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Application of Stable Isotopes to Investigate Hydrological Processes in Rivers in the Tropical Zones, South-Center, Cameroon

Ayuk Valery Takang[1*], Wotany Engome Regina[1], Wirmverm Mengnjo Jude[2], Agyinyi Christopher[1], Ngai Jude[2], Kimbi Bertrand[1], Muka Boris[1], Mbu God-promise[1]

[1]Department of Geology, Faculty of Science, University of Buea, Cameroon.

[2]Institute of Geological and Mining Research, Yaounde, Cameroon.

[*]Corresponding Author's Email: takangayukvalery@gmail.com

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Abstract

Aim: Surface water remains the primary source of drinking and agricultural supply in the tropical rainforests of South-Centre Cameroon, yet seasonal hydrological processes that govern its availability remain limited. The study examines river recharge mechanisms and water residence time.

Methods: The study used stable isotopes, oxygen-18 ($\delta^{18}O$) and deuterium ($\delta^{2}H$), from 56 river systems sampled in February 2024, the dry season and July 2024, the wet season. Sampling was done along a latitudinal transect from Yaoundé to Manjo and Manjo to the Littoral, covering diverse elevations and hydrological settings. Isotope Ratio Mass Spectrometry (IRMS) was used to measure $\delta^{18}O$ and $\delta^{2}H$, alongside hydrochemical indicators such as total dissolved solids (TDS), chloride, and deuterium excess (d-excess).

Results: The study found a strong seasonal contrast: wet season $\delta^{18}O$ and $\delta^{2}H$ values ranged from -5.22‰ to -2.77‰ and -25.74‰ to -8.68‰, respectively, suggesting direct rainfall recharge. In the dry season, $\delta^{18}O$ values ranged from -4.16‰ to -0.04‰ and $\delta^{2}H$ from -20.82‰ to 0.19‰, with elevated TDS (up to 10,020 mg/L) and lower d-excess, indicating increased evaporation and groundwater input. LMWL-GMWL comparisons confirmed rapid recharge during the wet season and stronger evaporative enrichment in the dry season.

Conclusion: These findings point to shorter residence times in the wet season and longer retention during dry periods, highlighting climate sensitivity in river recharge.

Recommendations: These findings support the need for integrated surface water management, emphasizing protection of recharge areas and implementation of long-term isotopic monitoring. The study offers valuable baseline data for safeguarding surface waters and informs strategies for other vulnerable sources in other regions.

Keywords: *Stable isotopes (^{18}O, ^{2}H), seasonal hydrology, river recharge, isotope ratio mass spectrometry, Central Cameroon*

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INTRODUCTION

The application of stable isotopes, notably oxygen-18 (^{18}O) and deuterium (^{2}H), has gained significance in hydrological research, particularly in tropical areas characterized by intricate hydrological processes (Tweed *et al.,* 2019; Nyamgerel *et al.,* 2021; Peralta Vital *et al.,* 2024). In Cameroon and other tropical regions, these isotopes have proved pivotal in elucidating numerous facets of river hydrology (Nlend *et al.,* 2023). The utilization of stable isotopes in tropical hydrology relies on the notion that various water sources and processes confer unique isotopic fingerprints. The Global Meteoric Water Line (GMWL), defined by the equation $\delta^{2}H = 8 \times \delta^{18}O + 10‰$, serves as a fundamental isotopic reference line for precipitation (Craig 1961; Smith *et al.,* 2021). In tropical climates, local conditions can result in deviations from the GMWL, hence requiring the formulation of Local Meteoric Water Lines (LMWLs). Studies have highlighted the importance of establishing LMWLs to accurately interpret isotopic data in specific regions (Rozanski *et al.,* 1993; Chen *et al.,* 2021).

Both regional and local factors determine the isotopic composition of precipitation in tropical zones notably the "amount effect," which indicates that greater rainfall episodes are generally more isotopically depleted (Dansgaard, 1964; Hollins *et al.,* 2018; Ren *et al.,* 2024). A prominent application of stable isotopes in tropical river hydrology is the identification of water sources. Maréchal *et al.* (2011) employed stable isotopes within the Nyong River basin in Cameroon to distinguish between groundwater and surface water contributions to river flow. Groundwater was the primary source of river water during the baseflow period, while in the rainy season, the contributions from direct precipitation and surface runoff markedly increased. In the adjacent Congo Basin, Spencer *et al.* (2012) and Guenet *et al.,* (2021) employed stable isotopes to ascertain the sources of water in the Congo River and its tributaries. They discerned unique isotopic signals for fluids from various portions of the basin, underscoring the utility of isotopes in extensive hydrological research in tropical areas.

High evaporation rates in tropical climates can substantially influence the isotopic composition of river water (Laonamsai *et al.,* 2022). Gonfiantini (1986) and Bonazza, (2021), provided the theoretical framework for comprehending isotopic fractionation during evaporation. Sigha-Nkamdjou *et al.* (2007) and Nkoue *et al.,* (2021), noted substantial seasonal fluctuations in the isotopic composition of the Sanaga River in Cameroon. During the dry season, the river water exhibited a gradual enrichment of heavy isotopes as a result of evaporation. In contrast, the wet season saw isotopic depletion due to the introduction of isotopically lighter rains (Jiang *et al.,* 2021; Xia *et al.,* 2024).

Regionally, several studies have applied isotope hydrology to understand the dynamics of river systems in Central Africa. For instance, Maréchal *et al.* (2011) used isotopes in the Nyong River Basin to differentiate groundwater and surface water contributions during baseflow and flood seasons. In the Congo Basin, Spencer *et al.* (2012) and Guenet *et al.* (2021) revealed distinct isotopic fingerprints in various tributaries, reflecting heterogeneous moisture sources and landscape controls. Similarly, work in the Sanaga River by Sigha-Nkamdjou *et al.* (2007) and Nkoue *et al.* (2021) demonstrated seasonal isotopic enrichment and depletion due to alternating dominance of evaporation and rainfall input. These studies emphasize the utility of stable isotopes in delineating tropical hydrological processes.

