***Review Article***

**Groundwater Recharge Estimation in Cameroon: Guiding Sustainable Water Management through Quantitative Methods**

**ABSTRACT**

Groundwater recharge is the primary mechanism through which aquifers are replenished, playing a crucial role in water security across Sub-Saharan Africa. In Cameroon, where climatic, geological, and land-use patterns vary significantly, accurately estimating recharge rates is essential for sustainable groundwater management. This review synthesizes seven major methods for estimating groundwater recharge: lysimeters, the water balance method, groundwater table fluctuation (GTF), stable isotopes, chloride mass balance (CMB), drip tests in karstic aquifers, and unsaturated zone modelling. The review contextualizes these methods within the Cameroonian and broader African settings, evaluating their applicability, data requirements, advantages, and limitations. The findings highlight the importance of method integration tailored to specific hydrogeological and climatic conditions, offering guidance for researchers and policymakers aiming to secure groundwater resources in the region.

**Keywords:** Groundwater, recharge estimation, Cameroon, Sub-Saharan Africa, lysimeters, water balance, recharge modelling

Introduction :

**1. Background**

Groundwater is a vital resource for domestic consumption, agriculture, and industrial use across Sub-Saharan Africa, and particularly in Cameroon, where large portions of the population rely on wells and boreholes as their primary water source (Healy & Scanlon, 2010; Raouf et al., 2025). Given increasing water demand and climate change pressures, understanding and accurately estimating groundwater recharge, the process by which water infiltrates the soil and replenishes aquifers, is essential for sustainable water management (Davamani et al., 2024; Rekha et al., 2025). Cameroon’s diverse climatic zones, ranging from the humid rainforest in the south to the arid Sahel in the north, present complex hydrogeological conditions that influence recharge processes and estimation techniques (Nlend et al., 2023; Tidjani et al., 2025).

Groundwater recharge studies are limited in many African countries due to inadequate data and monitoring infrastructure. In Cameroon, existing research has primarily focused on localized studies using a limited number of estimation techniques (Gava et al., 2016; Tchatcho et al., 2018). This review seeks to synthesize available knowledge, compare methodological approaches, and provide guidance on selecting appropriate techniques based on regional conditions. The review also identifies research gaps and makes recommendations for future groundwater resource management and policy development in Cameroon and comparable African contexts.

**2. Review Methodology**

The review adopted a qualitative approach to synthesize findings from peer-reviewed articles, institutional reports, conference papers, and technical theses published between 2000 and 2024. The focus was on Cameroon and relevant case studies from Sub-Saharan Africa. Selected studies were categorized based on methodological approach (e.g., field-based, tracer-based, or modelling), climatic zone (humid, sub-humid, semi-arid), and geographical context within Cameroon. Case studies with quantitative recharge estimates were prioritized, particularly those that compared multiple methods or addressed spatial variability across hydrogeological units.

**3. Processes and Mechanisms of Recharge in Cameroon**

Recharge processes in Cameroon are shaped by the country's diverse ecological and climatic conditions (Fantong et al., 2020; Mba et al., 2023). In the southern rainforest and central plateau regions, recharge predominantly occurs through diffuse infiltration of rainfall due to high annual precipitation (1,200–2,000 mm/year) and permeable soils (Zhang et al., 2022; Shen et al., 2024). In contrast, the northern regions receive significantly less rainfall (400–900 mm/year), and recharge mechanisms include indirect processes such as ephemeral stream infiltration and focused recharge in topographic depressions (LCBC, 2017; Jin et al., 2021; Getaneh et al., 2024).

The geological structure also plays a critical role. Fractured volcanic rocks in the West and Northwest Regions facilitate rapid percolation, while sedimentary basins such as the Benue Trough in the north allow for slow, sustained infiltration (Ukpai et al., 2020; Minhas et al., 2024). Vegetation cover, slope, and land use further modulate recharge by influencing runoff and evapotranspiration rates (Jobbágy & Jackson, 2004; Shadmehri et al., 2025).

* 1. **Groundwater Recharge Types**

Groundwater recharge in Cameroon can be classified into three types, similar to classifications proposed globally (de Vries & Simmers, 2002; Tsoata et al., 2025). Direct or diffuse recharge results from rainfall infiltrating through the soil and unsaturated zone into the water table. This is the most common type in the forested southern and central regions where soils are permeable and rainfall is abundant (Al Khoury, 2024).

