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Stable Isotope Assessment of Groundwater Recharge and Climatic Sensitivity in the N'Kappa Coastal Aquifer, Cameroon

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Abstract

Groundwater in the N'Kappa area of the Douala Basin serves as a vital water source for domestic and agricultural use in a region where centralized water supply systems remain inadequate. With rapid population growth, expanding settlements, and the growing impacts of climate change, there's increasing pressure on this vital resource. Despite the importance of groundwater in this coastal basin, little is known about its recharge dynamics, limiting effective management and policy development. This study addresses this gap by applying stable isotope techniques ($\delta^{18}O$ and δ^2H) to characterize the recharge mechanisms and environmental changes of the N'Kappa Coastal Aquifer. Twenty groundwater samples were collected during the rainy season and analyzed using Cavity Ring-Down Spectroscopy. The isotopic composition revealed a narrow range ($\delta^{18}O$: –3.61 to –2.73‰; δ^2H: –12.8 to –4.7‰) and high d-excess values (12.96 to 17.13‰), indicating recharge from Atlantic-derived precipitation under humid conditions with limited evaporative loss. The Local Meteoric Water Line (LMWL: $\delta^2H = 8.161\delta^{18}O + 12.95$) closely mirrors the Global Meteoric Water Line, indicating rapid infiltration during high-intensity rainfall events. Isotopic homogeneity across samples suggests a young, well-mixed aquifer with short residence times. These findings indicate the aquifer is influenced by local climate patterns and may be vulnerable to future shifts in rainfall. The study underscores the need for integrated groundwater management strategies that incorporate long-term isotope monitoring, protection of recharge zones, and sustainable land-use planning to mitigate contamination risks and safeguard water resources in the N'Kappa area.

Keywords: *Groundwater recharge, stable isotopes, water resource management, aquifer sustainability.*

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1.0 BACKGROUND OF THE STUDY

Groundwater is increasingly recognized as a cornerstone of water security across much of Sub-Saharan Africa, serving as a critical source for domestic, agricultural, and industrial needs (Lapworth *et al.,* 2013; Leader *et al.,* 2018; Cheo *et al.,* 2022). In Cameroon, especially in peri-urban areas in the Littoral Region, groundwater accessed through boreholes is the dominant source of drinking water due to inadequate centralized supply (Fongoh *et al.,* 2024). However, the sustainability of this resource is under threat from rapid population growth, unplanned urban development, and environmental pressures such as climate change and poor sanitation.

In many parts of West and Central Africa, previous hydrogeochemical studies have highlighted the influence of lithology, land use, and climatic conditions on groundwater quality (Ako *et al.,* 2012; Sako *et al.,* 2021; Geris *et al.,* 2022; Ngai *et al.,*2024; Wotany *et al.,*2024). Such analyses often rely solely on physical and chemical parameters, providing limited insight into the deeper dynamics of groundwater movement and recharge. To address these limitations, isotope hydrology has emerged as a powerful tool (Sukanya & Joseph,2023; Dee *et al.,* 2023). The use of stable isotopes, primarily deuterium (δ^2H) and oxygen-18 ($\delta^{18}O$), has proven essential for tracing the origin of groundwater, identifying recharge mechanisms, estimating water residence time, and understanding interactions between surface water and aquifers (Clark & Fritz, 1997; Gat, 2010; Shakhashiro *et al.,* 2012).

Studies in various Cameroonian basins, including the Wouri Estuary, Mount Cameroon flanks, and the Rio del Rey Basin, have demonstrated the effectiveness of isotope techniques in revealing meteoric recharge processes, minimal evaporative effects, and rapid infiltration patterns (Fantong *et al.,* 2010; Wotany *et al.,* 2021). These findings have underscored the isotopic signature as a reliable tracer for deciphering the hydrological behavior of tropical aquifer systems. Despite the increasing application of stable isotopes in groundwater studies across Cameroon, the N'Kappa coastal aquifer remains poorly characterized in terms of isotopic composition and recharge behavior. This lack of data constrains the development of informed groundwater management policies in the face of rapid environmental and demographic change.

This study seeks to fill that gap by applying stable isotope techniques to characterize the groundwater in the study area. Specifically, it aims to determine the origin and recharge mechanisms of groundwater, assess the hydraulic residence time and degree of aquifer mixing, and evaluate the effects of altitude and evaporation on isotopic values. Through this approach, the study offers critical insights into the sustainability of aquifers under changing environmental conditions and human pressures.

Understanding the isotopic composition and recharge sources allows for more effective protection of recharge zones, improved land-use planning, and the formulation of adaptive strategies to cope with climate variability. In addition, this study contributes baseline isotope data to the limited dataset available for the Douala Basin, thereby strengthening regional efforts toward integrated water resource management and resilience-building in water-scarce communities.

2.0 STUDY AREA

2.1 Geographical Position, Climate and Hydrological Systems

2.1.1 Geographical Position and Setting

The study area is located within the Bonaléa Subdivision of the Moungo Division, part of the Littoral Region of Cameroon. Geographically, the study area lies between latitudes 4°13′5″ N and longitudes 9°36′39″ E, with an average elevation of approximately 14 meters above sea level (Fig. 1). The area is situated within the northern part of the Douala sedimentary basin, one of the most hydrologically and geologically significant lowland coastal basins in Central Africa (Emvoutou *et al.,* 2024). This basin extends along the Gulf of Guinea and is characterized by a sequence of unconsolidated to semi-consolidated sedimentary formations of Tertiary and Cretaceous age (Fantong *et al.,* 2016; Angengo, 2020).

The study area found in the Douala basin is characterised by low-relief topography, gently sloping from the northeast (approximately 100 meters a.s.l.) toward the Atlantic coastline in the southwest (Eisenberg,2012; Nlend, 2019). These subtle topographic gradient influences both surface and subsurface hydrological flow directions, favoring groundwater movement from inland recharge zones to coastal discharge areas. The land use in the area includes rural settlements, subsistence farming, industrial installations, and plantations.

2.1.2 Climate

The climate is characterized by bimodal rainfall distribution, with distinct wet and dry seasons. The rainy season spans from April to September, while the dry season extends from October to March. Average annual rainfall in the Douala Basin ranges from 2,500 mm to 4,000 mm, with the majority of precipitation occurring during the wet season (Njumbe,2004; Suchel, 1987; Wirmvem *et al.,* 2015; Tume,2016).

Temperatures are high and relatively stable throughout the year, with monthly average maximum temperatures ranging between 29°C and 34°C, and minimum temperatures between 23°C and 26°C. The warmest months are typically January and February, while July and August represent the coolest periods due to increased cloud cover and rainfall (Coumou *et al.,* 2013; Blunden *et al.,*2018; Rinzin *et al.,* 2024). The mean annual temperature ranges between 26°C and 28°C, supporting high rates of evapotranspiration, which influences both surface runoff and groundwater recharge dynamics (Amanambu *et al.,* 2020; Mensah *et al.,* 2022).

Relative humidity remains consistently high, often exceeding 80%, particularly during the rainy season. Such climatic conditions are favorable for groundwater recharge, especially in areas with permeable soils and fractured geologic units (Amanambu *et al.,* 2020). However, the high humidity and evapotranspiration also pose challenges for the isotopic stability of shallow water sources.

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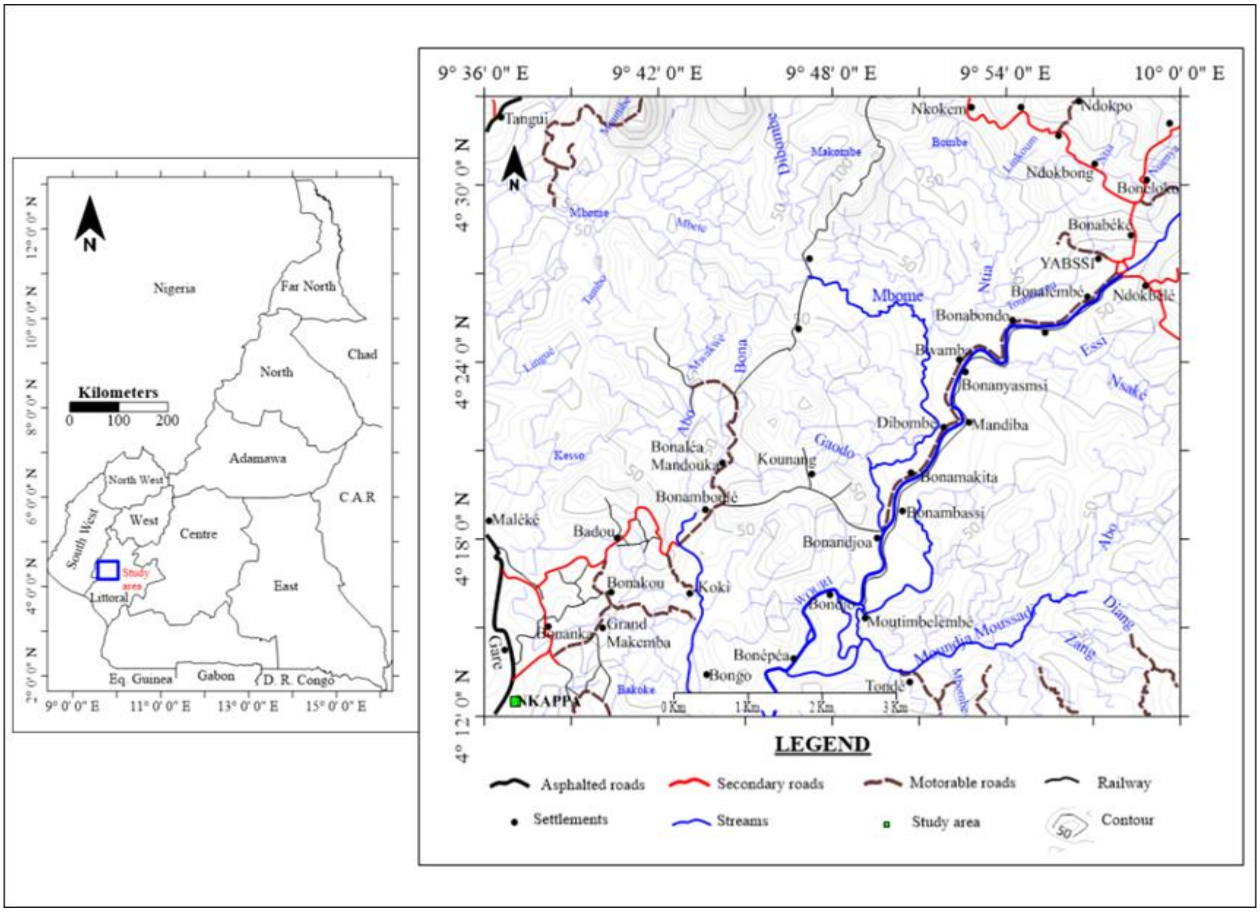