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Stable isotopes have demonstrated their utility in the intricate groundwater-surface water dynamics within tropical river systems. In the Lokoundjé watershed of South Cameroon, Takounjou *et al.* (2011) and Ketchemen-Tandia *et al.,* (2022), used isotopic tracers to measure groundwater contributions to streamflow. Groundwater was identified as essential for supporting baseflow during dry seasons, underscoring the significance of groundwater supplies in preserving regional river ecosystems. Isotopic studies help elucidate water residence durations throughout several compartments of the hydrological cycle. Ó Dochartaigh *et al.* (2016) and Fantong *et al.* (2023) conducted a regional investigation encompassing portions of Cameroon, utilizing stable isotopes alongside other tracers to assess groundwater age and occupancy times. Groundwater age exhibited considerable variation throughout the region, affecting water resource management and susceptibility to contamination. Understanding seasonal river recharge and residence time is critical for managing water resources in regions like Cameroon that are increasingly vulnerable to climate variability. Insights from stable isotope analysis can inform adaptive strategies for water allocation, ecosystem conservation, and drought preparedness. This research also provides valuable scientific evidence to support integrated water policy planning and climate-resilient infrastructure development in tropical river basins.

While previous studies have focused on groundwater systems in other Cameron there is a lack of comprehensive research on how seasonal variations, evaporation, and groundwater contributions influence river recharge and water residence time along rivers in the tropical zones in Central Cameroon. This research fills this gap by utilizing stable isotopes ($\delta^{18}O$ and δ^2H) to 1) analyze hydrological processes, 2) assess seasonal water dynamics, and 3) provide insights into sustainable water resource management under changing climatic conditions.

Geographical Position, Meteorological Conditions, and Hydrological Systems

This study covers a region stretching from Yaoundé to Manjo in Central and parts of Littoral Cameroon, encompassing a variety of ecological and geological settings within the tropical rainforest belt. The study area lies between longitudes 9.75422°E and 13.62648°E and latitudes 4.55267°N and 4.84945°N (WGS 84), covering both urban and peri-urban zones, upland watersheds, and lowland floodplains. The elevation across the region ranges from approximately 518 meters in Manjo to over 1,600 meters in areas such as Bangoua and Matazem, reflecting diverse topographical and climatic gradients. Stable temperatures ranging from 15°C to 22°C foster a pleasant climate. Due to recent climate change, the study area's four-month dry season, occurring from mid-November to mid-March, can occasionally attain 28°C. The eight-month precipitation period extends from mid-March to mid-November. The annual average precipitation in the study area is approximately 2000 mm. Laterites are generally formed when crystalline rock undergoes fracturing (Neba,1999; Van der Waarde *et al.,* 2007).

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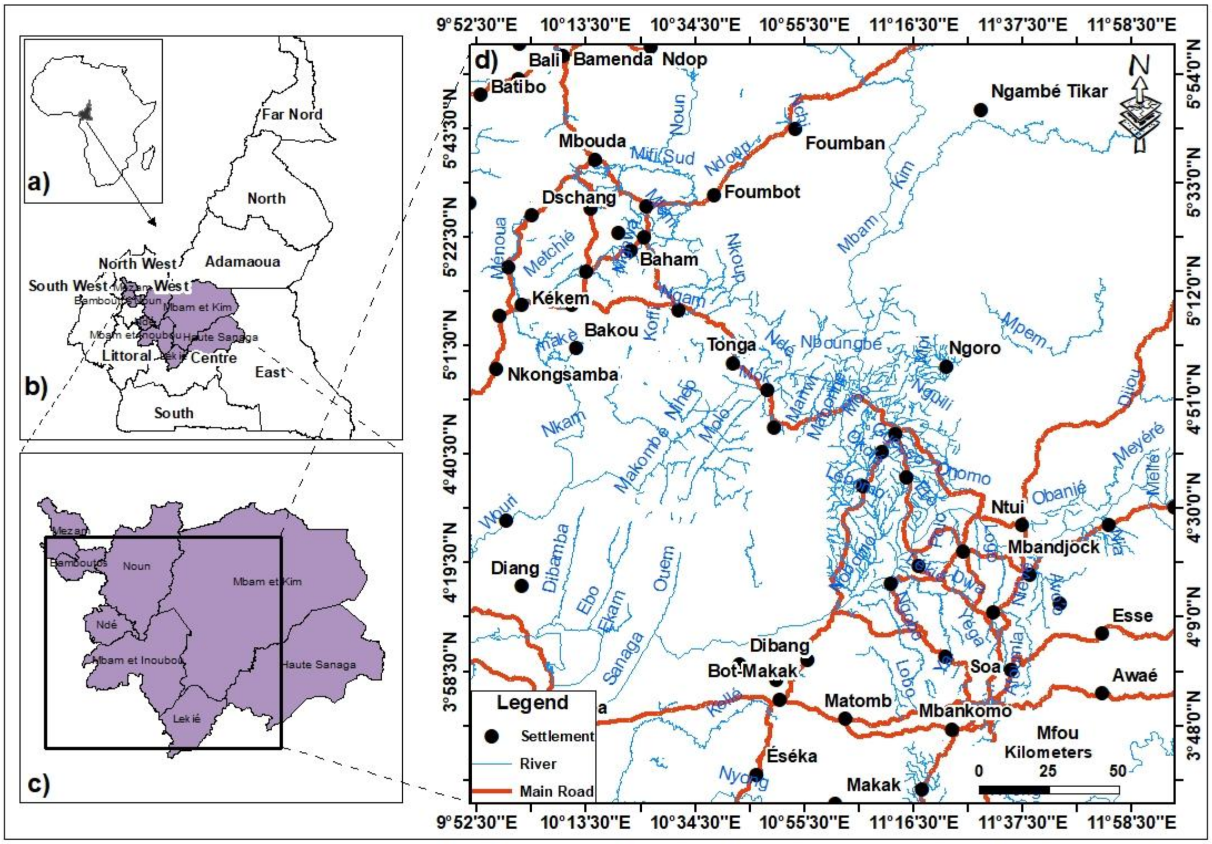

Figure 1. Location Map of the Study Area in Central Cameroon, Stretching from Yaoundé to Manjo. It Shows the Distribution of Sampled River Systems, Including Major Rivers Like the Sanaga, Nyong, and Wouri, and Smaller Tributaries.

Adapted from Maréchal et al., 2011).

