

Hydrogeochemical Assessment of Groundwater in Epe (Nigeria) for Drinking and Irrigation Purposes

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Abstract

Groundwater sustainability demands routine quality monitoring. This study assessed the hydrogeochemistry of groundwater in Epe, Lagos State, to evaluate its suitability for drinking and irrigation. Fifty well-water samples from eight communities were analyzed for pH and major ions. Results showed that parameters complied with regulatory standards in most locations except magnesium (65.70 ± 23.50 - 96.00 ± 19.68 mg/L) which consistently exceeded the Nigerian Standard for Drinking Water Quality of 20 mg/L. Dietary intake of essential elements was generally negligible, though magnesium levels in Poka exceeded recommended daily allowance for infants (0-6 months). The Water Quality Index (40.41 - 128.49) classified the water as 8% "excellent," 76% "good," and 16% "poor" while the Pollution Index of Groundwater (0.39 - 0.85) ranked all samples as having insignificant pollution. Though, majority of the irrigation indices indicated suitability for irrigation; Permeability Index (<25% in 88% of samples), Magnesium Adsorption Ratio (>50% in 86% samples) and Corrosivity Ratio (>1 in 50% samples) presented risks to long-term soil permeability and metallic water transport pipes. The ionic dominance was $Mg^{2+} > Ca^{2+} > Na^{+} > K^{+}$ and $HCO_3^{-} > SO_4^{2-} > Cl^{-}$. Geochemical diagrams (Piper, Chadha and Schoeller diagrams) revealed a Ca-Mg- HCO_3 facies, attributed to mixed carbonate-silicate weathering (Gaillardet diagram), rock-water interaction (Gibb's diagram) and ion exchange (CAI, CAII), with the Hydrochemical Facies Evolution Diagram indicating mixed facies. Principal Component Analysis identified bicarbonate (PC1: 57.33%), calcium (PC2: 17.35%), sulphate (PC3: 15.94%) and magnesium (PC4: 8.38%) as the primary factors controlling water quality. The study recommends water treatment, the use of corrosion-resistant pipes, and sustained monitoring to safeguard this resource.

Keywords: Coastal Lagos, Drinking and Irrigation Water Quality Indices, Groundwater Quality, Hydrogeochemical Facies, Southwestern Nigeria.

Introduction

Groundwater is a vital natural resource, essential for sustaining human health, agricultural productivity, and economic development, particularly where surface water is scarce or

contaminated (Sulaiman et al., 2025; Dheeraj et al., 2025). In Nigeria, as in many other developing nations, the reliance on groundwater has intensified due to population growth, urbanization, and the inconsistent supply of piped water (Abdu-Raheem et al., 2024; Ugbor et al., 2022). This dependency makes the assessment and protection of groundwater quality a critical imperative for public health and food security.

However, groundwater resources are increasingly vulnerable to degradation from both geogenic processes and anthropogenic activities. Uncontrolled urbanization, improper waste disposal, intensive agricultural practices, and industrial effluents can introduce pollutants into aquifer systems (Igwe and Omeke, 2022; Yahaya et al., 2022; Adamu et al., 2024). Concurrently, natural hydrogeochemical processes, such as rock-water interactions, silicate weathering, and ion exchange, govern the intrinsic ionic composition of groundwater, which can also pose suitability challenges for various uses (Omali, 2024; Shuaibu et al., 2024). For instance, elevated concentrations of magnesium, sodium, or certain anions can adversely affect human health, reduce soil permeability, and corrode water supply infrastructure.

To systematically evaluate these intertwined threats, a standard diagnostic framework has been widely adopted, integrating drinking-water indices (e.g., Water Quality Index [WQI] and Pollution Index of Groundwater [PIG]), irrigation-specific parameters (Sodium Adsorption Ratio [SAR], Magnesium Hazard [MH], and Permeability Index [PI]), and hydrogeochemical interpretation tools (multivariate statistics and Piper–Gibbs diagrams) to pinpoint contaminant sources and evolution pathways (Awomeso et al., 2020; Egbueri et al., 2021).

In Nigeria, numerous studies applying this integrated toolkit have reported varying degrees of contamination across diverse settings. Recent hydrogeochemical assessments in various regions, including Iworoko, Southwestern Nigeria (Abdu-Raheem et al., 2024), Okigwe, Southeastern Nigeria (Ugbor et al., 2022), and Ajaokuta, North-Central Nigeria (Omali, 2024), have reported varying degrees of groundwater contamination. Similar integrated approaches are applied globally, from the coal mining regions of India (Samal et al., 2022; Dheeraj et al., 2025) to arid regions in Saudi Arabia (Alogayell et al., 2023), underscoring the universal importance of comprehensive groundwater evaluation.

Despite the wealth of studies in Nigeria, a critical knowledge gap exists for the coastal community of Epe in Lagos State. Epe is a significant agricultural hub and a growing urban center, yet a detailed hydrogeochemical assessment of its groundwater resources, encompassing both drinking and irrigation suitability, is lacking. The existing studies in Lagos, such as those focusing on industrial areas (Yahaya et al., 2022; Salami and Ayinde, 2025) and dumpsites (Ige et al., 2022; Anaga et al., 2023), indicate significant anthropogenic pressures on water quality in the state. A recent study in Malajoye, Epe, by Mafimisebi (2024) assessed irrigation suitability but was limited in scope. Therefore, a more comprehensive investigation is required to characterize the groundwater facies, identify the controlling geochemical processes, and quantify the specific risks to health and agricultural sustainability in Epe.

This study aims to fill this gap by conducting a detailed hydrogeochemical assessment of groundwater in Epe, Lagos State. The specific objectives are to: (1) evaluate the physicochemical characteristics of groundwater and compare them with national (NSDWQ) and international (WHO) standards; (2) determine the dietary intake of essential elements in water in compliance with recommended dietary allowance or adequate intake; (3) assess the suitability of groundwater for drinking purposes using the Water Quality Index (WQI); (4) determine its suitability for irrigation using multiple indices (SAR, %Na, KR, MH, PI, PS, etc.); and (5) identify the hydrogeochemical facies and processes governing groundwater chemistry using graphical methods and multivariate statistics. The findings from this research will provide a scientific baseline for policymakers, water resource managers, and the local community to implement targeted protection measures and ensure the long-term viability of groundwater in Epe. It will provide recommendations for the sustainable management of this vital resource.

Materials and Methods

Study Area Description

Epe (Fig. 1) is a historically and culturally significant town in the Epe Local Government Area of Lagos State, southwestern Nigeria. Originally established by the indigenous Awori people in the pre-colonial era, its foundation is deeply rooted in the region's early history (Agunbiade et al., 2013; Akintude, 2025). The town is geographically positioned at coordinates 6.5867°N and 3.9700°E, situated on the northern bank of the Lagos Lagoon and approximately 90 kilometres from Ibadan, with road connections to Ijebu-Ode and Ikorodu (The Editors of Encyclopaedia Britannica, 2024; Akintude, 2025).

