relationships that could have appeared to influence the work reported in this paper.

References

Acharya, G., & Barbier, E. B. (2000). Valuing groundwater recharge through agricultural production in the Hadejia‐Nguru wetlands in northern Nigeria. *Agricultural Economics*, *22*(3), 247–259. https://doi.org/10.1111/j.1574-0862.2000.tb00073.x

Ali, Md. H., Hasanuzzaman, Md., Islam, Md. A., & Biswas, P. (2022). Groundwater Recharge Estimation at Barind Area, Bangladesh for Sustainable Groundwater Management: Application of Multiple Methods. *European Journal of Environment and Earth Sciences*, *3*(6), 23–29. https://doi.org/10.24018/ejgeo.2022.3.6.312

Allison, G. B., & Hughes, M. W. (1983). The use of natural tracers as indicators of soil-water movement in a temperate semi-arid region. *Journal of Hydrology*, *60*(1–4), 157–173. https://doi.org/10.1016/0022-1694(83)90019-7

Allison, & Hughes, M. (1978). The use of environmental chloride and tritium to estimate total recharge to an unconfined aquifer. *Soil Research*, *16*(2), 181. https://doi.org/10.1071/SR9780181

Bonacci, O. (2001). Analysis of the maximum discharge of karst springs. *Hydrogeology Journal*, *9*(4), 328–338. https://doi.org/10.1007/s100400100142

Carreira, P. M., Marques, J. M., Espinha Marques, J., Chaminé, H. I., Fonseca, P. E., Santos, F. M., Moura, R. M., & Carvalho, J. M. (2011). Defining the dynamics of groundwater in Serra da Estrela Mountain area, central Portugal: an isotopic and hydrogeochemical approach. *Hydrogeology Journal*, *19*(1), 117–131. https://doi.org/10.1007/s10040-010-0675-0

Cherkauer, D. S., & Ansari, S. A. (2005). Estimating Ground Water Recharge from Topography, Hydrogeology, and Land Cover. *Groundwater*, *43*(1), 102–112. https://doi.org/10.1111/j.1745-6584.2005.tb02289.x

Chinnasamy, P., Maheshwari, B., & Prathapar, S. (2015). Understanding Groundwater Storage Changes and Recharge in Rajasthan, India through Remote Sensing. *Water*, *7*(10), 5547–5565. https://doi.org/10.3390/w7105547

Clark, I. D., & Fritz, P. (2013). *Environmental Isotopes in Hydrogeology*. CRC Press. https://doi.org/10.1201/9781482242911

Coes, A. L., Spruill, T. B., & Thomasson, M. J. (2007). Multiple-method estimation of recharge rates at diverse locations in the North Carolina Coastal Plain, USA. *Hydrogeology Journal*, *15*(4), 773–788. https://doi.org/10.1007/s10040-006-0123-3

Coplen, T. B., Herczeg, A. L., & Barnes, C. (2000). Isotope Engineering—Using Stable Isotopes of the Water Molecule to Solve Practical Problems. In *Environmental Tracers in Subsurface Hydrology* (pp. 79–110). Springer US. https://doi.org/10.1007/978-1-4615-4557-6\_3

de Vries, J. J., Selaolo, E. T., & Beekman, H. E. (2000). Groundwater recharge in the Kalahari, with reference to paleo-hydrologic conditions. *Journal of Hydrology*, *238*(1–2), 110–123. https://doi.org/10.1016/S0022-1694(00)00325-5

de Vries, J. J., & Simmers, I. (2002). Groundwater recharge: an overview of processes and challenges. *Hydrogeology Journal*, *10*(1), 5–17. https://doi.org/10.1007/s10040-001-0171-7

Delin, G. N., Healy, R. W., Lorenz, D. L., & Nimmo, J. R. (2007). Comparison of local- to regional-scale estimates of ground-water recharge in Minnesota, USA. *Journal of Hydrology*, *334*(1–2), 231–249. https://doi.org/10.1016/j.jhydrol.2006.10.010

Dennehy, K. F., Litke, D. W., Tate, C. M., & Heiny, J. S. (1993). SOUTH PLATTE RIVER BASIN ‐ COLORADO, NEBRASKA, AND WYOMING 1. *JAWRA Journal of the American Water Resources Association*, *29*(4), 647–683. https://doi.org/10.1111/j.1752-1688.1993.tb03231.x