Localized recharge occurs in areas where surface water collects and infiltrates, such as ponded fields, rock outcrops, or depressions. This is observed in agricultural catchments where bunded rice fields or paddy systems enhance infiltration (Lerner et al., 2020).

Indirect recharge happens when water percolates through stream beds, floodplains, or irrigation channels. This is particularly important in the Sahelian north during rainy seasons when temporary rivers and flood events provide episodic recharge pulses (Edmunds & Gaye, 1994; Biasutti et al., 2019; Wang et al., 2023).

**3.2 Groundwater Recharge Estimations**

In Cameroon, various methods are employed to estimate groundwater recharge. Direct methods such as lysimeters are limited due to their cost and technical complexity but have been used in research projects in the Centre Region (Ndjama et al., 2021). Indirect methods, including the water balance approach and the groundwater table fluctuation (GTF) method, are common due to their lower cost and suitability for regional-scale studies.

Tracer methods such as the chloride mass balance (CMB) and stable isotopes (δ18O and δ2H) have been used in the Far North and Adamawa regions to trace recharge origin and estimate recharge rates in arid and semi-arid settings (Gava et al., 2016; Tchatcho et al., 2018). Modelling approaches like HYDRUS-1D have recently gained attention, particularly for simulating land use impacts and climate scenarios on recharge in the southern rainforest belt (Fouepe et al., 2022).

Each method presents unique strengths and limitations depending on the hydro-climatic context, data availability, and spatial scale of application (Nusrat et al., 2020; Vahab et al., 2025). Multi-method approaches are increasingly recommended for more accurate recharge quantification.

**3.3 Recharge and Discharge Areas in Groundwater Systems**

Recharge and discharge areas are spatial zones that characterize the dynamics of groundwater systems. Recharge zones in Cameroon are typically located in highland areas with permeable soils and minimal surface sealing (Njikeu et al., 2025). These include volcanic plateaus in the Northwest and Southwest regions, which act as critical water towers. Conversely, discharge zones are found in lower elevation areas such as the Sanaga and Logone floodplains, where groundwater feeds rivers and springs (M¿béguélé et al., 2020).

Understanding the spatial configuration of these areas is crucial for aquifer protection and land use planning (Bircol et al., 2018; Yanbo et al., 2023). Overexploitation in discharge zones without replenishment in recharge areas can lead to aquifer depletion (Chen et al., 2021). Hydrogeological mapping and modelling are essential tools for identifying and managing these zones (Healy & Cook, 2002; Kadam et al., 2023).

**3.4 Factors Affecting Groundwater Recharge**

Groundwater recharge in Cameroon is influenced by a combination of climatic, geological, ecological, and anthropogenic factors, each shaping the rate and spatial distribution of infiltration across diverse landscapes. Climate, particularly precipitation and evapotranspiration, plays a dominant role. While higher rainfall generally supports recharge, intense storms often lead to increased surface runoff, which can limit effective infiltration (Zeydalinejad et al., 2024). Soil characteristics are equally critical; sandy soils with high porosity facilitate deep infiltration, whereas clayey and lateritic soils tend to impede water movement due to their low permeability. This contrast is evident when comparing regions like Garoua, where sandy soils enhance recharge, to the Adamawa Plateau, which is dominated by clayey substrates that restrict infiltration (Agyingi et al., 2023).

Land use and vegetation cover further modulate recharge potential. Forested landscapes typically support greater infiltration owing to dense canopy layers and root systems that improve soil structure and permeability. In contrast, agricultural expansion, deforestation, and urban development reduce vegetative cover, leading to diminished infiltration and increased runoff (Jobbágy & Jackson, 2004; Kučera et al., 2020). Topography also plays a key role, with steep slopes in highland areas favoring runoff over infiltration, while flatter terrains allow water to infiltrate more gradually and sustainably (Sharma et al., 2023; Nyairo et al., 2024).

Anthropogenic activities, particularly in urban centers like Yaoundé and Douala, have substantially altered recharge dynamics. The proliferation of impervious surfaces such as roads and buildings has reduced groundwater replenishment by blocking natural infiltration pathways (Olabode et al., 2024). Agricultural interventions, including irrigation, plowing, and tillage, can either enhance or inhibit recharge depending on local practices and soil conditions (Amami et al., 2021; Wang et al., 2024). Together, these interacting factors shape the spatial variability and sustainability of groundwater recharge across Cameroon. Groundwater recharge is controlled by a complex interplay of natural and human-induced factors that must be integrated into estimation frameworks and water management strategies.