The local economy has a strong historical basis in fishing and trade, activities enabled by its strategic coastal location (Iwugo et al., 2003; Akintude, 2025). Today, Epe functions as a major collection and export point for various goods, including fish, cassava, maize, vegetables, coconuts, cocoa, palm products, rubber, and firewood, which are primarily destined for Lagos (The Editors of Encyclopaedia Britannica, 2024). The town also has a niche trade in special leaves used for preserving kola nuts, which are transported to major kola-shipping centres like Ijebu-Ode and Shagamu. Epe is notably recognized for its unique maritime industry, specializing in the construction of motorized, shallow-draft barges designed for navigation on the coastal lagoon system (The Editors of Encyclopaedia Britannica, 2024). Despite this economic diversification, fishing remains the predominant occupation. The town's infrastructure includes secondary schools, several hospitals, and a health office, serving an estimated population of over 269,000 people (The Editors of Encyclopaedia Britannica, 2024; Akinmoyeje, 2025).

Climatically, Epe experiences a warm, tropical regime with an average annual temperature of 29.48°C (Ojeh et al., 2016; Akintude, 2025). Its weather is defined by two distinct seasons: a rainy season from April to October and a dry season from November to March. The mean monthly rainfall varies between 19 and 64mm during the dry season and between 162 and 237 mm in the wet season (Omeru et al., 2018).

Geologically, the area lies within the Dahomey Basin and is underlain by the Miocene to Pleistocene-age Benin Formation, commonly referred to as the coastal plain sands (Whiteman, 1982; Akintude, 2025). This formation consists of poorly sorted, delta-top sands and sandstones, frequently exhibiting cross-bedding and containing interlayered clay lenses. The unit also hosts marine fossils, including foraminifera, ostracods, and mollusks (Jones & Hockey, 1964; Wilson & Willians, 1979; Omatsola.

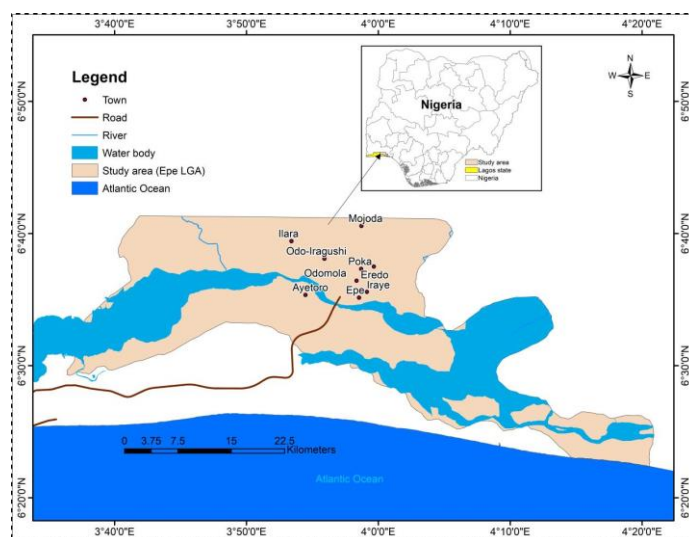


Fig. 1: Map of Epe in Lagos State showing sampled communities

The subsurface is characterized by a complex stratigraphy of alternating sand and clay layers, with the Precambrian basement rock located at a significant depth, beyond the reach of standard surficial survey methods (Longe et al., 1987).

The hydrogeology of Epe is defined by a multi-layered aquifer system, which is commonly accessed through shallow hand-dug wells. According to Longe (2011), as cited in Akintude (2025), aquifers have been identified in the region, associated with recent littoral and alluvial deposits as well as the deeper Benin Formation. The uppermost of these is an unconfined water table aquifer, found at depths ranging from 9 to 24 meters, with an average thickness of 8 to 12 meters. Due to its shallow depth, this aquifer serves as the primary water source for the local population and is highly vulnerable to contamination from surface activities (Oyedele & Oladele, 2011; Akintude, 2025).

Water Sampling and Analysis

A total of 50 groundwater samples were collected in a simple random sampling design from wells in eight communities in Epe namely Ayetoro (8), Iraye (3), Odomola (4), Mojoda (9), Ilara (6), Poka (4). Odo-Iragushi (6) and Eredo (10) Detailed information is presented in Table S1 (in the Supplementary Information). Sampling was conducted in the month of March, 2025 All sampling and analytical procedures followed APHA–AWWA–WEF (2023) protocols. The only parameter measured in situ was pH, using calibrated instruments, while

cations and anions were analysed ex situ in the laboratory. Samples for cation analysis were acidified with a few drops of concentrated nitric acid to a pH below 2 to prevent precipitation or adsorption losses using a dropper. All water samples were collected in pre-cleaned, labelled polyethylene bottles and stored in ice packs on the field before being taken to the laboratory for further analyses. Specific methods followed are in Gbadebo et al. (2026a).

Dietary Estimates for Major Ions

The dietary intake of major ions was estimated for all the age groups using the formula as given by Gbadebo et al. (2026a, 2026b and 2026c):

$$DI_i = TWI \times C_w \quad (1)$$

Where: DI_i = Dietary Intake of ion (mg/day); TWI = Total Water Intake (L/day); C_w = Concentration of ion in water (mg/L)

The calculation of dietary intake is largely dependent on the total water intake of each life stage and age group. The standard values utilized in the calculation are given in Table S3 (IOM 2005; 2011; NASEM 2019a; 2019b).

Determination of Water Quality Index (WQI)

The Water Quality Index (WQI) is an index that integrates multiple water quality parameters into a single value representing overall water quality (Akakuru et al., 2022; Okafor et al. 2023). In this study, pH, cations (Ca^{2+} , K^+ , Na^+ , Mg^{2+}), and anions (SO_4^{2-} , Cl^-) were used, with guideline values (National Environmental Standards and Regulations Enforcement Agency (NESREA), 2011; Standard Organization of Nigeria (SON), 2015; and World Health Organization (WHO), 2022) provided in Table S2 (Supplementary Information). The calculation followed the method reported in Gbadebo et al. (2026a):

Determination of Pollution Index of Groundwater (PIG)

The pollution index of groundwater was calculated to evaluate the effect of specific variables such as pH, K^+ , Ca^{2+} , Mg^{2+} , Na^+ , SO_4^{2-} and Cl^- on the overall quality of groundwater (Subba-Rao, 2012). The formula is thus:

$$WP = \frac{RW}{\sum RW} \quad (2)$$

$$SC = \frac{C_n}{WQS} \quad (3)$$

$$PIG = \sum (WP \times SC) \quad (4)$$

Where: WP = Weight of the parameter; RW = Relative weight; SC = Status of concentration; C_n = Concentration of the parameter; WQS = Water Quality Standard. The relative weights of pH, Ca^{2+} , Mg^{2+} , Na^+ , K^+ , HCO_3^- , Cl^- and SO_4^{2-} were respectively taken as: 5, 5, 2, 4, 1, 3, 4 and 5. The water quality standard for these parameters were respectively taken as: 7.5, 200

mg/L, 20 mg/L, 200 mg/L, 250 mg/L, 300 mg/L, 250 mg/L and 100 mg/L (NESREA, 2011; Subba-Rao, 2012; SON, 2015; WHO, 2022).