Edmunds, W. M., & Gaye, C. B. (1994). Estimating the spatial variability of groundwater recharge in the Sahel using chloride. *Journal of Hydrology*, *156*(1–4), 47–59. https://doi.org/10.1016/0022-1694(94)90070-1

Ferreira, V. G., Yang, H., Ndehedehe, C., Wang, H., Ge, Y., Xu, J., Xia, M., Kalu, I., Jing, M., & Agutu, N. (2024). Estimating groundwater recharge across Africa during 2003–2023 using GRACE-derived groundwater storage changes. *Journal of Hydrology: Regional Studies*, *56*, 102046. https://doi.org/10.1016/j.ejrh.2024.102046

Ford, D., & Williams, P. (2007). *Karst Hydrogeology and Geomorphology*. Wiley. https://doi.org/10.1002/9781118684986

Freeze, R. A., & Cherry, A. J. (1979). *Groundwater* (C. Brenn & M. Kim, Eds.). Prentice-Hall. Inc., Englewood Cliffs, N.J. 07632.

Gee, G. W., & Hillel, D. (1988). Groundwater recharge in arid regions: Review and critique of estimation methods. *Hydrological Processes*, *2*(3), 255–266. https://doi.org/10.1002/hyp.3360020306

Gibson, J. J., Fekete, B. M., & Bowen, G. J. (2010). Stable Isotopes in Large Scale Hydrological Applications. In *Isoscapes* (pp. 389–405). Springer Netherlands. https://doi.org/10.1007/978-90-481-3354-3\_18

Goldscheider, N., & Drew, D. (Eds.). (2014). *Methods in Karst Hydrogeology*. CRC Press. https://doi.org/10.1201/9781482266023

Healy, R. W., & Cook, P. G. (2002). Using groundwater levels to estimate recharge. *Hydrogeology Journal*, *10*(1), 91–109. https://doi.org/10.1007/s10040-001-0178-0

Healy, R. W., & Scanlon, B. R. (2010). *Estimating Groundwater Recharge*. Cambridge University Press. https://doi.org/10.1017/CBO9780511780745

Holman, I. P. (2006). Climate change impacts on groundwater recharge- uncertainty, shortcomings, and the way forward? *Hydrogeology Journal*, *14*(5), 637–647. https://doi.org/10.1007/s10040-005-0467-0

Humphreys, Kukal, S., Amanpreet-Kaur, Thaman, S., Yadav, S., Yadvinder-Singh, Balwinder-Singh, Timsina, J., Dhillon, S., Prashar, A., & Smith, D. (2008). Permanent beds for rice-wheat in Punjab, India. 2: Water balance and soil water dynamics. *Permanent Beds and Rice-Residue Management for Rice-Wheat Systems in the Indo-Gangetic Plain : Proceedings of a Workshop Held in Ludhiana, India, 7-9 September 2006*.

Jobbágy, E. G., & Jackson, R. B. (2004). Groundwater use and salinization with grassland afforestation. *Global Change Biology*, *10*(8), 1299–1312. https://doi.org/10.1111/j.1365-2486.2004.00806.x

Kendall, C., & Mcdonnell, J. J. (1998). *Isotope Tracers in Catchment Hydrology*. Elsevier. https://doi.org/10.1016/C2009-0-10239-8

Kovács, A., Perrochet, P., Király, L., & Jeannin, P.-Y. (2005). A quantitative method for the characterisation of karst aquifers based on spring hydrograph analysis. *Journal of Hydrology*, *303*(1–4), 152–164. https://doi.org/10.1016/j.jhydrol.2004.08.023

Lischeid, G. (2001). Investigating short-term dynamics and long-term trends of SO4 in the runoff of a forested catchment using artificial neural networks. *Journal of Hydrology*, *243*(1–2), 31–42. https://doi.org/10.1016/S0022-1694(00)00399-1

Lutz, A., Minyila, S., Saga, B., Diarra, S., Apambire, B., & Thomas, J. (2014). Fluctuation of Groundwater Levels and Recharge Patterns in Northern Ghana. *Climate*, *3*(1), 1–15. https://doi.org/10.3390/cli3010001

Mallareddy, M., Thirumalaikumar, R., Balasubramanian, P., Naseeruddin, R., Nithya, N., Mariadoss, A., Eazhilkrishna, N., Choudhary, A. K., Deiveegan, M., Subramanian, E., Padmaja, B., & Vijayakumar, S. (2023). Maximizing Water Use Efficiency in Rice Farming: A Comprehensive Review of Innovative Irrigation Management Technologies. *Water*, *15*(10), 1802. https://doi.org/10.3390/w15101802