Geology

The geological basement of Yaoundé consists of gneisses and migmatites. The rocks within these formations are classified as meta-plutonic, orthogneiss, metasedimentary, or paragneiss (Fig 2). This final group constitutes the foundation of the Olezoa watershed. Granite and trachyte are penetrated by underlying rocks, including migmatites and worn, fractured gneisses (Sato *et al.,* 1990; Marclin *et al.,* 2023). The foundation of the plain comprises cinder cones, pyroclastic surge deposits, and predominantly alkaline basaltic lavas, indicative of Quaternary volcanic activity (Makilo *et al.,* 1999; Rouwet *et al.,* 2021). As the most recent geological development, Alluvial deposits predominantly consist of arenaceous and argillaceous soils frequently located parallel to river systems. The study region contains multiple Cenozoic volcanoes and crater lakes. In regions underlain by orthogneiss and metaplutonic formations, permeability is largely governed by the density and interconnectivity of fractures, which influence groundwater contributions to river baseflow, particularly during the dry season, a pattern reflected in enriched isotope values (Fantong *et al.,* 2023; Ketchemen-Tandia *et al.,* 2022). Along river valleys, recent alluvial deposits composed of alternating sand and clay layers form unconfined aquifers that support rapid recharge

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and shallow subsurface mixing, often serving as transition zones where isotopic signatures are modified (Makilo *et al.,* 1999).

Volcanic zones in the western part of the study area, particularly near Bangoua and Manjo, are characterized by basaltic lavas, pyroclastic flows, and cinder cones associated with Quaternary activity (Rouwet *et al.,* 2021). These formations exhibit high porosity and transmissivity, facilitating quick infiltration of rainfall and enhancing aquifer recharge potential. The vesicular texture of the basalts and their permeability allow for rapid isotopic exchange between surface and subsurface waters, contributing to spatial variability in $\delta^{18}O$ and $\delta^{2}H$ values observed across catchments.

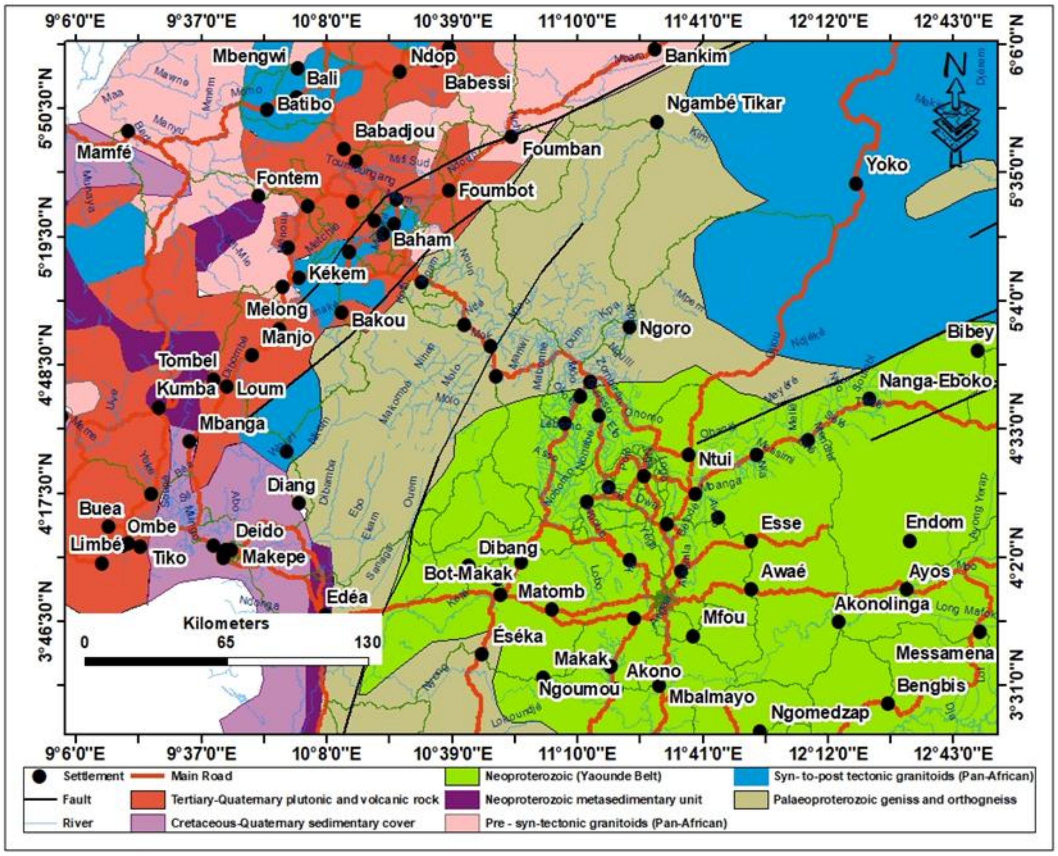

Figure 2. Geology Map of the Study Area

Hydrology

Hydrologically, the study area is characterized by a combination of perennial and seasonal rivers (Fig 3), with surface water availability varying significantly between the wet and dry seasons. The Sanaga River, originating from the Adamawa Plateau, plays a dominant role in regional water dynamics, with its numerous tributaries feeding into downstream reservoirs and lakes. The Nyong River basin exhibits a strong influence from both surface runoff and groundwater inputs (Maréchal *et al.,* 2011). Groundwater resources are essential for sustaining river baseflows during the dry season. Takounjou *et al.,* (2011) indicate that groundwater contributions are significant in

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maintaining perennial flow in smaller tributaries, particularly in fractured and porous rock formations. The hydrological balance between surface water and groundwater is influenced by seasonal precipitation patterns, evapotranspiration rates, and human activities, including water abstraction for agriculture and industry (Ó Dochartaigh *et al.,* 2016). Spatially, the distribution of surface water bodies highlights areas of high hydrological connectivity, where rivers, lakes, and wetlands act as integrated systems regulating water availability. Recent studies emphasize the need for continuous monitoring and sustainable water management practices to mitigate the impacts of climate change and anthropogenic activities on the hydrological cycle (Nyenje & Batelaan, 2009; Douville *et al.,* 2021; Ehtasham *et al.,* 2024; Guan *et al.,* 2024).

