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. The review emphasizes the applicability of these methods across various climatic and geological contexts, including arid, semi-arid, and humid regions. Research gaps, including scalability and data limitations, highlight the need for integrated approaches and advanced monitoring techniques. 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). Nevertheless, deep percolation does not represent an actual loss of water from the landscape, as the uncontaminated water eventually recharges the groundwater system, contributing to diffuse recharge and enhancing subsurface water storage that can be reused later (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

A clear understanding of the underlying mechanisms of recharge within a specific area is essential for accurately estimating groundwater recharge. de Vries & Simmers (2002) outlined the key processes governing groundwater replenishment. They described recharge as the volume of water that moves vertically through the unsaturated zone, beyond the depth of plant roots, ultimately reaching the water table and contributing to the groundwater reservoir. During rainfall or irrigation, a portion of water addresses soil moisture deficits or is lost through evapotranspiration. The remaining portion infiltrates deeper into the soil, and if it reaches the water table, it becomes groundwater recharge. Based on this understanding, recharge in a given area is often equated with the amount of infiltration occurring there.

However, not all infiltrated water necessarily contributes to recharge. Infiltration may be impeded by layers with low permeability, such as impermeable or semi-permeable strata, which restrict vertical movement. In such cases, water may instead move laterally toward surface depressions like ponds, where it may eventually evaporate, thereby not enhancing groundwater reserves. In regions where the aquifer is shallow relative to the surface, the water table may facilitate lateral flow or seepage within the area. Additionally, in high water table settings, water that reaches the saturated zone may quickly be removed by evapotranspiration, especially over longer timeframes.

Carreira et al. (2011) highlighted the influence of rainfall on recharge. In humid and subhumid climates, annual precipitation typically exceeds potential evapotranspiration, leading to consistent groundwater recharge. Conversely, in arid and semi-arid environments, rainfall is generally insufficient to surpass evapotranspiration, limiting recharge. However, over extended periods, even limited rainfall and preferential flow paths can still contribute to groundwater replenishment.

**3.1 Groundwater recharge types**

Based on the origin of the water, groundwater recharge is generally categorized into three main types: direct (or diffuse) recharge, localized recharge, and indirect (or non-diffuse) recharge (Acharya & Barbier, 2000; de Vries & Simmers, 2002). Direct recharge occurs when rainfall or irrigation water percolates vertically through the unsaturated zone into the groundwater system, having been separated from other components of the water balance such as evapotranspiration, surface runoff, and soil water deficits. Localized recharge takes place where water accumulates at specific surface depressions, leading to increased infiltration at those points for example, in ponded areas like rice fields. Indirect recharge involves the infiltration of water through the beds of surface water bodies such as rivers, streams, or canals, where the percolation contributes to groundwater storage.

**3.2 Groundwater recharge estimation**

Groundwater recharge estimation methods are generally grouped into two broad categories: direct and indirect approaches. Direct physical methods include the use of lysimeters, while direct chemical methods involve tracer techniques, which may be applied in the field or derived from historical data. Indirect physical approaches encompass methods such as the soil water balance, water budget analysis, and the groundwater table fluctuation technique. Although the Groundwater Table Fluctuation (GTF) method utilizes direct observations of changes in water table elevation, it is categorized as an indirect physical method because it does not measure recharge flux directly. Instead, recharge is inferred by relating observed water level rises to estimated aquifer properties, most notably the specific yield, which introduces uncertainty due to spatial variability and aquifer heterogeneity (Moeck et al., 2024). Furthermore, interpreting water level fluctuations requires careful consideration of delayed drainage, lateral flow, and human influences such as pumping, which complicate the direct attribution of recharge (Cuthbert et al., 2019).

These estimation techniques can also be classified based on climatic conditions, including arid, semi-arid, and humid regions. In arid and semi-arid areas, suitable methods include the water budget approach, isotopic tracer analysis, lysimeter studies, Darcy’s law, and various numerical models. In contrast, humid regions typically allow for the use of soil water balance methods, water budgets, lysimeters, Darcy’s law, applied tracers, groundwater level fluctuations, and numerical modelling (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**

A range of factors influences groundwater recharge, including climate, land use, vegetation or land cover, geological setting, topography, soil texture and structure, irrigation practices, depth to the water table, soil moisture content, characteristics of subsurface materials, and proximity to surface water bodies (Acharya & Barbier, 2000; Seiler & Gat, 2007). These variables may act independently or interactively, collectively impacting recharge rates. Among them, climate, soil texture, and surface cover are widely recognized as the most critical. Climatic variables such as precipitation and evapotranspiration directly affect the volume of water available at the surface, which ultimately governs how much water infiltrates into the subsurface and contributes to recharge (Healy & Scanlon, 2010).

Soil texture, particularly its porosity and pore size distribution, plays a significant role in determining water retention, infiltration capacity, and transpiration, thereby influencing recharge potential (Jobbágy & Jackson, 2004). Sandy soils, characterized by larger pores and higher permeability, typically allow greater infiltration and thus support higher recharge rates. Conversely, clayey soils, with finer pores and higher surface tension, restrict vertical water movement, resulting in lower infiltration. Although clayey soils retain more plant-available water due to abundant micropores, this also leads to increased evapotranspiration, which reduces the amount of water that reaches the aquifer.

Vegetation cover also significantly affects groundwater recharge (Seiler & Gat, 2007). The type and density of vegetation influence surface runoff and soil evaporation through interception and shading effects. Leaf canopies and root systems alter how water moves through the soil, which can either enhance or inhibit recharge depending on the vegetation type and soil condition (Jobbágy & Jackson, 2004).