Hydrogeochemical Indices and Irrigation Suitability

To evaluate the hydrogeochemical status of the aquifer as well as determine its suitability for irrigation, this study applied multiple hydrogeochemical indices and diagrams, categorized by their function.

Sodium-Related Hazards:

This included the Kelly's Ratio, KR (Kelly, 1940; Edet, 2017); Sodium Adsorption Ratio, SAR (Richard, 1954; Rawat et al., 2018; Okoroh & Ibuot, 2022); Sodium Percentage, Na% (Todd, 1980; Edet, 2017); and Soluble Sodium Percentage, SSP (Todd, 1980; Nagarju et al., 2006; Singh et al., 2020).

Soil Permeability & Magnesium Concerns:

Indices for this category were the Permeability Index, PI (Doneen, 1964; Edet, 2017; Rawat et al., 2018); Magnesium Adsorption Ratio, MAR (Szobolces & Darab, 1968; Amadi et al., 2020); and Magnesium Hazard, MH (Ragunath, 1987; Edet, 2017).

Alkalinity, Salinity, and Corrosivity Risks:

This assessment utilized the Chloride-Bicarbonate Ratio or Revelle Index, CBR/RI (Revelle, 1941; Davis & Wiest, 1996; Panjaitan et al., 2018); Residual Sodium Carbonate, RSC (Eaton, 1950; Ragunath, 1987; Edet, 2017); Potential Salinity, PS (Doneen, 1964; Edet, 2017); Bicarbonate Hazard, BH (Kacmaz & Nakoman, 2010; Agidi et al., 2022); and the Corrosivity Ratio, CR (Rutharvel et al., 2010).

Hydrogeochemical facies

This included the calculation of chloroalkaline indices and plotting of graphs. Chloroalkaline Indices (CA I and CA II) (Schoeller, 1965; Rawat et al., 2018) were calculated using Microsoft Excel while WQChartPy, an open-source Python package developed by Yang *et al.* (2022) for analysis of aqueous geochemical data was used to plot Piper, Chadha, Gibbs, Schoeller, Gaillardet and Hydrochemical Facies Evolution (HFE-D) diagrams. Detailed explanations and the mathematical formulae for all indices are reported in Gbadebo et al. (2026a).

Statistical Analyses

Descriptive and inferential statistics such as mean, range and principal component analysis were deployed in this study. Results were displayed using frequency tables, graphs and charts. Statistical packages including Microsoft Excel 2021 (Microsoft Corporation, 2021), IBM SPSS Statistics Version 28.0 (IBM Corporation, 2021) and PAST Version 4.03 (Hammer et al., 2001) were utilized in this study.

Results and Discussion

Physicochemical Parameters, Major Cations and Anions of Water Samples

The analysis of physical parameters and major ion chemistry in groundwater samples from Epe revealed a generally good quality water resource, characterized by neutral pH and high levels of magnesium, though with notable variability across locations.

Table 1: Physical, Chemical Parameters and Major Ions of Groundwater in Epe

Locat ion	SC	N	TD	SWL	pH	Na ⁺ (mg/L)	K ⁺ (mg/L)	Ca ²⁺ (mg/L)	Mg ²⁺ (mg/L)	HCO ₃ ⁻ (mg/L)	SO ₄ ²⁻ (mg/L)	Cl ⁻ (mg/L)
Ayeto ro	AY 1-8	8	5.81 ± 3.21	3.26 ± 1.93	7.03 ± 0.05	18.85 ± 8.84	9.00 ± 3.89	70.00 ± 36.24	78.25 ± 12.69	79.88 ± 66.98	30.13 ± 7.32	2.64 ± 0.43
Iraye	IR1 -3	3	7.44 ± 0.00	2.79 ± 0.93	7.03 ± 0.06	15.93 ± 1.81	7.33 ± 2.52	55.00 ± 3.00	73.67 ± 8.02	73.33 ± 40.72	59.00 ± 16.52	2.40 ± 0.53
Odom ola	OD 1-4	4	5.12 ± 2.21	2.09 ± 0.89	7.05 ± 0.06	17.00 ± 3.80	10.80 ± 6.40	62.30 ± 9.00	87.50 ± 7.00	102.00 ± 32.00	73.30 ± 9.10	2.00 ± 0.37
Mojod a	MJ 1-9	9	12.61 ± 2.79	4.55 ± 0.73	7.03 ± 0.05	16.07 ± 1.75	9.89 ± 4.88	60.89 ± 14.79	68.67 ± 22.89	84.00 ± 21.31	66.33 ± 29.95	2.23 ± 0.88
Ilara	IL1 -6	6	5.89 ± 4.10	2.79 ± 2.28	7.03 ± 0.05	16.35 ± 2.69	7.83 ± 3.49	58.17 ± 6.74	66.33 ± 17.06	45.50 ± 10.09	43.17 ± 10.28	1.75 ± 0.35
Poka	PK 1-4	4	10.46 ± 1.40	4.41 ± 0.90	5.53 ± 3.02	21.93 ± 12.33	11.00 ± 3.37	84.25 ± 50.13	96.00 ± 19.68	53.00 ± 13.90	29.25 ± 9.78	2.60 ± 0.16
Odo- Iragus hi	OI R1- 6	6	7.44 ± 1.76	2.64 ± 0.91	7.03 ± 0.05	16.85 ± 3.07	9.67 ± 5.47	59.83 ± 8.13	81.50 ± 10.99	101.50 ± 73.24	46.17 ± 17.61	2.58 ± 0.61
Eredo	ER 1- 10	1 0	5.60 ± 2.70	2.40 ± 1.30	7.03 ± 0.05	16.50 ± 2.10	10.10 ± 4.70	61.90 ± 14.30	65.70 ± 23.50	88.10 ± 28.40	73.00 ± 24.00	2.15 ± 0.62

Where: SC = Sample Code; N = Number of Samples; TD = Total Depth SWL = Static Water Level; pH = Hydrogen Ion Concentration; Ca, Mg, Na and K are cations while HCO₃, Cl and SO₄ are anions.

Source: Field Survey, 2025

As shown in Table 1, the total depth of the wells ranged from 5.12 ± 2.21 in Odomola to 12.61 ± 2.79 metres in Mojoda, while the static water level ranged from 2.09 ± 0.89 to 4.55 ± 0.73 metres across the same locations. The pH values across the sampled communities were consistently neutral, with mean values ranging from 7.03 to 7.05 in all areas except Poka. Poka exhibited a lower and highly variable mean pH of 5.53 ± 3.02, indicating acidic conditions in one of its wells (PK₄) in Table SI (Supplementary Information). This localized acidity is a critical observation, as it can increase the corrosiveness of water, potentially

mobilizing heavy metals from pipes and well fittings, and poses a risk to plumbing systems. This acidic anomaly in Poka finds parallels in other Nigerian studies. For instance, acidic groundwater (pH 5.2 -6.85) was reported in parts of Abuja, while studies in Ado-Ekiti and Lagos State University, Epe, also recorded acidic pH values, with the latter as low as 3.8, highlighting that localized acidic groundwater is a recurring issue in some Nigerian aquifers (Jibrin et al., 2015; Kayode et al., 2024; Salami and Ayinde, 2025). The neutral pH in all other locations is favourable, suggesting a natural buffering capacity, likely from the dissolution of minerals within the aquifer materials, a process also identified as a key control on groundwater chemistry in the Komadugu-Yobe Basin and Ajaokuta (Shuaibu et al., 2024; Omali, 2024).