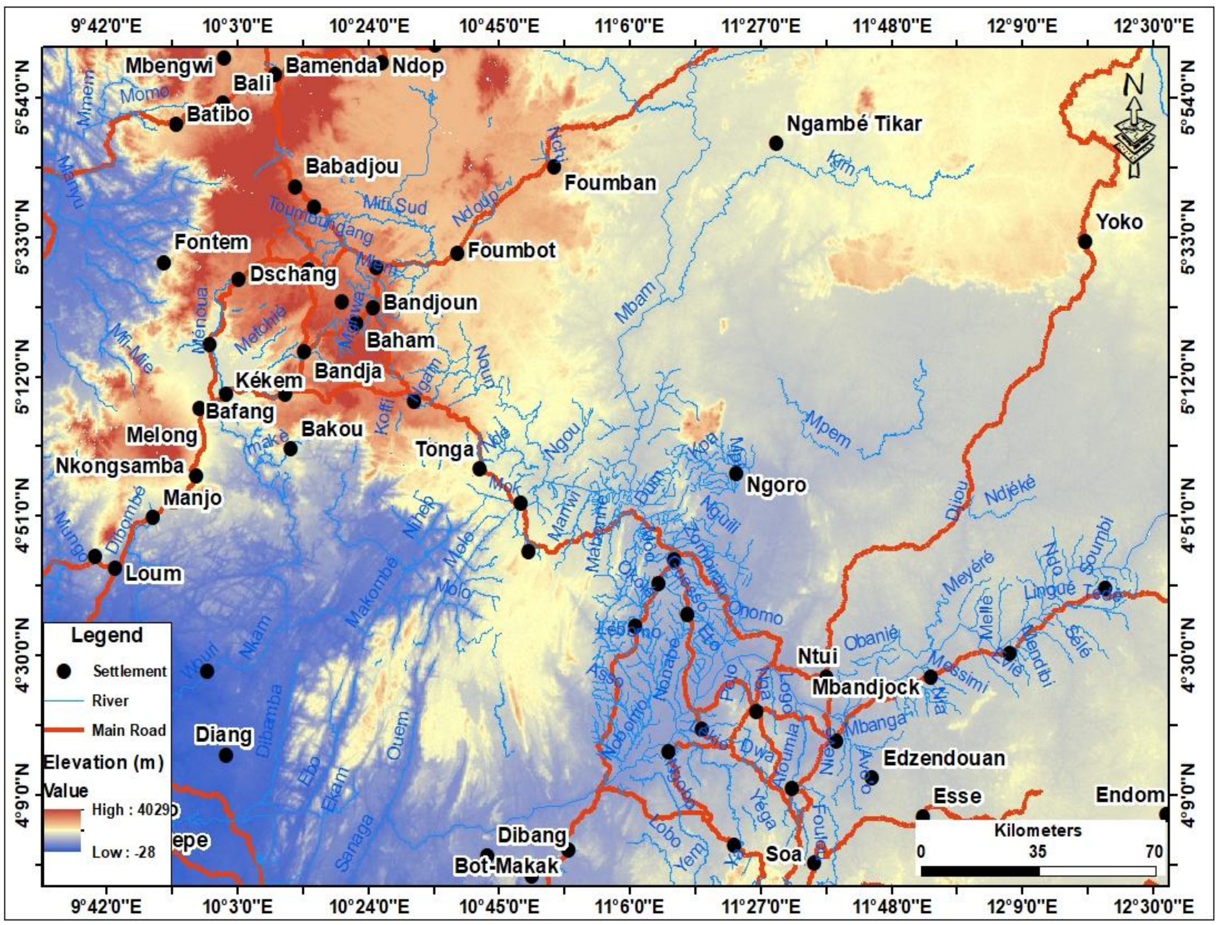

Figure 3. Hydrology Map of the Study Area.

MATERIALS AND ANALYTICAL APPROACH

Water samples were collected from 56 locations across diverse river systems within the Yaoundé–Manjo corridor in Central and Littoral Cameroon. These included major rivers such as the Sanaga, Nyong, Noun, and Wouri, and minor tributaries like the Olezoa, Obala, Manouile, and Mbone, representing a wide range of hydrogeological settings. A total of 56 water samples were collected, comprising 28 from the wet season (July 2024) and 28 from the dry season (February 2024). This balanced design allowed for direct seasonal comparison of isotopic and hydrochemical dynamics.

Sampling was conducted during the mid-point of each season to ensure that collected waters reflected characteristic hydrological conditions.

Sampling points were selected using a stratified purposive sampling approach, targeting rivers that differed in flow regime, elevation, and geological substrate. Site selection also considered accessibility, catchment representation, and proximity to recharge zones or human activity. Samples were collected using 30 mL high-density polyethylene (HDPE) bottles, pre-rinsed three times with sample water before final collection. In the field, water samples were filtered through 0.2 µm or 0.45 µm membrane filters where turbidity was present, and then immediately stored in insulated coolers at 4°C to minimize fractionation. The time between sampling and laboratory analysis ranged from 3 to 10 days, during which samples were continuously stored at 4°C in darkness to preserve isotopic integrity.

In the laboratory, isotope preparation followed IAEA (2006) protocols. For $\delta^{18}O$ analysis, samples were equilibrated with CO_2 gas at 25°C for 24 hours in sealed vials. For δ^2H, hydrogen gas was produced via a chromium reduction method. IRMS quantifies the ratio of stable isotopes ($^{18}O/^{16}O$ and $^2H/^1H$) in a sample by differentiating isotopic species according to their mass-to-charge ratio (Clark & Fritz, 1997; Kendall & McDonnell, 1998; Wang *et al.,* 2021; Dulinski., 2024). In Oxygen Isotope Analysis ($\delta^{18}O$), water was reacted with CO_2 in a regulated atmosphere at a designated temperature, of 25°C, to facilitate isotopic exchange. The CO_2 gas was subsequently analyzed using the mass spectrometer. In Hydrogen Isotope Analysis (δD), water is converted to H_2 gas via a reaction with a reducing agent (such as zinc or chromium) before isotope ratio analysis in the mass spectrometer. Results from IRMS are generally articulated as delta (δ) values in parts per thousand (‰) relative to an international reference, commonly the Vienna reference Mean Ocean Water (VSMOW), as demonstrated in eq.1 (Kendall & McDonnell, 1998).

δ (‰)= (R_sample / R_V-SMOW – 1) ×1000 (IAEA, 2006)………………………………….. (1)

Where, R _sample represent the ratio of heavy to light isotope (^{18}O or ^2H) of the sample

The isotope ratios of hydrogen and oxygen are denoted as δD and $\delta^{18}O$, respectively, or as δ values.

RESULTS AND DISCUSSION

Recharge Mechanism of Rivers

Oxygen- 18 ($\delta^{18}O$) values range from -5.22‰ to -2.77‰ in the wet season and from -4.16‰ to -0.04‰ in the dry season (Table 1a and Table 1b). Comparable variations are observed in δD, which spans from -25.74‰ to -8.68‰ during the wet season and from -20.82‰ to 0.19‰ in the dry season. The relatively lower $\delta^{18}O$ and δ^2H values observed during the wet season suggest that rainfall is the primary source of river recharge. Similar trends were observed in Bangladesh, where monsoonal dynamics influenced isotopic depletion during the rainy season (Rodríguez-Murillo *et al.,* 2020), and in Sri Lanka, where different seasonal precipitation sources caused distinct isotopic signatures (Edirisinghe *et al.,* 2018). This is further supported by the Local Meteoric Water Line (LMWL) for the wet season which is close to the GMWL, indicating minimal isotopic alteration due to evaporation before recharge (Fig 4). This aligns with the understanding that precipitation in tropical regions generally comprises lighter isotopes (Dansgaard, 1964). Conversely, the higher $\delta^{18}O$ and δ^2H values observed in surface water bodies during the dry season suggest evaporative enrichment. High temperatures and dry conditions promote evaporation, leading to preferential removal of lighter isotopes (^{16}O and ^{1}H) and a consequent increase in the heavier isotopes (^{18}O and ^{2}H) in the remaining water.