Figure 1: Location of the Study Area

2.1.3 Drainage Systems

Hydrologically, the study area is part of the greater Dibamba River watershed, one of the key catchments that drain the northern Douala Basin (Fig. 2). The region exhibits a dendritic drainage pattern, with several primary rivers including Ngoua, Bobongo, and Kambo flowing southwestward to discharge into the Dibamba River, which eventually empties into the Atlantic Ocean (Fantong *et al.,* 2016; Boum-Nkot *et al.,* 2023). These rivers are perennial due to high rainfall and a shallow groundwater table that sustains baseflow during the dry season.

The hydrographic network is dense and characterized by short, meandering streams and rivers due to the low-gradient terrain and clayey alluvial soils (Khan *et al.,*2018; Wohl, 2020). Seasonal flooding is common in lower elevations and near riverbanks during peak rainfall months, especially when river discharge exceeds channel capacity (Asinya *et al.,*2021). The interaction between surface water and groundwater is facilitated by these surface water bodies, which can act as both recharge and discharge zones depending on hydraulic gradients (Lewandowski *et al.,* 2020; Banerjee & Ganguly,2023).

The aquifer systems in the study area are influenced by both topography and stratigraphy. The Pleistocene and Pliocene alluvial deposits form the shallow unconfined aquifers, while the deeper confined aquifer is primarily hosted within the Palaeocene sands of the Nkappa Formation (Wirmvem *et al.,*2017; Ceccatelli,2020). This deeper aquifer is semi-confined to

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Vol.4, Issue 2, pp 11 – 33, 2025

confine due to the overlying impermeable marine shales, which restrict vertical water movement but allow lateral flow. Recharge to the deeper aquifer primarily occurs through vertical infiltration in outcrop zones and along fracture zones or fault lines, particularly during the peak of the rainy season (Manna *et al.,* 2017; Lerner,2020).

Hydraulically, the groundwater flow direction is predominantly southeast to northwest, with some minor flow paths trending northeast to southwest depending on local structural controls (El-Rayes *et al.,*2017; Inbar *et al.,* 2019). The generally shallow water table in the unconfined zones ranges from 3 to 15 meters below the ground surface, while boreholes tapping the confined aquifer reach depths of 30 to 100 meters.

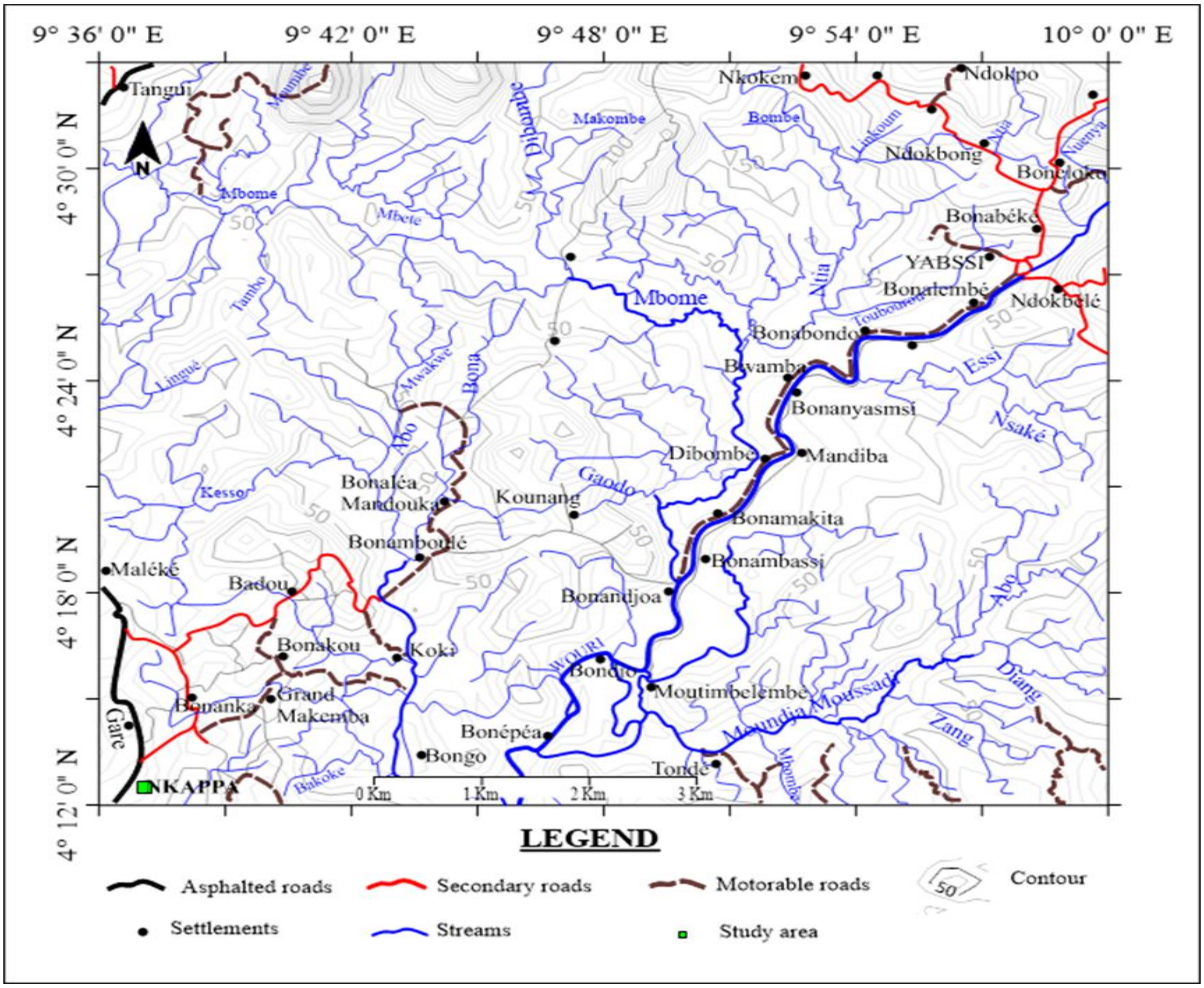

Figure 2: Drainage Map of the Study Area

2.2 Geology of the Study Area

The geology of the study area, located in the northern part of the Douala Basin in Cameroon, reflects a complex sedimentary history shaped by tectonic and depositional processes associated with the opening of the South Atlantic Ocean during the breakup of Gondwana in the Late Jurassic to Early Cretaceous (Mfayakouo *et al.,*2021; Tchouatcha *et al.,* 2023) (Fig 3). The

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Journal of Environmental and Geographical Studies
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Vol.4, Issue 2, pp 11 – 33, 2025

Douala Basin, a classic passive margin basin, contains a thick sedimentary succession ranging from Aptian to Quaternary age, with deposits reaching thicknesses exceeding 5000 meters in some locations (Nlend, 2019; Mfayakouo *et al.,*2021; Tchouatcha *et al.,* 2023). The stratigraphic sequence in the study area includes six key lithostratigraphic formations: Mundeck, Logbaba, Nkappa, Souellaba, Matanda, and Wouri, each reflecting different depositional environments and geological ages.

The Mundeck Formation, the oldest unit in the basin, consists of Aptian-age fluvio-deltaic sandstones, conglomerates, and claystones, unconformably overlying the Precambrian metamorphic basement (Fig. 4). It often acts as a basal aquifer where it is exposed or lies close to the surface (Kwankam *et al.,* 2021). Overlying it is the Cenomanian–Turonian Logbaba Formation, composed predominantly of marine shales, siltstones, and calcareous sandstones, representing a major marine transgression. This unit generally acts as a confining layer due to its fine-grained nature. The overlying Nkappa Formation is of Paleocene to Early Eocene age and is the most hydrogeologically significant unit in the study area (Abine, 2024). It comprises fine to medium-grained quartz-rich sandstones interbedded with marine shales and silts, deposited in transitional environments ranging from deltaic to shallow marine systems. These sandstones exhibit high porosity and moderate to high permeability, making the Nkappa Formation the principal aquifer system in the region. The intercalated shales function as aquitards, offering protection against vertical contamination and supporting a semi-confined aquifer system exploited through deep boreholes (Koah Na Lebogo *et al.,* 2021).