The mean concentrations of major cations provide insight into the aquifer's mineralogy. A striking feature was the consistent dominance of magnesium (Mg^{2+}) and calcium (Ca^{2+}). Magnesium concentrations were particularly high, ranging from 65.70 ± 23.50 mg/L in Eredo to 96.00 ± 19.68 mg/L in Poka exceeding the NSDWQ limit of 20 mg/L (SON, 2015). Similarly, calcium levels ranged from 55.00 ± 3.00 mg/L in Iraye to 84.25 ± 50.13 mg/L in Poka. These elevated levels of both calcium and magnesium are characteristic of groundwater interacting with carbonate minerals (like biogenic calcite) or magnesium-rich silicate minerals present in the Benin Formation. The $Mg^{2+} > Ca^{2+}$ dominance pattern observed in Epe is a notable feature also reported in studies from Okigwe, Akure, and other parts of southwestern Nigeria, confirming a regional hydrogeochemical signature linked to the weathering of specific rock types comprising of Migmatite-Gneiss, Quartzite, Charnokite, Biotite granite, Pelitic Schist, Granite Gneiss, and Granite (Falowo et al., 2019b; Ugbor et al., 2022). The very high concentrations in Poka are notable and align with its acidic pH, suggesting more aggressive weathering of these minerals.

In contrast, sodium (Na^+) and potassium (K^+) concentrations were low and uniform across all locations. Sodium ranged from 15.93 ± 1.81 mg/L in Iraye to 21.93 ± 12.33 mg/L in Poka, while potassium ranged from 7.33 ± 2.52 mg/L in Iraye to 11.00 ± 3.37 mg/L in Poka. All values were well below WHO, SON and NESREA guideline values. The low sodium levels are a positive finding, indicating minimal influence from seawater intrusion in the sampled shallow aquifers of this coastal region. This is a crucial distinction, as numerous studies in coastal areas like Eastern Obolo, Nigeria, and the Mekong Delta, Vietnam, have reported severe sodium and chloride contamination due to seawater intrusion, a threat from which Epe's aquifers appear to be currently shielded (Nkpoidet et al., 2025; Duc et al., 2025).

The distribution of anions further clarified the hydrochemical processes. Bicarbonate (HCO_3^-), the primary anion contributing to alkalinity, showed variability ranging from 45.50 ± 10.09 mg/L in Ilara to 102.00 ± 32.00 mg/L in Odomola. The elevated bicarbonate levels in areas like Odomola and Odo-Iragushi are consistent with active dissolution of biogenic calcite and rock-water interaction, which buffers the groundwater to a near-neutral pH. Sulphate (SO_4^{2-}) concentrations also showed considerable variation (29.25 ± 9.78 mg/L in Poka to 73.30 ± 9.10 mg/L in Odomola). The relatively higher sulphate in several locations could be attributed to the oxidation of sulphide minerals or the dissolution of gypsum within

the coastal plain sands, as well as potential anthropogenic inputs from agricultural fertilizers. Since gypsum is not among minerals listed in Epe area, the sulphate in water is probably from an anthropogenic source aligning with findings from Iworoko, Ekiti, where anthropogenic activities were identified as a major source of sulphate pollution (Abdu-Raheem et al., 2024).

Chloride (Cl^-) concentrations were remarkably low and consistent across all communities, varying narrowly from 1.75 ± 0.35 mg/L in Ilara to 2.64 ± 0.43 mg/L in Ayetoro. These values are far below the WHO permissible limit of 250 mg/L, providing strong evidence that the shallow aquifers in Epe are not currently experiencing salinity intrusion from the nearby lagoons or the Atlantic Ocean. This finding is important when contrasted with studies from the coastal community of Ayetoro, Ondo, and Makoko, Lagos, where high chloride levels confirmed saline intrusion, highlighting Epe's relatively pristine condition in this regard (Martins and Mafimisebi, 2024a; Martins and Mafimisebi, 2024b).

Overall, the general ionic dominance pattern for cations across the study area is $\text{Mg}^{2+} > \text{Ca}^{2+} > \text{Na}^+ > \text{K}^+$, highlighting the magnesium-rich nature of the groundwater, which is consistent with the described geology. For anions, the pattern is more variable but is generally $\text{HCO}_3^- > \text{SO}_4^{2-} > \text{Cl}^-$, confirming a bicarbonate water type with an important sulphate component.

Dietary Intake of Essential Elements from Groundwater

The assessment of dietary intake of essential elements from groundwater consumption in Epe revealed a clear public health finding: while the water poses no risk of toxicity, it provides a negligible to highly variable contribution to the daily nutritional requirements for most elements across all life stage groups.

A comparative analysis of the calculated dietary intake against the Recommended Dietary Allowance (RDA) or Adequate Intake (AI) showed a consistent and substantial deficit for most elements. Crucially, all recorded intake values from groundwater were orders of magnitude below the Tolerable Upper Intake Level (UL) where specified, indicating no risk of adverse health effects from overconsumption of these minerals through drinking water. The contribution of groundwater to daily calcium intake was minimal across all locations and demographics. As detailed in Table 2, the highest calcium intake from water was 320.15 mg/d for lactating women aged 14 - 50 years in Poka. When compared to the RDA of 1000 - 1300 mg/day for this age group, this represents only about 25 - 32% of the daily requirement. For other locations, this contribution was much lower. This indicates that while the groundwater is a source of calcium, the primary intake of this essential mineral must come from dietary sources. No community's water provides calcium close to the full RDA.

The data for magnesium revealed the most important and highly variable nutritional contribution from groundwater. The intake ranged from modest levels in locations like Eredo and Mojoda to remarkably high levels in Poka and Odomola. The intake from Poka's groundwater fulfilled approximately 85% of the RDA for adult males, making it a very substantial source of this essential mineral. This stark geographical variation underscores

the influence of local geology on water quality. The high magnesium content, while beneficial for nutrition, also contributes to water hardness. Elevated magnesium hazard (MH) for irrigation has been noted as a concern in studies from Burkina Faso and Morocco, but in Epe, from a dietary intake perspective, it represents a positive health aspect (Sehlaoui et al., 2020; Serge Gaëtan et al., 2022).

The contribution of potassium and sodium from groundwater was nutritionally unimportant.