This process can be described by the Craig-Gordon model (Craig & Gordon, 1965), which describes the isotopic enrichment during evaporation. Similar results were obtained in the Virunga region indicating that during dry periods, moisture sourced from the evaporation of nearby lakes contributes to precipitation with higher $\delta^{18}O$ and $\delta^{2}H$ values. This process results in surface waters that are isotopically enriched due to the dominance of evaporated lake water vapour in the atmosphere during the dry season (Stevenson *et al.,* 2023). The LMWL for the dry season has a significantly lower slope than the GMWL, confirming the influence of evaporation (Fig 4). The lower slope indicates kinetic fractionation during evaporation, where the lighter isotopes evaporate faster, altering the $\delta^{2}H/\delta^{18}O$ relationship (Prasad *et al.,* 2024). Considering that precipitation, especially in tropical and subtropical regions, generally comprises lighter isotopes, the relatively lower $\delta^{18}O$ and δD levels recorded during the wet season suggest that rainfall is the principal source of replenishment (Gimeno *et al.,* 2021; Li *et al.,* 2024). This depletion of heavy isotopes is often attributed to the "amount effect," where intense and frequent rainfall leads to isotopically lighter precipitation due to preferential condensation of heavier isotopes at earlier stages of atmospheric moisture transport (Dansgaard, 1964; Gat, 1996, Wotany *et al.,* 2021).

Similar findings have been documented in various tropical regions including Cameroon, Sri Lanka, and parts of East Africa, where $\delta^{18}O$ and δD values in groundwater and surface water during the rainy season reflect direct recharge from depleted rainwater (Wirmvem *et al.,* 2017; Stevenson *et al.,* 2023). These patterns reinforce the role of seasonal precipitation in replenishing surface and subsurface water resources in monsoon-dominated climates.

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Table 1: Seasonal Variations in Isotopic Composition ($\delta^{18}O$ and δ^2H), Total Dissolved Solids (TDS), and Chloride Levels in River Systems of the Study Area

Rivers	Elevation (m)	Wet Season					Dry Season				
		TDS	Chloride (mg/l)	$\delta^{18}O$ (‰)	δD (‰)	d-excess (‰)	TDS (mg/l)	Chloride (mg/l)	$\delta^{18}O$ (‰)	δD (‰)	d-excess (‰)
R. Olezoa	681	177.2	21.94	-2.86	-8.68	14.24	198.70	13.66	-3.77	-18.20	11.98
R. Ebendi	681	123.5	9.24	-3.27	-10.61	15.54	125.70	2.75	-3.90	-20.50	10.70
R. Obala	550	34.71	1.48	-3.54	-12.35	15.96	53.52	0.17	-3.55	-17.63	10.74
R. Sanaga	386	20	0.97	-2.77	-7.69	14.49	20.52	0.16	-3.21	-15.03	10.66
R. Mbam	384	22.98	0.69	-3.08	-9.72	14.90	20.55	0.22	-0.04	0.19	0.53
R. Bofovo	499	33.21	1.06	-3.56	-12.89	15.60	49.73	2.21	-4.01	-20.82	11.30
R. Ndikinem	500	32.68	0.65	-3.47	-12.59	15.20	78.33	0.50	-2.68	-13.71	7.74
R. Mbone	598	32.4	0.83	-3.63	-13.38	15.68	53.10	0.60	0.00	0.36	0.36
R. Manouile	671	28.24	0.57	-3.77	-14.72	15.47	25.50	0.97	-3.61	-18.65	10.20
R. Makenene	696	37.88	1.82	-3.82	-14.49	16.05	41.71	2.29	-3.83	-17.10	13.53
R. Nde	741	23.68	0.81	-4.11	-17.07	15.82	19.70	0.28	-3.76	-16.56	13.52
R. Bangante	1257	8.64	0.34	-3.89	-18.09	13.05	16.64	0.87	-3.33	-14.78	11.89
R. Bangoua	1288	16.21	0.85	-4.30	-19.04	15.39	16.96	0.41	-3.97	-17.36	14.42
R. Bandjoun	1488	14.57	1.32	-4.68	-21.09	16.38	30.44	1.00	-4.16	-19.15	14.12
R. Mifi	1316	28.99	1.16	-4.04	-17.97	14.39	40.15	0.57	-2.75	-14.46	7.56
R. Matazem	1633	21.41	0.99	-4.46	-20.49	15.17	39.42	2.01	0.66	1.18	-4.13
R. Noun	1052	42.3	1.39	-4.09	-18.58	14.11	18.40	0.58	-2.18	-6.67	10.80
R. Nkouop	1046	147.5	2.17	-3.16	-4.46	20.83	160.90	3.19	-1.40	-2.78	8.38
R. Machout	972	30.63	0.32	-3.62	-8.16	20.79	59.33	0.69	-2.46	-7.56	12.11
R. Noun 2	928	77.09	1.51	-3.35	-13.32	13.51	20.69	0.74	-1.97	-7.77	8.01
R. Tchitchi	1407	21.66	0.55	-3.00	-10.46	13.53	25.10	1.43	-0.03	0.26	0.51
R. Ndjahkam	117	34.15	1.21	-4.46	-20.82	14.86	24.48	1.72	-2.76	-10.25	11.86
R. mort	725	15.52	1.16	-3.80	-15.56	14.85	18.63	0.89	-0.74	-1.83	4.13
R. Nkam	707	34.85	2.00	-3.97	-16.22	15.50	31.70	0.87	-2.42	-9.19	10.15
R.Manegoule	609	13.41	0.61	-4.16	-17.75	15.50	105.30	0.95	-2.71	-10.76	10.90
R. Manjo	518	20.65	0.96	-3.83	-15.64	14.99	40.80	1.02	-2.98	-11.12	12.70
R. Ndibe	318	19.75	0.52	-4.45	-20.08	15.51	60.70	9.70	-3.20	-13.00	12.60
R. Wouri	4	21.21	0.51	-5.22	-25.74	16.03	10020.00	5803.82	-3.70	-16.09	13.55
Max		177.2	21.94	-2.77	-4.46	20.83	10020	5803.82	0.66	1.18	14.42
Min		8.64	0.32	-5.22	-25.74	13.05	16.64	0.16	-4.16	-20.82	-4.13
Mean		44.67	2.663	-3.81	-14.92	15.574	715.1	388.12	-2.53	-11.28	9.037