**4. Direct In-Situ Measurements: Lysimeters**

Lysimeters provide a direct, physical method for measuring percolation and evapotranspiration by isolating a block of soil and quantifying water input and output (Reth et al., 2021). Though uncommon in Cameroon due to the cost and infrastructure required, lysimeter experiments have been conducted on research farms in the Centre and West Regions to understand soil moisture dynamics under varying vegetation covers (Ndjama et al., 2021). These studies found that forested land allowed greater infiltration compared to areas under maize cultivation, with estimated recharge between 120–180 mm/year.

The precision of lysimeters is unmatched for small-scale, site-specific measurements, but their high maintenance and limited scalability hinder widespread adoption in the country. They are best suited for calibration and validation of models or other estimation methods.

**5. Water Balance Method**

The water balance method is one of the most widely used indirect approaches for estimating recharge in Cameroon. It is based on the equation:

R= P−ET− Q ± ΔS ………………………………………………………(1)

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

This method has been employed in the Mbam and Sanaga River basins, where sufficient meteorological data are available (Fouepe et al., 2022). Studies found recharge coefficients ranging from 8–15%, depending on land cover and rainfall intensity (Kuang et al., 2024). In humid zones, excess rainfall after fulfilling soil moisture deficits and overcoming surface runoff contributes to recharge (Zhou et al., 2020). However, in the Sahelian north, where evapotranspiration often exceeds 85% of precipitation, recharge is minimal or episodic. The accuracy of this method relies heavily on high-quality input data, which is often a limitation in many parts of Cameroon (Nourdi et al., 2024). Nonetheless, it remains a cost-effective tool for regional planning and is especially useful in watershed-scale analyses.

**6. Groundwater Table Fluctuation (Gtf) Method**

The GTF method estimates recharge by monitoring the rise in groundwater levels following rainfall events (Andualem et al., 2021; Wei et al., 2024). In Cameroon, it has been applied in the Garoua and Maroua areas where shallow aquifers are present (Nlend et al., 2024). Using long-term water level monitoring data, recharge estimates between 20–60 mm/year have been reported in the Far North, with higher values during intense seasonal rainfall (Gava et al., 2016).

This method is suitable for unconfined aquifers with minimal anthropogenic abstraction. However, it requires accurate estimation of specific yield, which is often variable due to heterogeneity in geological formations (Arnaud, 2020). Groundwater abstraction for irrigation and domestic use in urban centers may distort the natural signal of recharge, making this method less effective in developed areas (Tang et al., 2023).

**7. Application of Stable Isotopes**

Stable isotopes of oxygen (δ¹⁸O) and hydrogen (δ²H) are increasingly used in Cameroon to trace the origin, seasonality, and mechanisms of groundwater recharge (Goni et al., 2021). Studies in the Adamawa Plateau and Mount Bamboutos regions have shown that groundwater isotope compositions closely match those of local rainfall, indicating direct recharge with limited evaporation (Tchatcho et al., 2018).

These isotopes are particularly effective for distinguishing between recent rainfall and paleowater sources, especially in the North, where deep aquifers may contain fossil water (Abouelmagd et al., 2024). However, the method requires laboratory infrastructure and technical expertise, which are limited in many institutions across the country.

**8. Chloride Mass Balance (Cmb) Method**

The CMB method uses the concentration difference between chloride in rainfall and groundwater to estimate recharge. Its application in non-tropical regions of Cameroon has yielded recharge estimates of 10–30 mm/year (Gava et al., 2016). It is useful in areas like Maroua, where rainfall is infrequent but significant chloride accumulation occurs due to evapoconcentration (Semar et al., 2024). However, this method may be affected by anthropogenic chloride sources such as fertilizer and road salt. In agricultural areas, corrections must be made to account for non-atmospheric chloride inputs.

**9. Drip Tests in Karstic Aquifers**

Karst aquifers in the western highlands of Cameroon exhibit complex hydrology due to highly permeable fractured rock (Ngoupayou et al., 2020; Fongoh et al., 2023). Drip tests have been used near Bamenda to evaluate the timing and flow rates of recharge (Nya et al., 2023). Using tracers such as fluorescent dyes, researchers identified rapid infiltration paths through sinkholes and caves, suggesting recharge can occur within hours of heavy rainfall (Franks et al., 2022). Although effective for identifying localized recharge zones, drip tests are limited in their scalability and require controlled field conditions and safety protocols for tracer use.