Table 2: Comparison of Dietary Intake of Essential Elements from Groundwater in Epe with RDA/AI and UL

LSG	Age Group	Ca (mg/d)									
		RDA /AI	UL	Ayet oro	Iray e	Odo mola	Moj oda	llar a	Pok a	Odo-Iragushi	Ere do
Infants	0–6 mo	200 *	1,000g	49.00	38.50	43.61	42.62	40.72	58.98	41.88	43.33
	7–12 mo	260 *	1,500g	56.00	44.00	49.84	48.71	46.54	67.40	47.86	49.52
Children	1–3 y	700	2500	91.00	71.50	80.99	79.16	75.62	109.53	77.78	80.47
	4–8 y	1,000	2,500	119.00	93.50	105.91	103.51	98.89	143.23	101.71	105.23
Males	9–13 y	1,300	3,000	168.00	132.00	149.52	146.14	139.61	202.20	143.59	148.56
	14–18 y	1,300	3,000	231.00	181.50	205.59	200.94	191.96	278.03	197.44	204.27
	19–30 y	1,000	2,500	259.00	203.50	230.51	225.29	215.23	311.73	221.37	229.03
	31–50 y	1,000	2,500	259.00	203.50	230.51	225.29	215.23	311.73	221.37	229.03
	51–70 y	1,000	2,000	259.00	203.50	230.51	225.29	215.23	311.73	221.37	229.03
	> 70 y	1,200	2,000	259.00	203.50	230.51	225.29	215.23	311.73	221.37	229.03

LSG	Age Group	Ca (mg/d)									
		RDA /AI	UL	Ayet oro	Iray e	Odo mola	Moj oda	llar a	Pok a	Odo-Iragushi	Ere do
Females	9–13 y	1,300	3,000	147.00	115.50	130.83	127.87	122.16	176.93	125.64	129.99
	14–18 y	1,300	3,000	161.00	126.50	143.29	140.05	133.79	193.78	137.61	142.37
	19–30 y	1,000	2,500	189.00	148.50	168.21	164.40	157.06	227.48	161.54	167.13
	31–50 y	1,000	2,500	189.00	148.50	168.21	164.40	157.06	227.48	161.54	167.13
	51–70 y	1,200	2,000	189.00	148.50	168.21	164.40	157.06	227.48	161.54	167.13
	> 70 y	1,200	2,000	189.00	148.50	168.21	164.40	157.06	227.48	161.54	167.13
Pregnancy	14–18 y	1,300	3,000	210.00	165.00	186.90	182.67	174.51	252.75	179.49	185.70
	19–30 y	1,000	2,500	210.00	165.00	186.90	182.67	174.51	252.75	179.49	185.70
	31–50 y	1,000	2,500	210.00	165.00	186.90	182.67	174.51	252.75	179.49	185.70
Lactation	14–18 y	1,300	3,000	266.00	209.00	236.74	231.38	221.05	320.15	227.35	235.22
	19–30 y	1,000	2,500	266.00	209.00	236.74	231.38	221.05	320.15	227.35	235.22
	31–50 y	1,000	2,500	266.00	209.00	236.74	231.38	221.05	320.15	227.35	235.22

Where: mo = month(s); y = year(s); UL = Tolerable Upper Intake Level; Values with asterisk are Adequate Intake (AI) and those without are Recommended Dietary Allowance (RDA)

Source: Field Survey, 2025

Table 2: Comparison of Dietary Intake of Essential Elements from Groundwater in Epe with RDA/AI and UL Continued

LSG	Age Group	Mg (mg/d)									
		RDA /AI	U L	Ayet oro	Iray e	Odo mola	Moj oda	Ilara	Pok a	Odo-Iragushi	Ered o
Infants	0-6 mo	30*	N D	54.78	51.57	61.25	48.07	46.43	67.20	57.05	45.99
	7-12 mo	75*	N D	62.60	58.94	70.00	54.94	53.06	76.80	65.20	52.56
Children	1-3 y	80	N D	101.73	95.77	113.75	89.27	86.23	124.80	105.95	85.41
	4-8 y	130	N D	133.03	125.24	148.75	116.74	112.76	163.20	138.55	111.69
Males	9-13 y	240	N D	187.80	176.81	210.00	164.81	159.19	230.40	195.60	157.68
	14-18 y	410	N D	258.23	243.11	288.75	226.61	218.89	316.80	268.95	216.81
	19-30 y	400	N D	289.53	272.58	323.75	254.08	245.42	355.20	301.55	243.09
	31-50 y	420	N D	289.53	272.58	323.75	254.08	245.42	355.20	301.55	243.09
	51-70 y	420	N D	289.53	272.58	323.75	254.08	245.42	355.20	301.55	243.09
	> 70 y	420	N D	289.53	272.58	323.75	254.08	245.42	355.20	301.55	243.09
Females	9-13 y	240	N D	164.33	154.71	183.75	144.21	139.29	201.60	171.15	137.97
	14-18 y	360	N D	179.98	169.44	201.25	157.94	152.56	220.80	187.45	151.11

LSG	Age Group	Mg (mg/d)									
		RDA /AI	U L	Ayet oro	Iray e	Odo mola	Moj oda	Ilara	Pok a	Odo-Iragushi	Ered o
	19-30 y	310	N D	211.28	198.91	236.25	185.41	179.09	259.20	220.05	177.39
	31-50 y	320	N D	211.28	198.91	236.25	185.41	179.09	259.20	220.05	177.39
	51-70 y	320	N D	211.28	198.91	236.25	185.41	179.09	259.20	220.05	177.39
	> 70 y	320	N D	211.28	198.91	236.25	185.41	179.09	259.20	220.05	177.39
Pregnancy	14-18 y	400	N D	234.75	221.01	262.50	206.01	198.99	288.00	244.50	197.10
	19-30 y	350	N D	234.75	221.01	262.50	206.01	198.99	288.00	244.50	197.10
	31-50 y	360	N D	234.75	221.01	262.50	206.01	198.99	288.00	244.50	197.10
Lactation	14-18 y	360	N D	297.35	279.95	332.50	260.95	252.05	364.80	309.70	249.66
	19-30 y	310	N D	297.35	279.95	332.50	260.95	252.05	364.80	309.70	249.66
	31-50 y	320	N D	297.35	279.95	332.50	260.95	252.05	364.80	309.70	249.66

Where: mo = month(s); y = year(s); UL = Tolerable Upper Intake Level; Values with asterisk are Adequate Intake (AI) and those without are Recommended Dietary Allowance (RDA)

Source: Field Survey, 2025

Table 2: Comparison of Dietary Intake of Essential Elements from Groundwater in Epe with RDA/AI and UL Continued