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As shown in Table 1, $\delta^{18}O$ values range from -5.22‰ to -2.77‰ in the wet season and from -4.16‰ to -0.04‰ in the dry season (Table 1). Comparable variations are observed in δD, which spans from -25.74‰ to -8.68‰ during the wet season and from -20.82‰ to 0.19‰ in the dry season (Table 1). The relatively lower $\delta^{18}O$ and δ^2H values observed during the wet season suggest that rainfall is the primary source of river recharge. This is further supported by the Local Meteoric Water Line (LMWL) for the wet season ($\delta^2H = 7.9243 * \delta^{18}O + 15.154$), which is close to the GMWL, indicating minimal isotopic alteration due to evaporation before recharge (Fig 4). This aligns with the understanding that precipitation in tropical regions generally comprises lighter isotopes (Dansgaard, 1964). Conversely, the higher $\delta^{18}O$ and δ^2H values observed in surface water bodies during the dry season suggest evaporative enrichment.

High temperatures and dry conditions promote evaporation, leading to preferential removal of lighter isotopes (^{16}O and ^1H) and a consequent increase in the heavier isotopes (^{18}O and ^2H) in the remaining water. This process can be described by the Craig-Gordon model (Craig & Gordon, 1965), which describes the isotopic enrichment during evaporation. The LMWL for the dry season ($\delta^2H = 4.8474 * \delta^{18}O + 1.1418$) has a significantly lower slope than the GMWL, confirming the influence of evaporation (Figure 3). The lower slope indicates kinetic fractionation during evaporation, where the lighter isotopes evaporate faster, altering the $\delta^2H/\delta^{18}O$ relationship. Considering that precipitation, especially in tropical and subtropical regions, generally comprises lighter isotopes, the relatively lower $\delta^{18}O$ and δD levels recorded during the wet season suggest that rainfall is the principal source of replenishment.

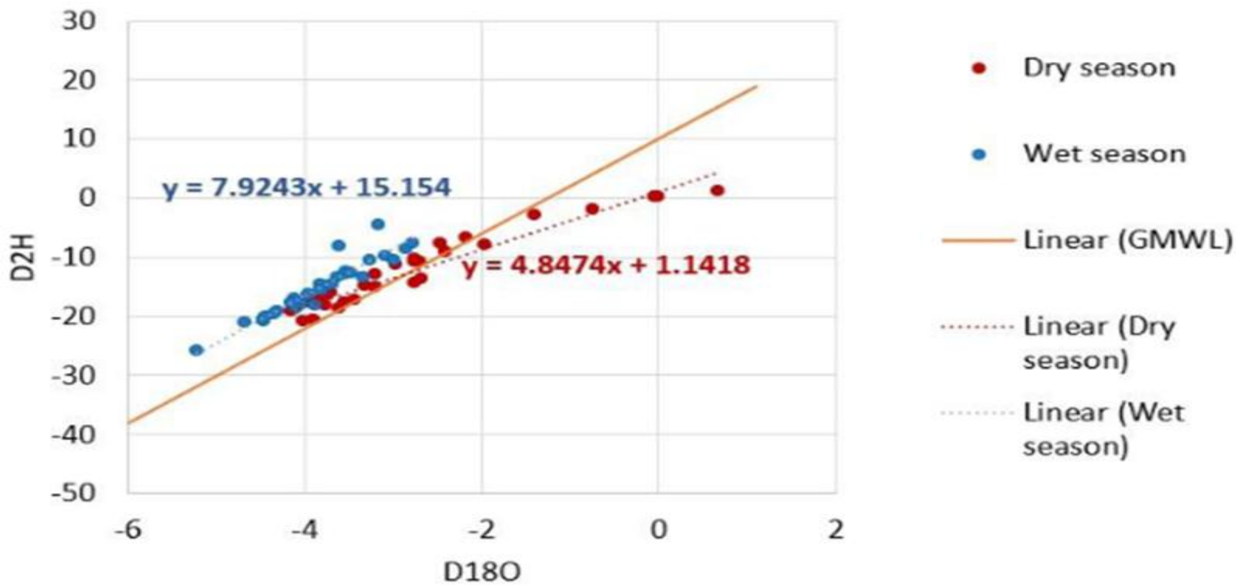

Figure 4: Meteoric water origin and rapid surface water recharge during the wet and dry seasons plotted along the Global meteoric line (GMWL) (Craig ,1961).

Deuterium excess (d-excess), defined as:

d-excess = $\delta^2H - 8 * \delta^{18}O$…………………………………………………………… (2)

is a useful parameter for tracing the origin and evaporation history of water (Gat, 1996; Clark & Fritz, 1997; Dansgaard, 1964; Wirmvem *et al.* 2017). In the wet season, d-excess values range

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from 13.05 ‰ to 20.83‰, suggesting limited evaporation before recharge. High d-excess values are often associated with reduced water evaporation. However, d-excess values decline throughout the dry season, indicating increased evaporation, particularly in surface waters. This result is typical of rivers in tropical zones where evaporation significantly modifies the isotopic signature of river bodies during the dry season (Gibson *et al.,* 2016: Wirmvem *et al.* 2017). The results provide evidence of mixing processes, suggesting that groundwater may contribute to river recharge during the dry season (Fig 4). The contribution of groundwater, which may have undergone prior evaporation or water-rock interaction, can further explain the deviation of dry season samples from the GMWL (Kendall & McDonnell, 1998).

The isotopic data in Table 1 indicate that direct precipitation is the primary source of river recharge during the wet season, with minimal evaporative alteration. In contrast, rivers exhibit evaporative enrichment during the dry season, coupled with potential contributions from groundwater sources. These findings highlight the dynamic interplay of precipitation, evaporation, and groundwater interaction in regulating river recharge within the study region

Hydraulic Residence Time of the Rivers

TDS, chloride and isotopic data were analyzed to ascertain the residence time of rivers (Soulsby *et al.,* 2006; McGuire & McDonnell, 2006). Examining the relationship between $\delta^{18}O$ and TDS/Cl^- concentrations reveals distinct patterns in the wet and dry seasons.