Recharge tends to be higher in sparsely vegetated areas compared to those with dense cover, such as croplands or grasslands. For instance, Mathenge et al. (2020) studied groundwater recharge in Kenya’s Stony Athi sub-catchment and found that areas with forest cover on sandy loam soil exhibited recharge rates of 197 mm/year, whereas regions with clay soils and impervious layers had much lower rates of about 36 mm/year. The higher recharge in forested zones was attributed to improved infiltration facilitated by reduced surface runoff.

**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 | Lysimeter  Water budget WTF[[1]](#footnote-1) | 311  308 | 29%  29% | (Risser et al., 2009) |
| USA, North Carolina | 1170 mm | WTF | 252  140 | 24 %  12 % | (Coes et al., 2007) |
| North-east Bangladesh | 1050 mm | Chloride tracer Water balance | 110  49 | 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=0.09  WTF, Sy=0.07 | 210  164 | 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:

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:

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).

When using the water balance method, accurate estimation of all variables on the right-hand side of the equation, precipitation, evapotranspiration, runoff, and changes in soil moisture is essential for deriving reliable recharge values. Errors in measuring these inputs can significantly distort recharge estimates (M. Sophocleous, 2002)The unsaturated zone, also known as the vadose zone, plays a pivotal role in this process. In humid regions, this zone often permits easy infiltration of rainfall, promoting consistent recharge to the groundwater table. However, in arid climates, where evapotranspiration often exceeds 90% of total precipitation, little water remains available for recharge (Acharya & Barbier, 2000). Thus, the arid region requires a more precise measurement of the recharge. Consequently, water balance methods are generally more reliable in humid regions and require greater precision when applied in arid zones (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).

In India, Indraja et al. (2023) applied the water balance approach to estimate groundwater recharge in the Krishna Central Delta command area. Their study incorporated data on rainfall, irrigation inputs, and evapotranspiration to determine seasonal and annual recharge variability. The results demonstrated the significant influence of irrigation return flow in augmenting recharge, especially in intensively cultivated command regions. This underscores the utility of the water balance method in managing groundwater resources in agriculturally dominated landscapes.

**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:

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). Specific yield values can vary considerably due to aquifer heterogeneity, including variations in lithology, porosity, and compaction (Healy & Scanlon, 2010). This spatial variability introduces uncertainty in recharge estimation and necessitates localized field testing or calibration.

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.

Gat (2010) provides an in-depth explanation of isotopic fractionation processes and their implications for hydrological studies. According to his work, isotopic compositions in precipitation are influenced by multiple factors including temperature, humidity, altitude, and distance from the ocean, which collectively shape the spatial and temporal variability in δ¹⁸O and δ²H values. He emphasizes that fractionation during phase changes especially evaporation and condensation leads to systematic enrichment or depletion of heavier isotopes, a principle that underpins the use of stable isotopes as natural tracers in hydrology. Gat (2010) further highlights that isotope ratios in groundwater reflect the integrated signal of recharge events, and deviations from the Global Meteoric Water Line (GMWL) can indicate mixing, evaporation, or non-equilibrium processes. These insights are critical for interpreting groundwater recharge sources, timing, and history, particularly in regions where recharge is episodic or derived from different 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:

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). In addition, chloride recycling from agricultural return flows, irrigation, or industrial discharge can affect chloride concentrations in soil and groundwater, potentially leading to inaccurate recharge estimates if not accounted for during sampling and interpretation (Subyani, 2004).

**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.

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, 2007).

**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:

* 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). Scanlon et al. (2006) conducted a global synthesis of groundwater recharge estimates in semiarid and arid environments, emphasizing the value of unsaturated zone modeling in characterizing low-magnitude recharge processes under variable climatic conditions. Their study highlights that recharge in dry regions is often episodic, strongly controlled by extreme precipitation events, and modulated by soil texture, vegetation, and land use. The authors demonstrate that numerical models like HYDRUS are particularly effective in simulating water fluxes in unsaturated soils of arid zones, where direct observations are limited. Through incorporating detailed soil hydraulic properties and climate inputs, unsaturated zone models can help distinguish between transient and steady-state recharge mechanisms. Scanlon et al. (2006) further stress the importance of validating model outputs with independent tracers or long-term monitoring data to ensure reliability in regions prone to overestimation or underestimation due to high evapotranspiration losses.

**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.Emerging technologies such as remote sensing, artificial intelligence, and machine learning are increasingly being explored for recharge estimation. These tools offer potential for enhancing data collection, real-time monitoring, and predictive modeling across broad spatial scales. To improve geographic inclusivity, future reviews should incorporate more case studies from underrepresented regions such as South Asia and Sub-Saharan Africa, where groundwater reliance is high and monitoring infrastructure is limited.

**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.

Disclaimer (Artificial intelligence)

Author(s) hereby declare that generative AI technologies such as Large Language Models, etc. have been used during the writing or editing of manuscripts. This explanation will include the name, version, model, and source of the generative AI technology and as well as all input prompts provided to the generative AI technology

Details of the AI usage are given below:

1. scispace.com was used as a literature discovery tool to locate peer-reviewed publications, technical reports, and foundational hydrological texts on groundwater recharge estimation methods.

* AI Use: Assisted in refining search queries and identifying relevant sources based on keyword combinations (e.g., “lysimeter recharge estimation,” “tracer application in karst,” “GTF method recharge”).
* Tool: SciSpace Literature Review AI (2024 version).
* Output: Literature lists and summaries, which were manually reviewed and integrated into the structured review methodology described in the manuscript.

2.  ChatGPT (OpenAI GPT‑4o, 2024) was used to improve the readability, academic tone, and clarity of specific sections (e.g., paraphrasing technical paragraphs, and summarizing cited works).

*All AI-generated outputs were carefully reviewed and edited by the authors for technical accuracy and originality.*

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