LSG	Age Group	K (mg/d)									
		RD A/ AI	UL	Ayet oro	Iray e	Odom ola	Mojo da	Ilar a	Pok a	Odo- Iragushi	Ere do
Infants	0–6 mo	400*	ND	6.30	5.13	7.56	6.92	5.48	7.70	6.77	7.07
	7–12 mo	860*	ND	7.20	5.86	8.64	7.91	6.26	8.80	7.74	8.08
Children	1–3 y	2,000*	ND	11.70	9.53	14.04	12.86	10.18	14.30	12.57	13.13
	4–8 y	2,300*	ND	15.30	12.46	18.36	16.81	13.31	18.70	16.44	17.17
Males	9–13 y	2,500*	ND	21.60	17.59	25.92	23.74	18.79	26.40	23.21	24.24
	14–18 y	3,000*	ND	29.70	24.19	35.64	32.64	25.84	36.30	31.91	33.33
	19–30 y	3,400*	ND	33.30	27.12	39.96	36.59	28.97	40.70	35.78	37.37
	31–50 y	3,400*	ND	33.30	27.12	39.96	36.59	28.97	40.70	35.78	37.37
	51–70 y	3,400*	ND	33.30	27.12	39.96	36.59	28.97	40.70	35.78	37.37
	> 70 y	3,400*	ND	33.30	27.12	39.96	36.59	28.97	40.70	35.78	37.37
Females	9–13 y	2,300*	ND	18.90	15.39	22.68	20.77	16.44	23.10	20.31	21.21
	14–18 y	2,300*	ND	20.70	16.86	24.84	22.75	18.01	25.30	22.24	23.23

LSG	Age Group	K (mg/d)									
		RD A/ AI	UL	Ayet oro	Iray e	Odom ola	Mojo da	llar a	Pok a	Odo-Iragushi	Ere do
	19–30 y	2,600 *	ND	24.30	19.79	29.16	26.70	21.14	29.70	26.11	27.27
	31–50 y	2,600 *	ND	24.30	19.79	29.16	26.70	21.14	29.70	26.11	27.27
	51–70 y	2,600 *	ND	24.30	19.79	29.16	26.70	21.14	29.70	26.11	27.27
	> 70 y	2,600 *	ND	24.30	19.79	29.16	26.70	21.14	29.70	26.11	27.27
Pregna ncy	14–18 y	2,600 *	ND	27.00	21.99	32.40	29.67	23.49	33.00	29.01	30.30
	19–30 y	2,900 *	ND	27.00	21.99	32.40	29.67	23.49	33.00	29.01	30.30
	31–50 y	2,900 *	ND	27.00	21.99	32.40	29.67	23.49	33.00	29.01	30.30
Lactati on	14–18 y	2,500 *	ND	34.20	27.85	41.04	37.58	29.75	41.80	36.75	38.38
	19–30 y	2,800 *	ND	34.20	27.85	41.04	37.58	29.75	41.80	36.75	38.38
	31–50 y	2,800 *	ND	34.20	27.85	41.04	37.58	29.75	41.80	36.75	38.38

Where: mo = month(s); y = year(s); UL = Tolerable Upper Intake Level; Values with asterisk are Adequate Intake (AI) and those without are Recommended Dietary Allowance (RDA)

Source: Field Survey, 2025

Table 2: Comparison of Dietary Intake of Essential Elements from Groundwater in Epe with RDA/AI and UL Continued

LSG	Age Group	Na (mg/d)									
		RDA /AI	U L	Ayet oro	Iray e	Odom ola	Mojo da	Ilar a	Pok a	Odo-Iragushi	Ere do
Infants	0–6 mo	110*	N D	13.20	11.15	11.90	11.25	11.45	15.35	11.80	11.55
	7–12 mo	370*	N D	15.08	12.74	13.60	12.86	13.08	17.54	13.48	13.20
Children	1–3 y	800*	N D	24.51	20.71	22.10	20.89	21.26	28.51	21.91	21.45
	4–8 y	1,000*	N D	32.05	27.08	28.90	27.32	27.80	37.28	28.65	28.05
Males	9–13 y	1,200*	N D	45.24	38.23	40.80	38.57	39.24	52.63	40.44	39.60
	14–18 y	1,500*	N D	62.21	52.57	56.10	53.03	53.96	72.37	55.61	54.45
	19–30 y	1,500*	N D	69.75	58.94	62.90	59.46	60.50	81.14	62.35	61.05
	31–50 y	1,500*	N D	69.75	58.94	62.90	59.46	60.50	81.14	62.35	61.05
	51–70 y	1,500*	N D	69.75	58.94	62.90	59.46	60.50	81.14	62.35	61.05
	> 70 y	1,500*	N D	69.75	58.94	62.90	59.46	60.50	81.14	62.35	61.05
Females	9–13 y	1,200*	N D	39.59	33.45	35.70	33.75	34.34	46.05	35.39	34.65
	14–18 y	1,500*	N D	43.36	36.64	39.10	36.96	37.61	50.44	38.76	37.95

LSG	Age Group	Na (mg/d)									
		RDA /AI	U L	Ayet oro	Iray e	Odom ola	Mojo da	Ilar a	Pok a	Odo-Iragushi	Ere do
	19–30 y	1,500*	N D	50.90	43.01	45.90	43.39	44.15	59.21	45.50	44.55
	31–50 y	1,500*	N D	50.90	43.01	45.90	43.39	44.15	59.21	45.50	44.55
	51–70 y	1,500*	N D	50.90	43.01	45.90	43.39	44.15	59.21	45.50	44.55
	> 70 y	1,500*	N D	50.90	43.01	45.90	43.39	44.15	59.21	45.50	44.55
Pregna ncy	14–18 y	1,500*	N D	56.55	47.79	51.00	48.21	49.05	65.79	50.55	49.50
	19–30 y	1,500*	N D	56.55	47.79	51.00	48.21	49.05	65.79	50.55	49.50
	31–50 y	1,500*	N D	56.55	47.79	51.00	48.21	49.05	65.79	50.55	49.50
Lactati on	14–18 y	1,500*	N D	71.63	60.53	64.60	61.07	62.13	83.33	64.03	62.70
	19–30 y	1,500*	N D	71.63	60.53	64.60	61.07	62.13	83.33	64.03	62.70
	31–50 y	1,500*	N D	71.63	60.53	64.60	61.07	62.13	83.33	64.03	62.70

Where: mo = month(s); y = year(s); UL = Tolerable Upper Intake Level; Values with asterisk are Adequate Intake (AI) and those without are Recommended Dietary Allowance (RDA)

Source: Field Survey, 2025

Table 2: Comparison of Dietary Intake of Essential Elements from Groundwater in Epe with RDA/AI and UL Continued

LSG	Age Group	CI (mg/d)									
		RDA /AI	UL	Ayet oro	Ira ye	Odom ola	Mojo da	Ilar a	Po ka	Odo-Iragushi	Ere do
Infants	0–6 mo	180*	ND	1.85	1.68	1.40	1.56	1.23	1.82	1.81	1.51
	7–12 mo	570*	ND	2.11	1.92	1.60	1.78	1.40	2.08	2.06	1.72
Children	1–3 y	1500*	2300	3.43	3.12	2.60	2.90	2.28	3.38	3.35	2.80
	4–8 y	1900*	2,900	4.49	4.08	3.40	3.79	2.98	4.42	4.39	3.66
Males	9–13 y	2300*	3,400	6.34	5.76	4.80	5.35	4.20	6.24	6.19	5.16
	14–18 y	2300*	3,600	8.71	7.92	6.60	7.36	5.78	8.58	8.51	7.10
	19–30 y	2300*	3,600	9.77	8.88	7.40	8.25	6.48	9.62	9.55	7.96
	31–50 y	2300*	3,600	9.77	8.88	7.40	8.25	6.48	9.62	9.55	7.96
	51–70 y	2000*	3,600	9.77	8.88	7.40	8.25	6.48	9.62	9.55	7.96
	> 70 y	1800*	3,600	9.77	8.88	7.40	8.25	6.48	9.62	9.55	7.96
Females	9–13 y	2300*	3,400	5.54	5.04	4.20	4.68	3.68	5.46	5.42	4.52
	14–18 y	2300*	3,600	6.07	5.52	4.60	5.13	4.03	5.98	5.93	4.95