During the wet season (Fig 5), the relatively tight clustering of data points shows a narrow range of TDS and Cl^- concentrations for a given range of $\delta^{18}O$ values, suggesting a homogenous water source and rapid mixing due to high discharge and short residence times (the relationship between $\delta^{18}O$ and both TDS and chloride concentrations shows a strong inverse correlation ($R^2 = 0.71$ for $\delta^{18}O$ vs. TDS; $R^2 = 0.68$ for $\delta^{18}O$ vs. Cl^-). This consistent trend, along with a relatively narrow spread of data points, coefficient of variation for TDS = 34%, and Cl^- = 28%), inverse correlation between $\delta^{18}O$ and TDS/Cl^- indicates a rapid hydrological response, where rainwater with depleted isotopic signatures quickly dilutes the solute load in the rivers (Kendall & McDonnell, 1998). This is typical of tropical rivers that respond quickly to rainfall events (Roa-García *et al.,* 2020). The lower TDS values also indicate a shorter duration of water-rock interaction, as water spends less time in the subsurface (White, 2009).

During the dry season (Fig 6), the wider dispersion of data points indicates more variable sources and processes affecting water chemistry, such as evaporation, groundwater contributions, and mineral dissolution. The weaker correlation suggests more complex mixing patterns and longer water-rock interactions (Elsenbeer *et al.,* 2020). Higher TDS and chloride concentrations, accompanied by higher evaporation rates and lower streamflow, lead to extended water-rock interactions, which further increase solute concentrations. Higher evaporation rates are also typical during baseflow conditions during the dry season. This extended water-rock interactions can be longer residence times and higher solute concentrations (Cartwright *et al.,* 2012). The data from the figures indicate longer residence times during the dry season.

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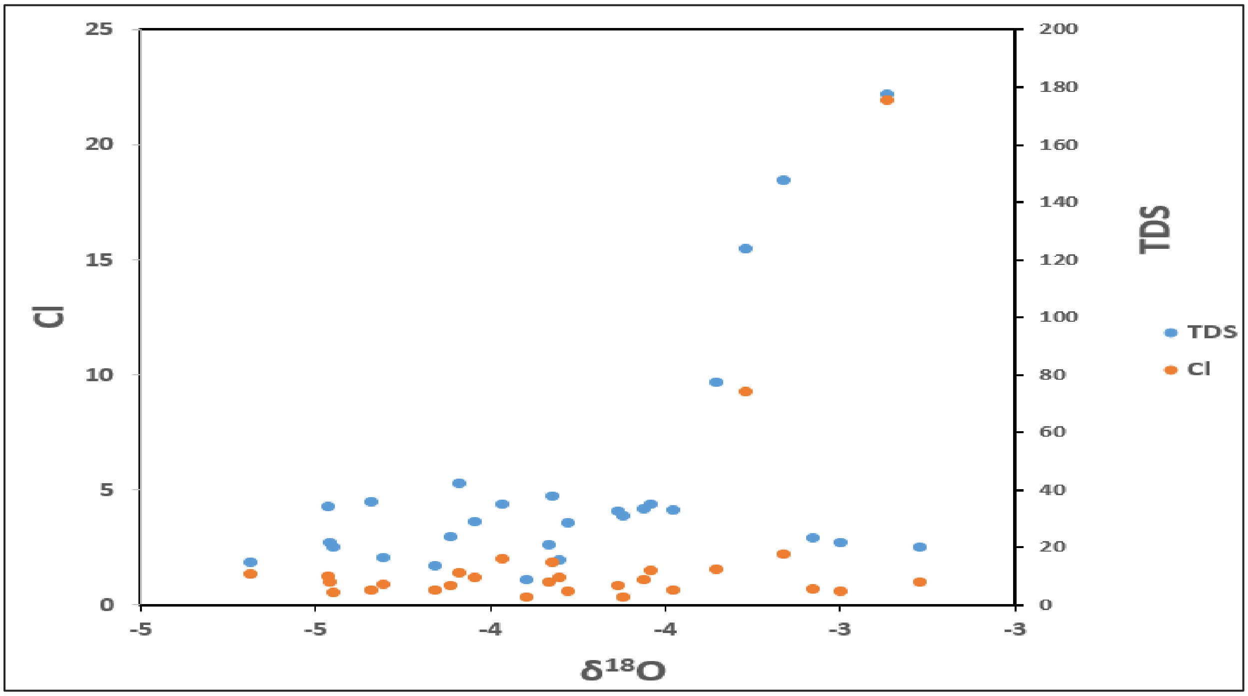

Figure 5. A Cross-Plot of Δ¹⁸O Against TDS and Cl⁻ in Surface Water Within the Study Area During the Wet Season.

Figure 5 revealed a relatively tight clustering of data points with an inverse correlation, consistent with rapid mixing and a homogenous water source.

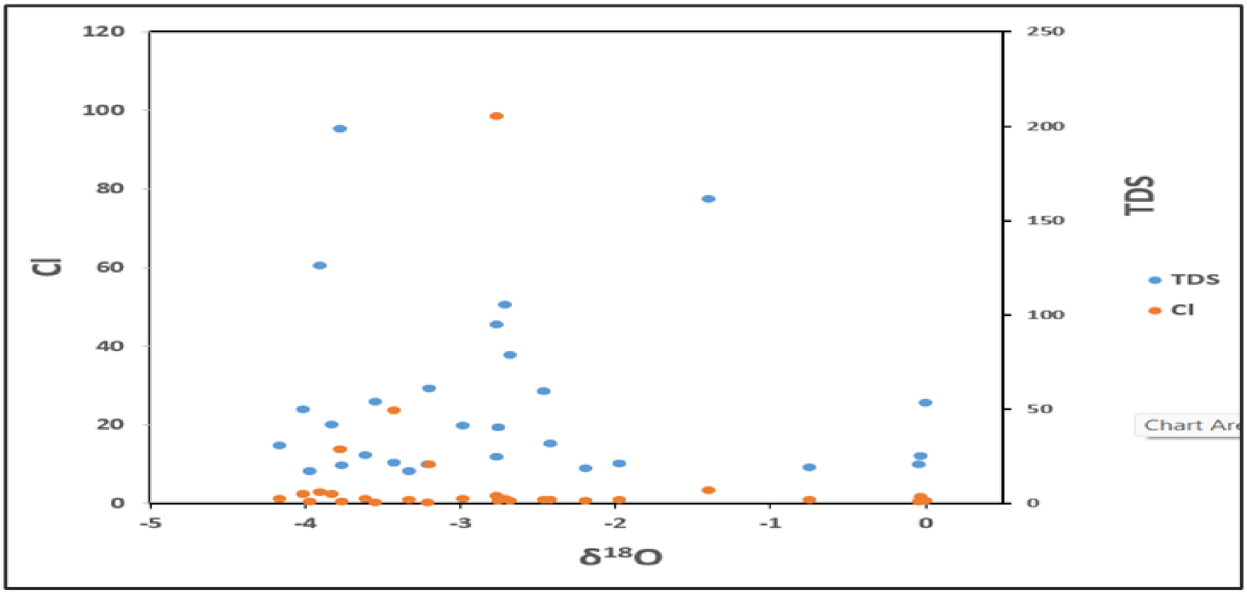

Figure 6: A Cross-Plot of Δ¹⁸O Against TDS and Cl⁻ in Surface Water Within the Study Area During the Dry Season.