Above the Nkappa Formation lies the Souellaba Formation, of Oligocene age, characterized by deeper marine deposits such as marls, calcareous sandstones, and ferruginous limestones (Wotanie, *et al.,* 2024) (Fig 4). Due to the predominance of marl and carbonate cementation, its aquifer potential is limited, although it can act as a leaky aquitard in localized settings (Zheng *et al.,* 2021). The Miocene-age Matanda Formation follows, comprising alternating shales and coarse sands, sometimes interbedded with basaltic flows linked to volcanic activity from Mount Cameroon. While this formation occasionally shows localized aquifer potential due to its sandy layers, it is generally less significant in the N'Kappa area due to its limited thickness and surface extent.

The youngest unit, the Wouri Formation, spans the Plio-Quaternary and is composed mainly of alluvial sands, gravels, lateritic soils, and organic-rich clays deposited through fluvial and coastal processes (Fig. 4). This formation supports the shallowest aquifer systems, widely used by hand-dug wells and shallow boreholes. However, the Wouri aquifer is highly vulnerable to contamination from surface sources, including domestic and agricultural waste, and is subject to seawater intrusion due to its proximity to the Wouri estuary and the Atlantic Ocean (Wirmvem *et al.,* 2015; Tchakam Kamtchueng *et al.,*2022). Compared to this shallow system, the deeper Nkappa aquifer offers significantly more reliable groundwater quality and yield, demonstrated by lower nitrate concentrations and more stable isotopic signatures (Kwankam *et al.,* 2021).

The Douala Basin has undergone multiple phases of tectonic deformation, particularly during the Late Cretaceous and Tertiary, resulting in the development of faults, fractures, and gentle folds that influence groundwater movement. Fault-controlled recharge zones and lineament intersections often correspond with areas of enhanced borehole yield, suggesting that tectonic

Journal of Environmental and Geographical Studies
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Vol.4, Issue 2, pp 11 – 33, 2025

structures may enhance vertical permeability and facilitate deep infiltration of meteoric water (Djeuda-Tchapnga *et al.,* 2001; Njoh *et al.,* 2020; Olaka *et al.,*2022).

These tectonic features also define the basin's stratigraphic configuration and control the geometry and continuity of aquifer units. In the N'Kappa area, buried fault zones may serve as preferential flow paths, potentially influencing the spatial isotopic variability of groundwater.

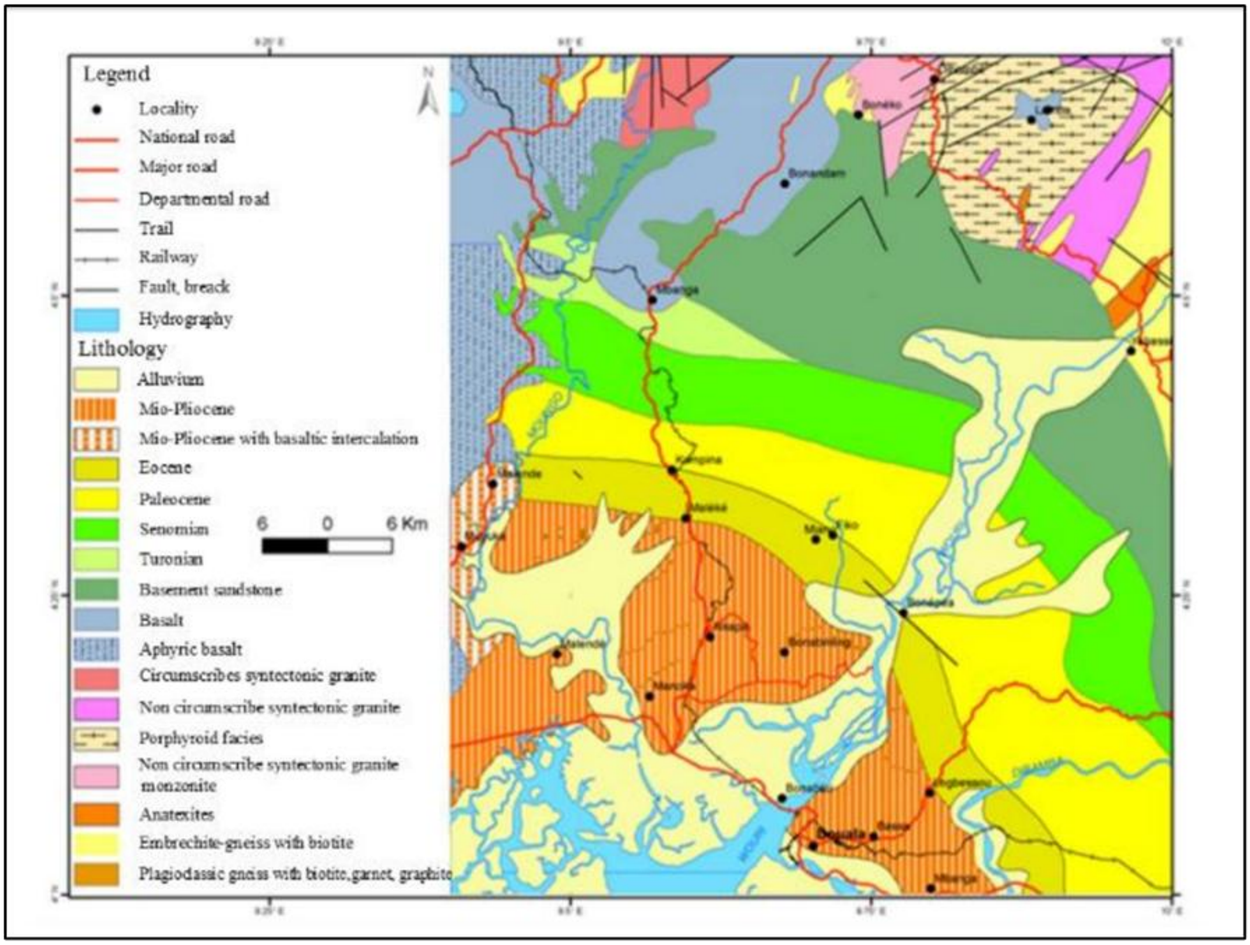

Figure 3: Geologic Map of the Study Area Showing the Different Rock Types (Anzeuga *et al.*, 2017)

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Vol.4, Issue 2, pp 11 – 33, 2025

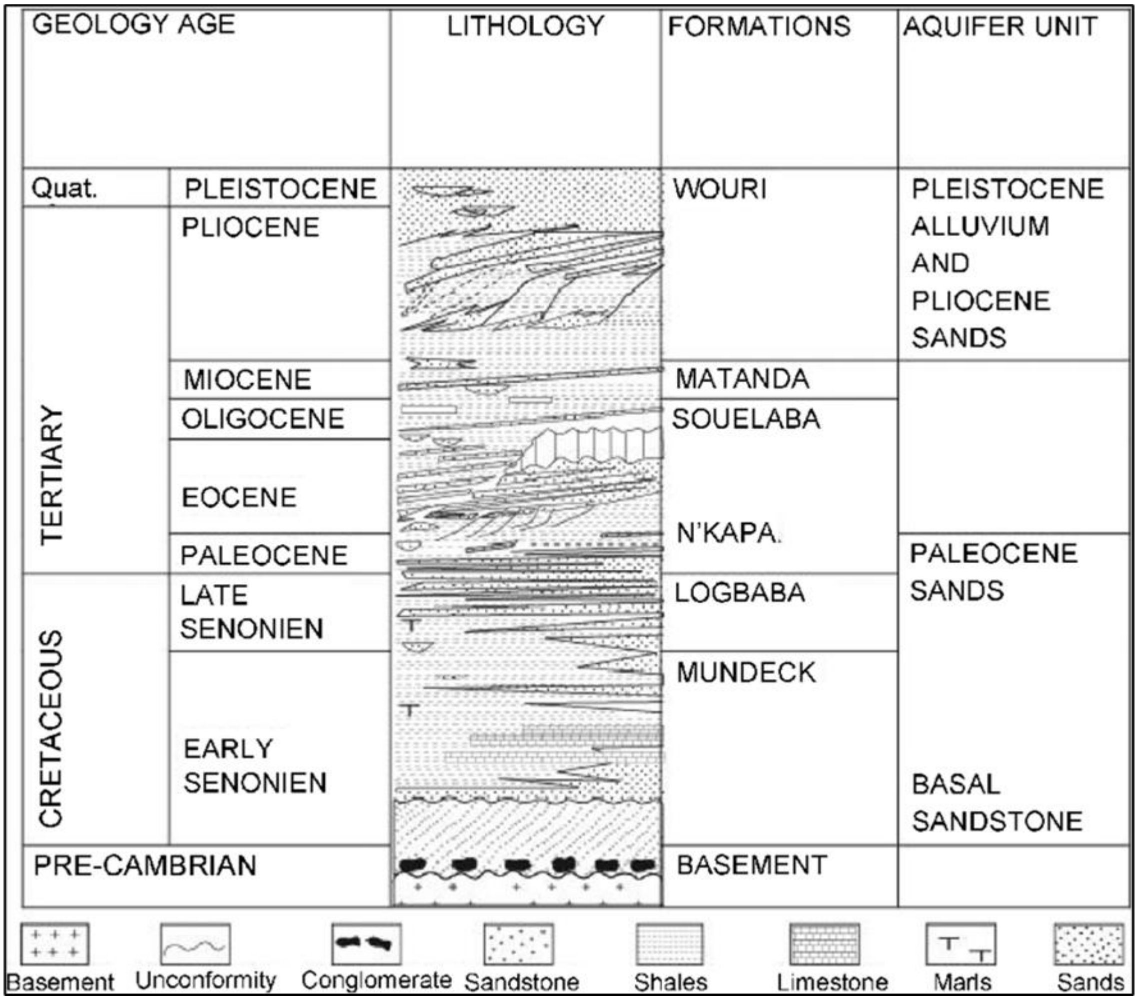

Figure 4: Chronostratigraphic Column of the Douala Basin Showing the Four Major Aquifer Units (Regnoult, 1986; Manga, 2008).