LSG	Age Group	Cl (mg/d)									
		RDA /AI	UL	Ayet oro	Ira ye	Odom ola	Mojo da	Ilar a	Po ka	Odo-Iragushi	Ere do
	19–30 y	2300 *	3,600	7.13	6.48	5.40	6.02	4.73	7.02	6.97	5.81
	31–50 y	2300 *	3,600	7.13	6.48	5.40	6.02	4.73	7.02	6.97	5.81
	51–70 y	2000 *	3,600	7.13	6.48	5.40	6.02	4.73	7.02	6.97	5.81
	> 70 y	1800 *	3,600	7.13	6.48	5.40	6.02	4.73	7.02	6.97	5.81
Pregna ncy	14–18 y	2300 *	3,600	7.92	7.20	6.00	6.69	5.25	7.80	7.74	6.45
	19–30 y	2300 *	3,600	7.92	7.20	6.00	6.69	5.25	7.80	7.74	6.45
	31–50 y	2300 *	3,600	7.92	7.20	6.00	6.69	5.25	7.80	7.74	6.45
Lactati on	14–18 y	2300 *	3,600	10.03	9.12	7.60	8.47	6.65	9.88	9.80	8.17
	19–30 y	2300 *	3,600	10.03	9.12	7.60	8.47	6.65	9.88	9.80	8.17
	31–50 y	2300 *	3,600	10.03	9.12	7.60	8.47	6.65	9.88	9.80	8.17

Where: mo = month(s); y = year(s); UL = Tolerable Upper Intake Level; Values with asterisk are Adequate Intake (AI) and those without are Recommended Dietary Allowance (RDA)

Source: Field Survey, 2025

unimportant. For most adult groups, the contribution was around 1% of the AI. This confirms that groundwater in Epe is not a meaningful source of these electrolytes. From a public health perspective, the low sodium content is beneficial, as it does not contribute to excessive sodium consumption, a known risk factor for hypertension. Mirroring the findings for sodium, the dietary intake of chloride from groundwater was minimal. Therefore, the groundwater's contribution is nutritionally irrelevant.

Overall, the groundwater in Epe can be considered a very safe source of essential elements from a toxicity standpoint, with all intake levels far below the tolerable upper intake level (UL). However, from a nutritional perspective, its value is limited and highly element-specific. The water is a notably poor source of potassium, sodium, and chloride, a modest source of calcium, and a potentially valuable source of magnesium in specific locations like Poka and Odomola. Public health guidance should therefore focus on promoting dietary diversification to ensure adequate intake of all essential elements, rather than relying on groundwater as a primary nutritional source.

Water Quality Index (WQI)

The calculated WQI values for groundwater samples in Epe ranged between 40.41 and 128.49 (Table S4 in Supplementary Information). Magnesium was the chief parameter that contributed most to the overall WQI value. The groundwater sources as illustrated in Fig. 2 and shown in the interpretation key in Table S5 (Supplementary Information) were classed as: 8% "excellent", 76% "good" and 16% "poor." This finding indicates that the vast majority of the studied groundwater sources are suitable for direct human consumption without prior treatment. This result aligns with findings from studies in Akure, Akoko, and parts of Ilorin where a higher proportion of "good" to "excellent" water was reported (Olatunji et al., 2015; Falowo et al., 2017; Falowo et al., 2019a).

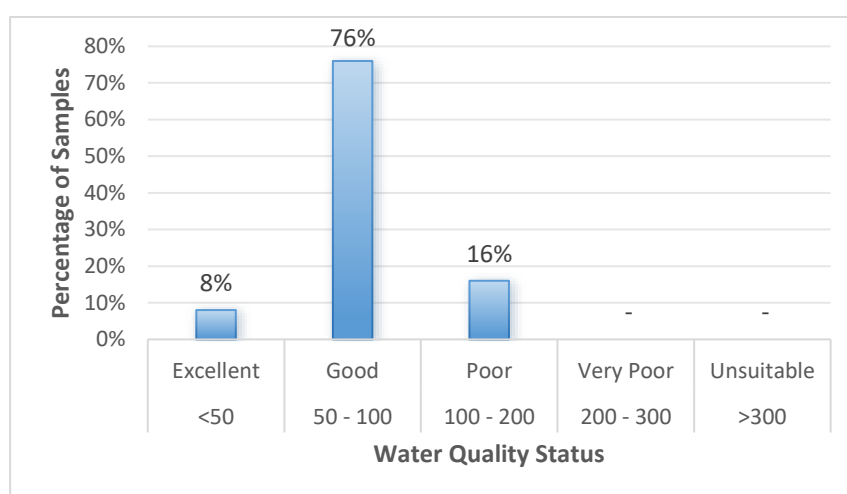


Fig. 2: Quality Status of Groundwater from Epe

Source: Field Survey, 2025

Pollution Index of Groundwater (PIG)

The Pollution Index of Groundwater (PIG) values (0.39 - 0.85) were generally below 1 for all samples, signifying insignificant levels of pollution. Magnesium also contributed most to the PIG values (Table S6 in Supplementary Information). The classification key is in Table S7 (Supplementary Information). This finding aligns with several global studies that have reported similarly low PIG values in regions with comparable hydrogeological settings. For

instance, in the Kurukshetra district of Haryana, India, the PIG ranged from 0.49 to 0.84, with an average value of 0.59, which also falls within the "insignificant pollution" category (Raheja et al., 2024). Also, in a rural area of Telangana State, India, Adimalla (2021) reported PIG values ranging from 0.69 to 1.37, with 80% of the study area classified into the insignificant pollution zone ($PIG < 1.0$), attributing this to predominantly geogenic sources such as rock-weathering and mineral dissolution. Similarly, in the Mnasra region of Morocco's Gharb Plain, Sanad et al. (2024) found that 86.66% of groundwater samples exhibited "insignificant pollution" with PIG values predominantly below 1.0, despite notable agricultural pressures in the region. Also, an assessment of a semi-arid region in northwestern Algeria found that calculated PIG values ranged from 0.35 to 1.15, with 95% of the study area classified as having "insignificant pollution" (Benamina et al., 2025). In the eastern Niger Delta, the PIG result showed "insignificant pollution" of groundwater (Akakuru et al., 2022).