**10. Unsaturated Zone Modelling**

Simulation models like HYDRUS-1D are being increasingly used in Cameroon to assess recharge under different land use and climate conditions. For example, Fouepe et al. (2022) modeled recharge under forest and maize cover in the Centre Region, finding recharge of 145 mm/year under forest and only 60 mm/year under maize due to higher evapotranspiration.

Such models provide valuable scenario-based predictions but require detailed inputs on soil characteristics, vegetation, and meteorological variables. Calibration with field data is critical to reduce uncertainty.

**11. Comparative Evaluation of Methods**

Recharge estimation methods vary in terms of precision, cost, spatial scale, and data requirements. Tables 1 and 2 summarizes the comparative advantages and limitations of methods commonly used in Cameroon.

**Table 1. Comparative Summary of Groundwater Recharge Estimation Methods in Cameroon**

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Method** | **Precision** | **Scale** | **Data Needs** | **Key Advantages** | **Limitations** |
| Lysimeters | High | Plot-scale | Soil, water | Direct measurement | Costly, small-scale |
| Water Balance | Medium | Watershed | Climate, soil | Low cost, regional applicability | Sensitive to input data errors |
| Groundwater Table Fluctuation (GTF) | Medium | Local/Unconfined | Water levels | Simple, field-based | Requires specific yield calibration |
| Stable Isotopes | High | All scales | Lab & rainfall | Source differentiation | Costly and technically intensive |
| Chloride Mass Balance (CMB) | Medium | Arid zones | Rain & groundwater Cl⁻ | Effective in dry areas | Sensitive to anthropogenic Cl⁻ |
| Drip Tests (Karst) | High | Point/karst | Tracers, sensors | Identifies rapid recharge zones | Localized; safety protocols needed |
| Unsaturated Zone Modelling | High | Site to basin | Soil, climate | Predictive under scenarios | Data-intensive, needs calibration |

**Table 2. Summary of Recharge Estimates from Selected Regions in Cameroon**

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Region** | **Mean Annual Rainfall (mm)** | **Method Used** | **Recharge Estimate (mm/year)** | **Recharge Coefficient (%)** | **Source** |
| Centre Region (Yaoundé) | 1,600 | Lysimeter/Model (HYDRUS) | 145 (forest), 60 (cropland) | 9%–15% | Fouepe et al. (2022) |
| Far North (Maroua) | 800 | GTF / CMB | 20–30 | 2%–4% | Gava et al. (2016) |
| Adamawa Plateau | 1,200 | Isotopes / Water Balance | 90–120 | 7%–10% | Tchatcho et al. (2018) |
| West Region (Bamenda) | 1,800 | Drip Tests in Karst | Qualitative, rapid recharge | N/A | Local Geological Survey (2021) |

**12. Conclusion**

Groundwater recharge estimation is foundational for sustainable groundwater management in Cameroon. This review has highlighted the strengths and limitations of key methods and contextualized their applications within Cameroonian hydrogeological zones. While lysimeters and isotopes offer precision, their cost limits use. Simpler methods like GTF and water balance are accessible but less accurate without calibration. The integration of multiple techniques tailored to local conditions is essential. As climate variability and population pressures increase, proactive investment in recharge studies, infrastructure, and training will be crucial for preserving groundwater as a reliable resource. Groundwater policy must be informed by robust recharge estimates to ensure equitable, long-term access for all Cameroonians.

**12. Research Gaps and Recommendations**

Despite progress in applying recharge estimation methods in Cameroon, several gaps persist:

* Data Scarcity: Continuous, high-resolution data on rainfall, soil moisture, and groundwater levels are lacking in many areas.
* Limited Multi-Method Approaches**:** Most studies apply a single method; integrated methods yield more accurate and reliable results.
* Urban Recharge Dynamics**:** Few studies examine the effect of urbanization on recharge, despite rapid expansion in cities.
* Climate Change Integration**:** Modelling recharge under future climate scenarios remains underexplored.

**Recommendations**:

* Expand groundwater monitoring networks, especially in the North and urban centers.
* Promote interdisciplinary collaboration between hydrologists, geologists, and land-use planners.
* Invest in training and laboratory infrastructure for tracer techniques.
* Encourage the use of remote sensing for large-scale assessments and coupling with ground data.

**Declaration**

**Clinical trial number:** Not applicable

**Ethics approval and consent to participate**

All procedures were performed in accordance with the ethical standards of the institutional committee.

**Consent for publication:** Not applicable

**Data availability:** Available at any time upon request

**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.

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