3.0 MATERIALS AND METHODS

Groundwater samples were collected from 20 boreholes distributed across the study area. Before sampling, each borehole was purged for approximately 10–15 minutes, or until field parameters such as temperature, pH, and electrical conductivity (EC) stabilized, ensuring that the sample collected represented groundwater from the aquifer and not stagnant water in the well casing. Water samples were collected in high-density polyethylene (HDPE) bottles with tight-fitting screw caps. For isotope analysis, bottles were filled to prevent headspace, minimizing atmospheric exchange and isotopic fractionation.

Field parameters, including pH, EC, total dissolved solids (TDS), temperature, and oxidation-reduction potential (ORP) were measured in situ using a multi-parameter HANNA HI 98128 portable water quality meter. Borehole coordinates and elevation data were recorded using a Garmin handheld GPS receiver, with an average location accuracy of ±3 meters and vertical accuracy within ±10 meters. All measurements were taken following standard field protocols outlined by the American Public Health Association (APHA, 2017) and the IAEA (2006).

Journal of Environmental and Geographical Studies
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3.1 Isotope Analysis ($\delta^{18}O$ and $\delta^{2}H$)

The determination of stable isotope ratios of oxygen-18 ($\delta^{18}O$) and deuterium ($\delta^{2}H$) was performed at the Meteorological Research Institute and Ohba Laboratory, Department of Chemistry, Tokai University, Japan. The analysis was conducted using Cavity Ring-Down Spectroscopy (CRDS), a technique known for high precision, rapid throughput, and minimal sample preparation.

The specific instrument used was a Picarro L2140-i CRDS Analyzer, capable of measuring $\delta^{18}O$ and $\delta^{2}H$ in water vapor with precision better than ±0.1‰ for $\delta^{18}O$ and ±0.5‰ for $\delta^{2}H$. Water samples were first vaporized, and the resulting vapor passed through a high-precision optical cavity, where absorption at specific wavelengths was measured to derive isotopic ratios. Each sample was measured in triplicate, and internal laboratory standards calibrated against Vienna Standard Mean Ocean Water (VSMOW) and Standard Light Antarctic Precipitation (SLAP) were used for quality assurance. Isotopic results are expressed in delta (δ) notation in parts per thousand (‰), calculated relative to the VSMOW reference standard using the equation:

$$\delta = \left(\frac{R_{\text{sample}} - R_{\text{VSMOW}}}{R_{\text{VSMOW}}} \right) \times 1000 \quad \text{…………………...………………………….. (1)}$$

where R is the ratio of heavy to light isotopes. Data quality was ensured by repeating 10% of the samples and confirming that deviations remained within the analytical uncertainty range. Blanks and duplicates were routinely analyzed alongside samples to check for contamination or memory effects.

3.2 Quality Control and Limitations

To ensure analytical reliability, all isotope measurements adhered to internationally recognized standards for sample handling, storage, and instrument calibration. Samples were stored in cool, dark environments before analysis and transported using insulated containers to minimize temperature-induced fractionation.

Limitations of the study include the seasonal constraint of sampling (conducted only at the end of the rainy season), which may not capture full isotopic variability across the hydrological year.

4.0 RESULTS AND DISCUSSION

4.1 Groundwater Recharge Mechanism

The isotopic analysis of groundwater samples of the study area reveals valuable insights into the local recharge mechanisms and moisture source conditions. The $\delta^{18}O$ values range from –3.61 to –2.73 ‰, and $\delta^{2}H$ values range from –12.8 to –4.7 ‰, indicating a narrow spread in isotopic composition (Kabaghe *et al.,* 2024). This relative homogeneity suggests that the recharge water is derived primarily from a consistent meteoric source, most likely regional rainfall. The d-excess values, which range from 12.96 to 17.13 ‰ (with a mean of 15 ‰), are notably higher than the global average of approximately 10 ‰, pointing to marine-sourced precipitation under high humidity and low kinetic fractionation conditions (Dansgaard, 1964; Gat, 1996; Jasechko,2019). These elevated d-excess values are characteristic of moisture originating from the Atlantic Ocean

Journal of Environmental and Geographical Studies
ISSN 2958 - 4116 (Online)
Vol.4, Issue 2, pp 11 – 33, 2025

and transported inland by humid air masses, consistent with Cameroon's coastal climatology (Emvoutou *et al.,* 2024).

Table 1: Summary Statistics of Stable Isotope Composition in Groundwater Samples in the Study Area

Location	Sample number	Δ^{18}o (‰)	Δ^{2}h (‰)	D-excess (‰)
Muyenge quartier	Bh01	-2.73	-7.4	14.40
Muyenge quartier	Bh02	-2.76	-8.6	13.52
Muyenge quartier	Bh03	-2.79	-9.3	12.96
Muyenge quartier 1	Bh04	-3.03	-9.6	14.69
Muyenge quartier2	Bh05	-3.19	-8.8	16.77
Muyenge quartier 5	Bh06	-3.03	-9.0	15.18
Bonaleya dernier	Bh07	-3.61	-12.2	16.66
Muyenge block 2	Bh08	-3.07	-8.2	16.36
Muyenge block 3	Bh09	-2.73	-4.7	17.08
Mundane	Bh10	-2.74	-8.3	13.63
Carefou smoke	Bh11	-3.19	-9.3	16.17
Mundane	Bh12	-3.28	-10.2	16.02
Nkolo	Bh13	-3.38	-12.8	14.24
Quartier nchang	Bh14	-2.85	-9.1	13.70
Mundane	Bh15	-2.95	-8.8	14.81
Tantion	Bh16	-2.80	-7.8	14.63
Quartier papa etoo	Bh17	-2.92	-10.4	12.97
Quartier papa etoo	Bh18	-3.02	-7.1	17.13
Mundane	Bh19	-2.91	-7.2	16.04
Mundane	Bh20	-3.38	-10.5	16.54
	Min	**–3.61**	**–12.80**	**12.96**
	Max	**–2.73**	**–4.70**	**17.13**
	Mean	**–3.02**	**–8.96**	**15.18**

d-excess = δD - 8 δ^{18}O (Dansgaard 1964),

4.2 Groundwater Isotopes Pattern and Meteoric Water Line Analysis

The Local Meteoric Water Line (LMWL) for the study area, defined by δ2H=8.161δ18O+12.95, exhibits a slight deviation from the Global Meteoric Water Line (GMWL), which is typically described by δ2H=8δ18O+10 (Fig. 5). This observed LMWL slope, being slightly steeper than the GMWL, indicates a well-preserved meteoric signal, suggesting negligible evaporation during groundwater recharge. However, an alternative LMWL defined by δ2H=6.837δ18O+10.04 with an R2 of 0.7881 presents a lower slope. This suggests that some groundwater samples might have experienced minor evaporative enrichment before infiltration, likely influenced by variable seasonal or microclimatic conditions (Wu *et al.,*2017; Kuhlemann *et al.,*2021). A significant observation is that the majority of groundwater samples plot close to or above the GMWL. This clustering implies minimal isotopic fractionation and points to a dominant recharge mechanism:

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ISSN 2958 - 4116 (Online)
Vol.4, Issue 2, pp 11 – 33, 2025

direct infiltration of rainfall. This type of recharge is particularly characteristic of high-intensity convective storm events that are typical of the rainy season in the region (Mafilika,2021; Coffie-Anum *et al.,* 2024).

These interpretations are consistent with findings from other coastal regions in Cameroon. For instance, in the Rio del Rey Basin, groundwater δ18O values range from −3.81 to −2.52‰, and associated d-excess values are similarly elevated (Table 2). This strongly suggests that recharge in this basin predominantly occurs from Atlantic-sourced rainfall with minimal soil evaporation (Wotany *et al.,* 2021). The recharge in this coastal area is concentrated during the major rainy season, a period characterized by high humidity and rapid infiltration. In contrast, inland areas like the Ndop Plain exhibit a broader isotopic range (δ18O from −6.8 to −2.1‰) and more variable d-excess values (Wirmvem *et al.,* 2014). This broader range reflects the influence of factors such as elevation, seasonal differences, and more complex recharge dynamics that involve both diffuse infiltration and evaporation (Gnann *et al.,*2025).