Martin, N., & van de Giesen, N. (2005). Spatial Distribution of Groundwater Production and Development Potential in the Volta River basin of Ghana and Burkina Faso. *Water International*, *30*(2), 239–249. https://doi.org/10.1080/02508060508691852

Mathenge, M. W., Gathuru, Dr. G. M., & Kitur, Dr. E. L. (2020). Spatial-Temporal Variation of Groundwater Recharge from Precipitation in the Stony Athi Sub-Catchment, Kenya. *International Journal of Environmental Sciences*, *3*(1), 21–41. https://doi.org/10.47604/ijes.1079

McGuire, V. L., Johnson, M. R., Schieffer, R. L., Stanton, J. S., Sebree, S. K., & Verstraeten, I. M. (2003). *Water in storage and approaches to ground-water management, High Plains aquifer, 2000* (Vol. 1243). US Geological Survey Reston, VA, USA.

Neuman, S. P. (1987). On Methods of Determining Specific Yield. *Groundwater*, *25*(6), 679–684. https://doi.org/10.1111/j.1745-6584.1987.tb02208.x

Rai, S. N., Manglik, A., & Singh, V. S. (2006). Water table fluctuation owing to time-varying recharge, pumping and leakage. *Journal of Hydrology*, *324*(1–4), 350–358. https://doi.org/10.1016/j.jhydrol.2005.09.029

Risser, D. W., Gburek, W. J., & Folmar, G. J. (2009). Comparison of recharge estimates at a small watershed in east-central Pennsylvania, USA. *Hydrogeology Journal*, *17*(2), 287–298. https://doi.org/10.1007/s10040-008-0406-y

Saxena, K. V, Mondal, C. N., & Singh S. V. (2004). Identification of seawater ingress using strontium and boron in Krishna Delta, India. *Current Science*, *86*, 586–590. https://doi.org/10.2307/24107915

Segobaetso, T. K., Tafesse, N. T., Mapeo, R. B. M., & Laletsang, K. (2022). Groundwater recharge using the chloride mass balance method in the Kanye area, in southeast Botswana. *Journal of African Earth Sciences*, *193*, 104534. https://doi.org/10.1016/j.jafrearsci.2022.104534

Seiler, K.-P., & Gat, J. R. (2007). *Groundwater Recharge from Run-Off, Infiltration and Percolation* (Vol. 55). Springer Netherlands. https://doi.org/10.1007/978-1-4020-5306-1

Sharma, M. L., & Hughes, M. W. (1985). Groundwater recharge estimation using chloride, deuterium and oxygen-18 profiles in the deep coastal sands of Western Australia. *Journal of Hydrology*, *81*(1–2), 93–109. https://doi.org/10.1016/0022-1694(85)90169-6

Šimůnek, J., van Genuchten, M. Th., & Šejna, M. (2008). Development and Applications of the HYDRUS and STANMOD Software Packages and Related Codes. *Vadose Zone Journal*, *7*(2), 587–600. https://doi.org/10.2136/vzj2007.0077

Sophocleous, M. A. (1991). Combining the soilwater balance and water-level fluctuation methods to estimate natural groundwater recharge: Practical aspects. *Journal of Hydrology*, *124*(3–4), 229–241. https://doi.org/10.1016/0022-1694(91)90016-B

Sophocleous, M. (2002). Interactions between groundwater and surface water: the state of the science. *Hydrogeology Journal*, *10*(1), 52–67. https://doi.org/10.1007/s10040-001-0170-8

Subyani, A. M. (2004). Use of chloride-mass balance and environmental isotopes for evaluation of groundwater recharge in the alluvial aquifer, Wadi Tharad, western Saudi Arabia. *Environmental Geology*, *46*(6–7), 741–749. https://doi.org/10.1007/s00254-004-1096-y

Varni, M., Comas, R., Weinzettel, P., & Dietrich, S. (2013). Application of the water table fluctuation method to characterize groundwater recharge in the Pampa plain, Argentina. *Hydrological Sciences Journal*, *58*(7), 1445–1455. https://doi.org/10.1080/02626667.2013.833663

Winter, T. C., Harvey, J. W., Franke, O. L., & Alley, W. M. (1998). *Ground water and surface water: A single resource*. https://doi.org/10.3133/cir1139

1. WTF= water table fluctuation [↑](#footnote-ref-1)