Figure 6 shows a wider dispersion of data points indicating variable water sources, longer residence times, and influences from evaporation and water-rock interaction.

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Altitude Effect on $\delta^{18}O$ and $\delta^{2}H$

Higher-altitude locations, such as R. Matazem (1633 m) and R. Bandjoun (1488 m), exhibit more negative $\delta^{18}O$ values (-4.46‰ and -4.68‰,) respectively (Table 4.25). This trend aligns with findings from Ndop Plain and Lake Nyos, where increased elevation leads to isotopic depletion due to condensation and rainout effects (Wirmvem *et al.,* 2013; Wirmvem *et al.,* 2016). This depletion occurs because, as moist air masses rise, they cool and condense, causing preferential removal of heavier isotopes (^{18}O and ^{2}H). Consequently, higher elevations receive isotopically lighter precipitation (Dansgaard, 1964), reflected in river water isotopes. A similar altitude effect was observed in the Ethiopian Highlands (Kebede & Travi, 2012), where increasing elevation correlated with isotopic depletion in precipitation and surface waters.

A study in the Sierra Nevada, California, reported isotopic lapse rates of approximately -0.22‰/100 m for $\delta^{18}O$ and -1.9‰/100 m for δD in mountain stream waters, supporting the use of isotopes as tracers of water source elevation (Liu *et al.,* 2024). Similarly, in the Peruvian Andes, strong isotopic gradients of up to -98‰/km for δD were observed due to sharp altitudinal transitions and shifts in moisture sources (White *et al.,* 2024).

In the Southern Ecuadorian Andes, $\delta^{18}O$ values in surface water decreased from -3.2‰ at low altitudes (~300 m) to -10.6‰ at higher elevations (~3000 m), directly linking isotopic depletion to elevation (Gébelin *et al.,* 2021). In Tibet, the Yarlung Tsangpo River showed seasonal variation in the lapse rate, with values around -0.0025‰/m during the dry seasons and -0.0018‰/m during the rainy seasons, highlighting not just the elevation impact but also the role of seasonal climatic shifts (Li *et al.,* 2021).

Despite the overall trend of isotopic depletion with increasing elevation, a few rivers exhibit deviations from the expected altitude-isotope relationship. These include lower-elevation rivers such as R. Ndjahkam (117 m) and R. Ndibe (318 m), which show more depleted $\delta^{18}O$ values (-4.46‰), comparable to those found at higher elevations. Such exceptions may result from inputs of isotopically light water from upstream highland tributaries, or direct recharge from recent, intense rainfall events, particularly during the wet season. These localized deviations underscore the complexity of hydrological processes in tropical basins, where factors such as subsurface flow paths, catchment connectivity, and rainfall variability can override simple altitudinal controls on isotope distribution.

Implications for Future Water Management

Comprehending the dynamics of river recharge, flow variability, and temporal water quality is essential for effectively managing water resources (Kirchner, 2009; Nyenje & Batelaan, 2009). Seasonal fluctuations are observed in TDS and chloride concentrations, with TDS significantly elevated during the dry season (reaching 10020 mg/L in DF12 (R. Wouri), compared to 177.2 mg/L in the wet season), a pattern also observed in tropical regions of Africa (Abiye *et al.,* 2011). The isotopic signatures ($\delta^{1}8O$ and δD) demonstrate significant seasonal fluctuations, indicating evaporation and a lack of substantial recharge during the dry season, similar to findings in the Sahel region (Goni *et al.,* 2021). The rivers are especially susceptible to seasonal water scarcity owing to diminished river flows and increased evaporation rates in the dry season, as indicated by elevated isotope measurements (less negative $\delta^{18}O$ and δD), a phenomenon also noted in East African rivers (Levin *et al.,* 2009; Letshele *et al.,* 2023). Surface water is more available in the rainy season due to refilled rivers; yet, during the dry season, diminished flow rates, evidenced by high TDS and chloride concentrations, complicate water supply management, challenges similarly faced in West African catchments (Descroix *et al.,* 2009).

CONCLUSION

Isotopic data ($\delta^{18}O$ and $\delta^{2}H$) suggest that river recharge during the wet season is dominated by direct rainfall, with minimal evaporative influence, as supported by alignment with the Local Meteoric Water Line. Rivers demonstrate extended residence lengths in the dry season because of diminished flow rates, groundwater contributions, and elevated evaporation. The isotopic and chemical data indicate slower, more evaporative river systems in the dry season and faster-moving systems in the wet season. Rivers in the study area seem vulnerable to the prolonged impacts of climate change and seasonal variations, as indicated by isotopic and chemical data. The increasing dependence on groundwater during dry periods elevated TDS levels in the dry season, and the effects of evaporation underscore the need for adaptive water management strategies that address both current and future climatic challenges. To enhance water security, adaptive strategies such as seasonal flow monitoring, community-led groundwater regulation, watershed protection, and artificial recharge programs should be prioritised. These measures can help buffer the impacts of evaporation, over-abstraction, and erratic rainfall. Future research should implement long-term isotopic and hydrochemical monitoring to detect temporal shifts in recharge patterns and water quality, especially in the face of accelerating climate change. Integrating isotope hydrology with hydrological modelling and policy planning will be essential for sustaining surface and groundwater resources in tropical environments.

Conflict of Interest

The authors declare no competing interests.

Author Contributions

Mr. Ayuk Valery Takang contributed to conceptualisation, methodology, formal analysis, resource allocation, and the preparation of the original draft; Dr. Engome Regina Wotany oversaw supervision and the writing, review, and editing process. The authors have reviewed and approved the final version of the manuscript.

Data availability

Available at any time upon request

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