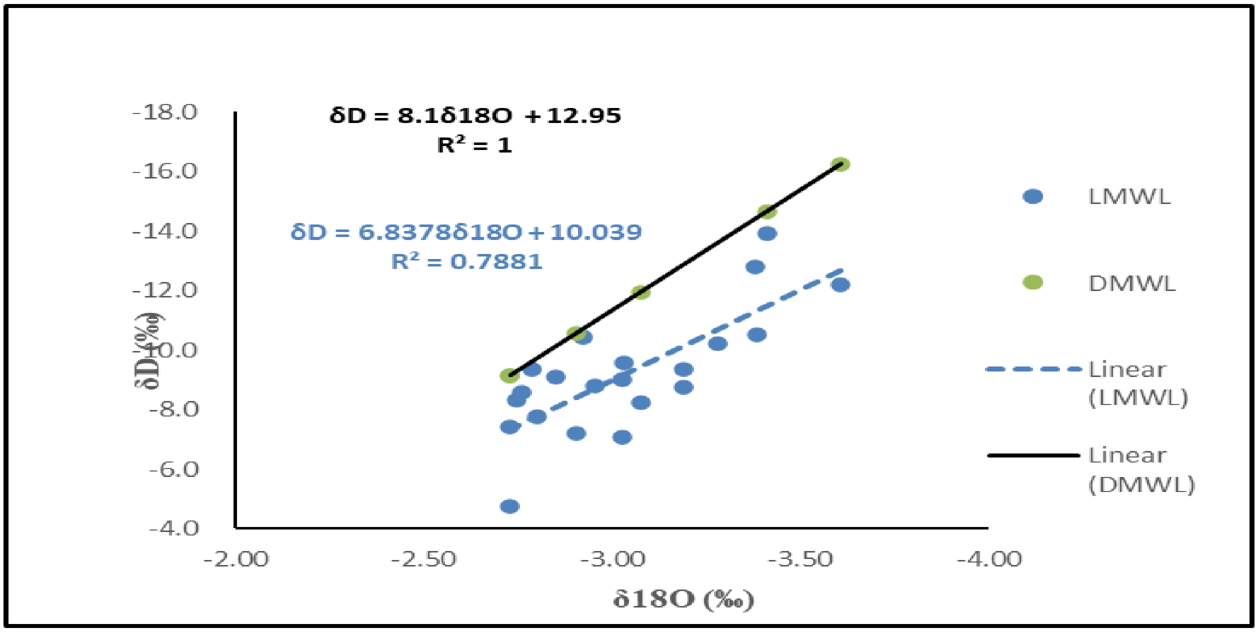

Figure 5: Conventional d[18]O–dD relationships of groundwater in the study area

4.3 Evaporation and d-Excess Signatures

Isotopic characteristics observed in the study area align with findings from other humid tropical regions. For example, studies in the Littoral zone of Cameroon report similar isotopic signatures in groundwater, which plots along or slightly above the GMWL and exhibits high d-excess values (Henry,2021; Nlend *et al.,* 2023). This indicates recharge primarily from marine air masses with limited evaporative influence. In stark contrast, studies in semi-arid environments, such as SW Maharashtra in India, reveal markedly different patterns. Groundwater in these regions shows δ18O values ranging from −6.17 to −3.23‰ and notably lower d-excess values (1.8–8.1‰) (Gopinath *et al.,* 2021; Pandey *et al.,*2023). Such characteristics are indicative of significant evaporation occurring before recharge and shallower infiltration paths, typical of drier conditions. The isotopic evidence from the current study area strongly supports a recharge regime dominated by direct, rapid infiltration of local rainfall with minimal evaporative loss.

This pattern is highly consistent with the region's coastal geographic setting and prevailing humid climatic conditions (Kleine *et al.,* 2020; Zhu *et al.,*2022). The close alignment of groundwater samples with both the DMWL (presumably Local Meteoric Water Line, though it wasn't explicitly defined as DMWL in the previous section) and GMWL, coupled with high d-excess values and a tight δ-distribution, collectively leads to the conclusion that the aquifer is primarily replenished by Atlantic-derived precipitation during high-humidity convective storm periods.

4.4 Climatic and Geographic Influences

The stable isotope composition of groundwater in the study area provides key insights into its hydrological system. We observe a relatively narrow δ18O range (−3.61 to −2.73‰) and δ2H values between −12.8 and −4.7‰ (Mafilika *et al.,* 2021) (Table 3). These values collectively signify a coherent meteoric signature, with limited evidence of evaporative enrichment (Wirmvem *et al.,*2017; Chakraborty *et al.,* 2025). A particularly significant finding is the high deuterium excess (d-excess), which ranges from 12.96 to 17.13‰. This is notably higher than the global average of approximately 10‰ (Dansgaard, 1964; Wei *et al.,* 2023). Such elevated d-excess values strongly suggest that the moisture contributing to groundwater recharge originates primarily from humid marine sources, most likely the Atlantic Ocean. This occurs under conditions of high relative humidity and limited re-evaporation before infiltration (Yusuf *et al.,*2018; Sánchez-Murillo *et al.,* 2020).

The isotopic characteristics of the study area bear strong similarities to groundwater systems found in the Douala Basin of Cameroon (Tchakam Kamtchueng *et al.,*2022; Nlend *et al.,*2023). In Douala, δ18O values range from −4.5 to −2.0‰, with corresponding δ2H values of −28 to −10‰ and d-excess values between 10 and 14‰. These figures also point towards rapid recharge during the rainy season, driven by convective storms and minimal evaporative loss (Emvoutou *et al.,* 2024). Furthermore, the Local Meteoric Water Line (LMWL) slope in Douala (approximately 7.2) is consistent with meteoric recharge but slightly below the Global Meteoric Water Line (GMWL), indicating minor fractionation, similar to the results obtained in our study area (Durowoju *et al.,* 2019). In contrast, inland regions such as the Ndop Plain in northwestern Cameroon exhibit broader δ18O and δ2H ranges and more variable d-excess values.

This variability reflects the influence of elevation gradients, soil moisture differences, and potential partial evaporation within the unsaturated zone (Wirmvem *et al.,* 2014). For instance, Wirmvem *et al.* (2017) reported δ18O values from −6.8 to −2.1‰ and LMWL slopes below 7 for the Ndop Plain, consistent with fractionation from soil evaporation and more complex recharge dynamics. Similarly, studies in other regions highlight the impact of evaporation: Kumar *et al.* (2020) found δ18O values ranging from −6.17 to −3.23‰ in India with low d-excess values (1.8 to 8.1‰), indicating that groundwater recharge in these areas is significantly affected by pre-infiltration evaporation. Likewise, Salem *et al.* (2022) observed δ18O values from −6.5 to −3.0‰ in Egypt's Nile Delta, with low d-excess and LMWL slopes less than 7.0, suggesting evaporative losses and anthropogenic influences like irrigation return flows.

Table 3: Comparative Isotopic Characteristics and Recharge Mechanisms of Groundwater in Nkappa and Other Regions

Study Location	$\delta^{18}O$ (‰)	$\delta^{2}H$ (‰)	d-excess (‰)	LMWL	Recharge Mechanism
Nkappa(this study)	–3.61 to –2.73	–12.8 – 4.7	12.96-17.13	6.84	Direct meteoric recharge from Atlantic rainfall
Douala Basin (Emvoutou et 2024)	–4.5 to –2.0	–28 to – 10	10–14	~7.2	Rapid recharge during rainy season, coastal Atlantic influence
Rio del Rey Basin (Wotany *et al.,*2021)	–3.81 to –2.52	–24 to – 10	12–16	~8.0	Dominantly meteoric recharge during wet season
Ndop Plain (Wirmvem *et al.,* 2017)	–6.8 to –2.1	–48 to – 12	8–14	<7.0	Diffuse recharge, altitude-driven variability
Yaoundé Region (Ngoupayou *et al.,*2020)	–5.5 to –2.5	–35 to – 15	9–12	~7.0	Combination of local meteoric recharge and minor evaporation
SW India (Biswas *et al.,*2017)	–6.17 to –3.23	–40 to – 20	1.8–8.1	<7.0	Evaporative recharge before infiltration

4.5 Implications for Future Water Management

The isotopic evidence gleaned from groundwater samples in the study area carries significant implications for future water resource management in the region (Ahmed *et al.,* 2022; Ren *et al.,* 2024). The consistently narrow δ18O (−3.61 to −2.73‰) and δ2H (−12.8 to −4.7‰) ranges, coupled with elevated d-excess values (13–17.1‰), strongly indicate a recharge system dominated by direct infiltration of marine-derived precipitation with minimal evaporative enrichment. This suggests that groundwater in the study area is rapidly recharged during high-intensity rainfall events typical of the coastal humid zone, likely occurring during the major rainy season from June to August (Wang *et al.,*2015; Acworth *et al.,* 2021). Consequently, water resource managers can view this aquifer as relatively resilient under current climatic conditions, with a steady recharge mechanism that can support sustainable extraction, at least for the next decade.

However, the recharge system of the study area is inherently climate-sensitive. Changes in rainfall patterns due to global climate change, such as shortened rainy seasons, more erratic convective storms, or lower humidity during rainfall events, could disrupt this delicate recharge balance. A reduction in high-humidity, Atlantic-derived precipitation would likely lead to lower d-excess values and reduced recharge rates, thereby threatening long-term groundwater availability (Keesari *et al.,* 2020; Esquivel-Hernández *et al.,* 2022). This underscores the critical importance of integrating stable isotope monitoring into long-term water management frameworks as a vital tool to detect early signs of climatic shifts affecting recharge.

Furthermore, the study area's proximity to the Atlantic coast and its reliance on marine air masses for recharge highlight a vulnerability to overextraction, particularly near the coastline. If abstraction rates exceed natural recharge, the aquifer may face saltwater intrusion, a phenomenon well-documented in other coastal aquifers across West and Central Africa (Chacha,2020; Edet,2021; Wotany *et al.,* 2021). Preventing such outcomes necessitates robust regulation of borehole drilling, restriction of pumping rates in vulnerable zones, and prioritization of water conservation strategies.

The observed isotopic homogeneity suggests that the groundwater body is relatively well-mixed and likely young, characterized by limited residence time and minimal stratification (Hathaway,2021; Cole & Boutt,2021). This can be advantageous for managing a reliable and quickly replenished water supply. However, it also implies that contaminants from surface activities (such as agriculture, septic systems, or industrial effluents) can rapidly reach and affect the aquifer (Sarker *et al.,* 2022). Therefore, future water management policies must prioritize the protection of recharge zones, enforce stringent land-use controls, and promote community education on pollution prevention (Makanda *et al.,* 2022; Hassan *et al.,* 2024). Future water management must comprehensively consider this climatic sensitivity, the inherent risk of saltwater intrusion, and the potential for rapid contamination (Mishra & Tiwari,2023; Davamani *et al.,*2024). A shift toward Integrated Water Resource Management (IWRM) that incorporates isotopic monitoring, policy enforcement, and public engagement is essential to ensure sustainable groundwater use in the study area and similar coastal environments across Cameroon (Tang & Adesina,2022; Banso *et al.,* 2023)

5.0 CONCLUSION

This study provides a robust isotopic assessment of groundwater recharge dynamics within the N'Kappa Coastal Aquifer, Douala Basin, Cameroon. Our analyses of δ18O and δ2H reveal a narrow isotopic range (−3.61 to −2.73‰ for δ18O; −12.8 to −4.7‰ for δ2H) coupled with consistently elevated d-excess values (12.96 to 17.13‰). These signatures collectively indicate a dominant recharge mechanism characterized by direct infiltration of Atlantic-derived precipitation under humid conditions, with minimal evaporative modification. The derived Local Meteoric Water Line (LMWL: δ2H=8.161δ18O+12.95) closely aligns with the Global Meteoric Water Line, further reinforcing the prevalence of meteoric recharge and negligible post-infiltration isotopic fractionation. Isotopic homogeneity across samples supports the inference of a young, rapidly replenished aquifer system with relatively short residence times. These isotopic patterns are consistent with those observed in similar humid coastal aquifers across Cameroon, such as in the Douala Basin and the Rio del Rey Basin.

Our findings underscore the critical dependence of this aquifer system on prevailing climatic variables, particularly rainfall intensity and high relative humidity associated with marine air masses. This highlights the potential vulnerability of groundwater resources to projected climate change scenarios, which could alter precipitation patterns and humidity regimes. Moreover, the young and well-mixed nature of the aquifer, while advantageous for rapid replenishment, implies an increased susceptibility to surface contamination. From a water resource management perspective, these results strongly advocate for the integration of stable isotope monitoring into regional groundwater governance frameworks. Such monitoring will serve as an essential tool for the early detection of shifts in recharge dynamics caused by climatic variability or anthropogenic pressures.

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Based on robust isotopic evidence, enhancing groundwater sustainability in the N'Kappa Coastal Aquifer requires integrating continuous isotopic monitoring to track recharge dynamics and provide early warnings for climate-induced shifts affecting replenishment. Concurrently, it is crucial to delineate and rigorously protect critical recharge zones through stringent land-use policies to mitigate surface contamination and safeguard water quality. Ultimately, advocating for comprehensive Integrated Water Resource Management (IWRM) that combines scientific monitoring, robust policy implementation, and extensive community engagement is essential for sustainable groundwater use and protection against overextraction in this coastal environment.

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Ethics approval and consent to participate

All procedures were performed by the ethical standards of the institutional committee.

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Available at any time upon request

Conflict of interest

The authors declare no conflict of interest

Authors contributions statement

Dr. Engome Regina, Virgine Ajindong Ebia, Ayuk Valery Takang, Ngai Nfor Jude, Mbalang Betrand Kimbi and Mbu God Promise contributed to conceptualization, methodology, formal analysis, resource allocation, and the preparation of the original draft. The authors have reviewed and sanctioned the final version of the material for publication.

REFERENCES

Abine, R E. (2024). *Sustainability of groundwater resources in urban areas in cameroon: challenges and management opportunities* (doctoral dissertation, ghent university).

Acworth, R. I., Rau, G. C., Cuthbert, M. O., Leggett, K., & Andersen, M. S. (2021). Runoff and focused groundwater-recharge response to flooding rains in the arid zone of Australia. *Hydrogeology Journal*, *29*(2), 737-764.

Ahmed, M., Chen, Y., & Khalil, M. M. (2022). Isotopic composition of groundwater resources in arid environments. *Journal of Hydrology*, *609*, 127773.

Ako, A. A., Shimada, J., Hosono, T., Ichiyanagi, K., Nkeng, G. E., Eyong, G. E. T., & Roger, N. N. (2012). Hydrogeochemical and isotopic characteristics of groundwater in Mbanga, Njombe and Penja (Banana Plain)–Cameroon. *Journal of African Earth Sciences*, *75*, 25-36.

Amanambu, A. C., Obarein, O. A., Mossa, J., Li, L., Ayeni, S. S., Balogun, O., ... & Ochege, F. U. (2020). Groundwater system and climate change: Present status and future considerations. *Journal of Hydrology*, *589*, 125163.

Angengo, J. H. (2020). *Structure and Stratigraphy of the Bogal Inversion Zone, Anza Basin, Kenya: implications for the Petroleum System University of Nairobi* (Doctoral dissertation, University of Nairobi).

APHA. (2017). *Standard Methods for the Examination of Water and Wastewater* (23rd ed.). American Public Health Association, American Water Works Association, and Water Environment Federation.

Asinya, E. A., & Alam, M. J. B. (2021). Flood risk in rivers: climate-driven or morphological adjustment. *Earth Systems and Environment*, *5*(4), 861-871.

Baijjali, W., Clark, I. D., & Fritz, P. (1997). The artesian thermal groundwaters of northern Jordan: insights into their recharge history and age. *Journal of Hydrology*, *192*(1-4), 355-382.

Banerjee, D., & Ganguly, S. (2023). A review of the research advances in groundwater–surface water interaction with an overview of the phenomenon. *Water*, *15*(8), 1552.

Banso, A. A., Olurin, J. O., Okem, E. S., & Ogunjobi, O. A. (2023). Integrated water resource management in South West Nigeria: A comprehensive review of strategies and outcomes. *International Journal of Applied Research in Social Sciences*, *5*(8), 330-351.

Biswas, H., Sena, D. R., Kumar, G., Lakaria, B. L., Raizada, A., Kumar, S., & Mishra, P. K. (2017). Effect of water storage structures on groundwater recharge in India. *Groundwater for Sustainable Development*, *4*, 49-56.

Blunden, J., Hartfield, G., Arndt, D. S., Dunn, R. J. H., Tye, M. R., Blenkinsop, S., ... & JACOBS, S. (2018). State of the Climate in 2017. *Bulletin of the American Meteorological Society*, *99*(8), Si-S310.

Boum-Nkot, S. N., Nlend, B., Komba, D., Ndondo, G. N., Bello, M., Fongoh, E. J., ... & Etame, J. (2023). Hydrochemistry and assessment of heavy metals groundwater contamination in an industrialized city of sub-Saharan Africa (Douala, Cameroon). Implications on human health. *HydroResearch*, *6*, 52-64.

Ceccatelli, M. (2020). Integrated hydrologic and hydrogeologic modelling for basin-scale subsidence analysis.

Chacha, N. (2020). Assessment of groundwater abstraction and hydrogeochemical investigation in Arusha city, northern Tanzania.

Chakraborty, S., Sarkar, A., Datye, A., Praveen, V., Deb Burman, P. K., Shivamurthy, Y., ... & Sharma, A. (2025). Precipitation isotopes and monsoon dynamics in the core monsoon zone of India. *Scientific Reports*, *15*(1), 6761.

Cheo, A. E., Ibrahim, B., & Tambo, E. G. (2022). Groundwater resources development for livelihoods enhancement in the Sahel Region: A case study of Niger. In *Groundwater for Sustainable Livelihoods and Equitable Growth* (pp. 25-61). CRC Press.

Coffie-Anum, E., Kuma, J. S., Ewusi, A., & Ganyaglo, S. Y. (2024). Hydrogeochemical evolution and isotopic characteristics of groundwater-surface water interaction processes within the Kawere catchment and its hydrogeotechnical implication on pit slope stability at the Nsuta mine, Ghana. *Groundwater for Sustainable Development*, *26*, 101246.

Cole, A., & Boutt, D. F. (2021). Spatially-resolved integrated precipitation-surface-groundwater water isotope mapping from crowd sourcing: Toward understanding water cycling across a post-glacial landscape. *Frontiers in Water*, *3*, 645634.

Coumou, D., Robinson, A., & Rahmstorf, S. (2013). Global increase in record-breaking monthly-mean temperatures. *Climatic Change*, *118*(3), 771-782.

Dansgaard, W. (1964). Stable isotopes in precipitation. *tellus*, *16*(4), 436-468.

Davamani, V., John, J. E., Poornachandhra, C., Gopalakrishnan, B., Arulmani, S., Parameswari, E., ... & Naidu, R. (2024). A critical review of climate change impacts on groundwater resources: a focus on the current status, future possibilities, and role of simulation models. *Atmosphere*, *15*(1), 122.

Dee, S., Bailey, A., Conroy, J. L., Atwood, A., Stevenson, S., Nusbaumer, J., & Noone, D. (2023). Water isotopes, climate variability, and the hydrological cycle: Recent advances and new frontiers. *Environmental Research: Climate*, *2*(2), 022002.

Durowoju, O. S., Ekosse, G. I. E., & Odiyo, J. O. (2019). Determination of isotopic composition of rainwater to generate local meteoric water line in Thohoyandou, Limpopo Province, South Africa. *Water SA*, *45*(2), 183-189.

Edet, A. (2021). Aquifer characteristics and evidence of saltwater intrusion in coastal groundwater of the Niger Delta (Nigeria) based on historical and recent data. In *Water resources in arid lands: management and sustainability* (pp. 345-366). Cham: Springer International Publishing.

Eisenberg, J. (2012). Geomorphic evolution of the Nyong and Ntem River basins in Southern Cameroon considering neo-tectonic influences. *Landscape Evolution, Neotectonics and Quaternary Environmental Change in Southern Cameroon: Palaeoecology of Africa. Vol. 31. An International Yearbook of Landscape Evolution and Palaeoenvironments*.

El-Rayes, A. E., Arnous, M. O., & Aziz, A. M. (2017). Morphotectonic controls of groundwater flow regime and relating environmental impacts in Northwest Sinai, Egypt. *Arabian Journal of Geosciences*, *10*(18), 401.

Emvoutou, H. C., Ndomè, E. P. E., Diongue, D. M., Ndam, J. R., Stumpp, C., Ketchemen-T, B., ... & Faye, S. (2024). Hydrochemical and isotopic studies providing a new functional model for the coastal aquifers in Douala Coastal Sedimentary Basin (DCSB)/Cameroon. *Science of the Total Environment*, *912*, 169412.

Esquivel-Hernández, G., Sánchez-Murillo, R., Vargas-Salazar, E., & Quesada-Román, A. (2022). Water stable isotopes reveal the hydrological response of Costa Rican glacial lakes to climate variability. *Journal of South American Earth Sciences*, *120*, 104091.

Fantong, W. Y., Kamtchueng, B. T., Ketchemen-Tandia, B., Kuitcha, D., Ndjama, J., Fouepe, A. T., ... & Ohba, T. (2016). Variation of hydrogeochemical characteristics of water in surface flows, shallow wells, and boreholes in the coastal city of Douala (Cameroon). *Hydrological Sciences Journal*, *61*(16), 2916-2929.

Fantong, W. Y., Satake, H., Aka, F. T., Ayonghe, S. N., Asai, K., Mandal, A. K., & Ako, A. A. (2010). Hydrochemical and isotopic evidence of recharge, apparent age, and flow direction of groundwater in Mayo Tsanaga River Basin, Cameroon: bearings on contamination. *Environmental Earth Sciences*, *60*(1), 107-120.

Fongoh, E. J., Celle, H., Nlend, B., Huneau, F., Boum-Nkot, S. N., Takem, G. E., ... & Ntamak-Nida, M. J. (2024). Groundwater quality constraints and new opportunities for water supply from hard rock aquifers in a fast-expanding city of Sub-Saharan Africa, Yaoundé-Cameroon. *Journal of African Earth Sciences*, *212*, 105207.

Gat, J. (2010). *Isotope hydrology: a study of the water cycle* (Vol. 6). World Scientific.

Gat, J. R. (1996). Oxygen and hydrogen isotopes in the hydrologic cycle. *Annual Review of Earth and Planetary Sciences*, *24*(1), 225-262.

Geris, J., Comte, J. C., Franchi, F., Petros, A. K., Tirivarombo, S., Selepeng, A. T., & Villholth, K. G. (2022). Surface water-groundwater interactions and local land use control water quality impacts of extreme rainfall and flooding in a vulnerable semi-arid region of Sub-Saharan Africa. *Journal of Hydrology*, *609*, 127834.

Gnann, S., Baldwin, J. W., Cuthbert, M. O., Gleeson, T., Schwanghart, W., & Wagener, T. (2025). The influence of topography on the global terrestrial water cycle. *Reviews of Geophysics*, *63*(1), e2023RG000810.

Gopinath, G., Resmi, T. R., Pragath, M., Jesiya, N. P., Hameed, A. S., & Deshpande, R. D. (2021). Isotopic differentiation of groundwater recharge processes in a semi-arid region of southern India. *Environmental Earth Sciences*, *80*(16), 522.

Hassan, M. R., Alam, M. D., Haque, M. N., Khan, M. A. Q., & Talukder, M. A. K. (2024). A review of watershed management in Bangladesh: options, challenges and legal framework. *J. Mater. Environ. Sci., 15 (2), 225*, *241*.

Hathaway, J. M. A. H. (2021). *Using stable water isotopes to partition source water contribution and assess spatio-temporal source water dynamics of wetland ecosystems in the eastern Canadian Rocky Mountains* (Doctoral dissertation, University of Waterloo).

Henry, S. (2021). The hydrochemical and isotopic characterization of groundwater in southern Mozambique.

IAEA. (2006). *Collection and preparation of water samples for isotopic analysis*. Technical Document, International Atomic Energy Agency.

Inbar, N., Rosenthal, E., Magri, F., Alraggad, M., Möller, P., Flexer, A., ... & Siebert, C. (2019). Faulting patterns in the Lower Yarmouk Gorge potentially influence groundwater flow paths. *Hydrology and Earth System Sciences*, *23*(2), 763-771.

Jasechko, S. (2019). Global isotope hydrogeology―review. *Reviews of Geophysics*, *57*(3), 835-965.

Jude, N. N., Wotany, E. R., Agyingi, C., & Nelson, M. A. (2024). Geological influence on groundwater quality in volcanic aquifers of Eastern Mount Cameroon, West of the Penda Mboko River. *Discover Applied Sciences*, *6*(10), 541.

Keesari, T., Roy, A., Pant, D., Sinha, U.K., Kumar, P.N., & Rao, L.V. (2020). Major ion, trace metal and environmental isotope characterization of groundwater in selected parts of Uddanam coastal region, Andhra Pradesh, India. *Journal of Earth System Science*, *129*(1), 205.

Khan, A., Rao, L. A., Yunus, A. P., & Govil, H. (2018). Characterization of channel planform features and sinuosity indices in parts of Yamuna River flood plain using remote sensing and GIS techniques. *Arabian Journal of Geosciences*, *11*(17), 525.

Kleine, L., Tetzlaff, D., Smith, A., Wang, H., & Soulsby, C. (2020). Using water stable isotopes to understand evaporation, moisture stress, and re-wetting in catchment forest and grassland soils of the summer drought of 2018. *Hydrology and Earth System Sciences*, *24*(7), 3737-3752.

Koah Na Lebogo, S. P., Bisso, D., Ngo Elogan Ntem, J., & Mvondo Ondoa, J. (2021). Stratigraphic architecture and depositional environment of the Paleocene-Lower Eocene aquifers system (Douala onshore basin, SW Cameroon). *Journal of Petroleum Exploration and Production*, *11*(2), 549-560.

Kuhlemann, L. M., Tetzlaff, D., Smith, A., Kleinschmit, B., & Soulsby, C. (2021). Using soil water isotopes to infer the influence of contrasting urban green space on ecohydrological partitioning. *Hydrology and Earth System Sciences*, *25*(2), 927-943.

Kumar, O., Ramanathan, A. L., Bakke, J., Kotlia, B. S., & Shrivastava, J. P. (2020). Disentangling source of moisture driving glacier dynamics and identification of 8.2 ka event: evidence from pore water isotopes, Western Himalaya. *Scientific reports*, *10*(1), 15324.

Kwankam, F. N., Agyingi, C. M., Foba-Tendo, J., & Suh, C. E. (2021). Geochemistry of sedimentary rocks from the nkapa formation, North Western part of the Douala Basin, Cameroon: implications for provenance, tectonic setting and paleoenvironmental conditions. *International Journal of Geosciences*, *12*(9), 739-762.

Lapworth, D. J., Gooddy, D. C., Kent, F., Heaton, T. H., Cole, S. J., & Allen, D. (2013). A combined geochemical and hydrological approach for understanding macronutrient sources. *Journal of Hydrology*, *500*, 226-242.

Leader, D. P., Krause, S. A., Pandit, A., Davies, S. A., & Dow, J. A. T. (2018). FlyAtlas 2: a new version of the Drosophila melanogaster expression atlas with RNA-Seq, miRNA-Seq and sex-specific data. *Nucleic acids research*, *46*(D1), D809-D815.

Lerner, D. N. (2020). Groundwater recharge. In *Geochemical processes, weathering and groundwater recharge in catchments* (pp. 109-150). CRC Press.

Lewandowski, J., Meinikmann, K., & Krause, S. (2020). Groundwater–surface water interactions: Recent advances and interdisciplinary challenges. *Water*, *12*(1), 296.

Mafilika, S. B. (2021). *Using stable isotopes to understand relative contributions of evaporation and evapotranspiration on groundwater recharge in the Verlorenvlei catchment, west coast, South Africa* (Doctoral dissertation, Faculty of Science, Department of Earth Sciences, Stellenbosch University).

Makanda, K., Nzama, S., & Kanyerere, T. (2022). Assessing the role of water resources protection practice for sustainable water resources management: A review. *Water*, *14*(19), 3153.

Manga, M. (2008). *Groundwater Flow Systems in the Douala Sedimentary Basin, Cameroon*. Unpublished doctoral dissertation.

Manna, F., Walton, K. M., Cherry, J. A., & Parker, B. L. (2017). Mechanisms of recharge in a fractured porous rock aquifer in a semi-arid region. *Journal of Hydrology*, *555*, 869-880.

Mfayakouo, B. C., Ngaha, P. N., & Bitom, D. L. (2021). Age and paleoenvironmental evolution of the Douala Basin (Cameroon) during the Cenozoic: insights from palynology and sequence analysis. *Heliyon*, *7*(12).

Mihret, B., & Wuletaw, A. (2025). The Impact of Geological Structures on Groundwater Potential Assessment in Volcanic Rocks of the Northwestern Ethiopian Plateau: A Review. *EGUsphere*, *2025*, 1-14.

Mishra, V., & Tiwari, V. M. (2023). Climate, hydrology, and water-management challenges for water security in India. *Water Security*, *20*, 100156.

Ngoupayou, J. R. N., Bon, A. F., Mboudou, G. E., & Abdou, N. N. (2020). Hydrogeological Characteristics of Shallow Hard Rock Aquifers. *Groundwater Hydrology*, 1.

Njumbe, E. S. (2004). *The prevalence, distribution, and fate of organic and inorganic contaminants in the Douala drainage basin, SW Cameroon*. The University of Manchester (United Kingdom).

Nlend, B. (2019). *Hydrological processes in a hyper-humid coastal area with strong anthropogenic influences (Douala, Cameroon).: A geochemical study of water dynamics from the atmosphere to the subsurface* (Doctoral dissertation, Université Bourgogne Franche-Comté; Université de Douala).

Nlend, B., Huneau, F., Ngo Boum-Nkot, S., Song, F., Komba, D., Gwodog, B., ... & Fongoh, E. (2023). Review of isotope hydrology investigations on aquifers of Cameroon (Central Africa): What information for the sustainable management of groundwater resources?. *Water*, *15*(23), 4056.

Nzeuga, A. R., Nouayou, R., Enyegue-à-Nyam, F., & Fairhead, J. D. (2017). The use of aeromagnetic data interpretation to characterize the features in the Mamfe sedimentary basin, Cameroon and a part of eastern Nigeria. *Int. J. Sci. Res*, *6*, 2319-7064.

Olaka, L. A., Kasemann, S. A., Sültenfuß, J., Wilke, F. D. H., Olago, D. O., Mulch, A., & Musolff, A. (2022). Tectonic control of groundwater recharge and flow in faulted volcanic aquifers. *Water Resources Research*, *58*(7), e2022WR032016.

Pandey, A., Padhya, V., Ganguly, A., Chakra, S., & Deshpande, R. D. (2023). Surface water groundwater interaction in water-stressed semi-arid western India: Insights from environmental isotopes. *Journal of Arid Environments*, *208*, 104879.

Regnoult, J. M. (1986). *Synthèse géologique du Cameroun*. Document BRGM 125.

Ren, X., Li, P., He, X., & Zhang, Q. (2024). Tracing the sources and evaporation fate of surface water and groundwater using stable isotopes of hydrogen and oxygen. *Science of The Total Environment*, *931*, 172708.

Rinzin, P., Malla, M. K., & Arya, D. S. (2024). Past and future climate variability analysis in Bhutan. *Theoretical and Applied Climatology*, *155*(7), 6213-6239.

Sako, A., & Kafando, S. (2021). Hydrogeochemical and spatial assessment of groundwater quality from basement aquifers in the Central Plateau Region of Burkina Faso, West Africa. *Environmental Earth Sciences*, *80*(9), 358.

Salem, Z. E. S., Elnahrawy, A. M., Abdelrahman, K., Fnais, M. S., & Abu-Alam, T. (2022). Oxygen and hydrogen stable isotopes as recharge indicators, Central Nile Delta Quaternary aquifer, Egypt. *Journal of King Saud University-Science*, *34*(3), 101834.

Sánchez-Murillo, R., Esquivel-Hernández, G., Birkel, C., Correa, A., Welsh, K., Durán-Quesada, A. M., ... & Poca, M. (2020). Tracing water sources and fluxes in a dynamic tropical environment: From observations to modeling. *Frontiers in Earth Science*, *8*, 571477.

Sarker, B., Keya, K. N., Mahir, F. I., Nahiun, K. M., Shahida, S., & Khan, R. A. (2021). Surface and ground water pollution: causes and effects of urbanization and industrialization in South Asia. *Scientific Review*, *7*(3), 32-41.

Shakhashiro, A., Tarjan, S., Ceccatelli, A., Kis-Benedek, G., & Betti, M. (2012). IAEA-447: a new certified reference material for environmental radioactivity measurements. *Applied Radiation and Isotopes*, *70*(8), 1632-1643.

Suchel, JB (1987). *The climates of Cameroon* (Doctoral dissertation, Bordeaux 3).

Sukanya, S., & Joseph, S. (2023). *Environmental radon: a tracer for hydrological studies*. Springer Nature.

Tang, X., & Adesina, J. A. (2022). Integrated watershed management framework and groundwater resources in Africa—a review of the West Africa sub-region. *Water*, *14*(3), 288.

Tchakam Kamtchueng, B., Foupouagnigni, A., Yannah, M., Ndjama, J., Mimba, M. E., Wirmvem, M. J., ... & Ohba, T. (2022). Major ions, trace elements and stable isotope characteristics of shallow groundwater in the Bonaberi district, Douala, Cameroon. *Sustainable Water Resources Management*, *8*(5), 162.

Tchouatcha, M. S., Kouske, A. P., Galal, W. F., Mahmoud, M. S., Sobdjou, C. K., Ngantchu, L. D., ... & Njike Ngaha, P. R. (2023). The Cretaceous of the Cameroon Atlantic Basin (Central Africa): sediment provenance, correlation, paleoenvironment and paleogeographic evolution of the Eastern Proto-Atlantic margin (Central Gondwana). *Environmental Earth Sciences*, *82*(4), 103.

Tume, S. J. P. RAINFALL RELIABILITY IN THE BAMENDA HIGHLANDS AND COASTAL LOWLANDS OF CAMEROON: INSIGHTS FROM NDU AND DOUALA (1957-2016).

Wang, H., Gao, J. E., Zhang, M. J., Li, X. H., Zhang, S. L., & Jia, L. Z. (2015). Effects of rainfall intensity on groundwater recharge based on simulated rainfall experiments and a groundwater flow model. *Catena*, *127*, 80-91.

Wei, H., Wang, J., Li, M., Wen, M., & Lu, Y. (2023). Assessing the Applicability of Mainstream Global Isoscapes for Predicting δ18O, δ2H, and d-excess in Precipitation across China. *Water*, *15*(18), 3181.

Wirmvem, M. J., Ohba, T., Kamtchueng, B. T., Taylor, E. T., Fantong, W. Y., & Ako, A. A. (2017). Variation in stable isotope ratios of monthly rainfall in the Douala and Yaounde cities, Cameroon: local meteoric lines and relationship to regional precipitation cycle. *Applied Water Science*, *7*(5), 2343-2356.

Wirmvem, M. J., Ohba, T., Nche, L. A., Kamtchueng, B. T., Kongnso, W. E., Mimba, M. E., ... & Ako, A. A. (2017). Effect of diffuse recharge and wastewater on groundwater contamination in Douala, Cameroon. *Environmental Earth Sciences*, *76*(9), 354.

Wirmvem, M. J., Ohba, T., Suila, J. Y., Fantong, W. Y., Bate, N. O., Ooki, S., ... & Hell, J. V. (2014). Hydrochemical and isotopic characteristics of groundwater in the Ndop plain, northwest Cameroon: resilience to seasonal climatic changes. *Environmental Earth Sciences*, *72*(9), 3585-3598.

Wohl, E. (2020). *Rivers in the Landscape*. John Wiley & Sons.

Wotanie, L. V., Ngia, N. R., Ayuk, N. E., Anatole, D. L., Esue, M. F., Samuel, A. E., & Agyingi, C. M. (2024). Inorganic geochemistry of Paleogene strata in the N'kapa Formation of the western Douala Basin, Cameroon: implications for provenance and tectonic settings. *Arabian Journal of Geosciences*, *17*(9), 253.

Wotany, E. R., Wirmvem, M. J., Fantong, W. Y., Ayonghe, S. N., Wantim, M. N., & Ohba, T. (2021). Isotopic composition of precipitation and groundwater onshore of the Rio del Rey Basin, southwest Cameroon: local meteoric lines and recharge. *Applied Water Science*, *11*(8), 141.

Wotany, E.R., Egbe Clifford, N., Agyingi, C., Ayuk Valery, T., Ayuk, R., Mengnjo Jude, W., & Ngai N, J. (2024). Hydrogeochemical characterization and water quality assessment in Manjo, Cameroon. *Journal of Discoveries in Applied and Natural Science*, *2*(7), 9-30.

Wu, H., Zhao, G., Li, X. Y., Wang, Y., He, B., Jiang, Z., ... & Sun, W. (2019). Identifying water sources used by alpine riparian plants in a restoration zone on the Qinghai-Tibet Plateau: Evidence from stable isotopes. *Science of the Total Environment*, *697*, 134092.

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Yusuf, M. A., Abiye, T. A., Butler, M. J., & Ibrahim, K. O. (2018). Origin and residence time of shallow groundwater resources in Lagos coastal basin, south-west Nigeria: An isotopic approach. *Heliyon*, *4*(11).

Zheng, L., Nico, P., Spycher, N., Domen, J., & Credoz, A. (2021). Potential impacts of CO2 leakage on groundwater quality of overlying aquifer at geological carbon sequestration sites: A review and a proposed assessment procedure. *Greenhouse Gases: Science and Technology*, *11*(5), 1134-1166.

Zhu, G., Yong, L., Zhao, X., Liu, Y., Zhang, Z., Xu, Y., ... & Wang, L. (2022). Evaporation, infiltration and storage of soil water in different vegetation zones in the Qilian Mountains: a stable isotope perspective. *Hydrology and Earth System Sciences*, *26*(14), 3771-3784.

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