In contrast to these findings where $PIG < 1$ dominates, several other global studies reveal that PIG can identify significant contamination in other settings. In the Yazd-Ardakan plain of Iran, the PIG index in 2011 showed 51.43% of the total plain area had low and negligible pollution, 10.83% had moderate, 9.58% had high, and 28.16% had very high pollution. Critically, after only ten years (by 2021), groundwater quality declined so that only 24.80% had low and negligible pollution, while 42.04% fell into the "very high pollution" category (Soltani-Gerdefaramarzi and Rahmani-Samani, 2025). Also, the town of Sidi Slimane in Morocco was classified as highly polluted ($PIG = 10.8$) and unfit for consumption due to excessive salinization from rock dissolution (Al-Aizari et al. 2023). These comparative values suggest that the Epe aquifer system is currently experiencing minimal anthropogenic stress relative to other semi-urban and agricultural settings globally.

Hydrogeochemical Indices and Irrigation Suitability

Table S8 presents a comprehensive evaluation of hydrogeochemical indices for assessing the irrigation suitability of groundwater in Epe. The analysis revealed water that is generally excellent in terms of sodium hazard but highlights a widespread magnesium hazard as a primary constraint for agricultural use.

Sodium-Related Hazards

Kelly's Ratio (KR) is an indicator of sodium hazard. The KR values in this study ranged from 0.06 to 0.13 (Table S8 in Supplementary Information). Since all values (Fig. 3a) were well below the critical threshold of 1.0, they confirm that sodium is not excessively high compared to calcium and magnesium, hence, excellent for irrigation from a sodium perspective. This aligns with the findings of Samanta et al. (2013). In contrast, studies by Kumar et al. (2017) and Awad et al. (2022) reported unsuitable KR values in other regions, highlighting that the favorable sodium conditions in Epe are not universal.

The Sodium Adsorption Ratio (SAR) is another critical indicator of the sodium hazard in irrigation water. The SAR values (Fig. 3b) in the water samples were uniformly low, ranging

from 0.22 (OD 4, OIR 6) to 0.51 (AY 8). These values fell within the "excellent" category for irrigation ($SAR < 10$), suggesting a very low risk of sodium-induced soil permeability issues. This excellent status is consistent with findings from Singh et al. (2020) in India (0.01-1.49), Samanta et al. (2013) in West Bengal (0.51-1.25), and Awad et al. (2022), who reported all groundwater samples in Iraq as suitable based on SAR.

Both Sodium Percentage (%Na) and Soluble Sodium Percentage (SSP) confirmed the low sodium hazard. The %Na ranged from 6.62% to 15.04%, while SSP values ranged from 5.34% to 11.78%. All samples (Fig. 3c and Fig. 3d) fall within the "excellent" to "good" categories for irrigation, confirming that sodium accumulation in soils would not pose a high risk. This excellent quality is supported by Singh et al. (2020), Al-Mashreki et al. (2023), and Awad et al. (2022), though it contrasts with the more variable results of Agidi et al. (2022) in Nigeria.

Soil Permeability & Magnesium Concerns:

The Permeability Index (PI) assesses the long-term effects of water on soil hydraulic conductivity. The PI values ranged from 13.69% (PK 2) to 31.50% (ER 8). Following Doneen's classification (Fig. 3e), these values place 88% of samples in Class III (<25%) and 12% of samples in Class II (25–75%), indicating that majority are unsuitable for irrigation because they pose high risks to soil permeability.

The Magnesium Adsorption Ratio (MAR) and Magnesium Hazard (MH) are measures of the potential for magnesium to negatively affect soil structure. This is one of the most important findings of the irrigation assessment. The MAR/MH values in the study area ranged from 45.18% (MJ 8, ER 8) to 73.31% (MJ 3, ER 3). With values consistently exceeding the 50% threshold in 86% of samples (Fig. 3f), the groundwater is considered problematic for irrigation. Elevated magnesium levels can lead to the dispersion of clay particles, which reduces soil permeability, impedes drainage, and can negatively impact crop growth. This widespread magnesium hazard is a critical constraint also identified by other researchers. Singh et al. (2020) found that 56% of their samples exceeded the MH threshold of 50, while Rawat et al. (2018) and Agidi et al. (2022) reported that a majority or a large portion of groundwater in their study areas in India and Nigeria, respectively, was unsuitable for irrigation due to high MAR/MH.

Alkalinity, Salinity, and Corrosivity Risks:

The Chloride-Bicarbonate Ratio (CBR) / Revelle Index (RI) is used to assess the potential for seawater intrusion. The values varied narrowly between 0.03 and 0.11. All values (Fig. 3g) were well below 1, indicating seawater influence was not high and suggesting that the aquifer is not currently experiencing salinization from the nearby lagoon and ocean. This is a favorable condition when compared to the findings of Eyankware et al. (2021) in the Niger Delta, who reported salinization in several of their sample locations.

The Residual Sodium Carbonate (RSC) index assesses the excess of carbonate and bicarbonate over calcium and magnesium, which can lead to soil alkalinity. The RSC values

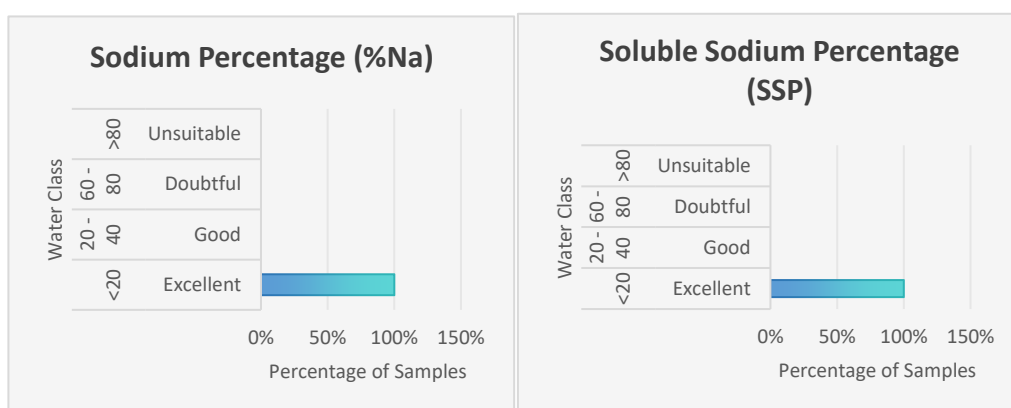
in this study were consistently and strongly negative, ranging from -17.16 (PK 3) to -3.89 (ER 8). These negative values (Fig. 3h) confirm that there is no risk of soil alkalization, a conclusion reinforced by the identical and also negative Bicarbonate Hazard (BH) values (Fig. 3i). This absence of a carbonate threat is widely observed, as noted by Al-Mashreki et al. (2023) and Awad et al. (2022). Singh et al. (2020) explained that negative RSC values prevent the precipitation of calcium and magnesium, thereby avoiding a relative increase in sodium and its associated hazards.

Potential Salinity (PS) measures the concentration of chloride and sulfate ions, which can accumulate in the soil. The PS values in the study ranged from 0.28 to 1.45, which are all (Fig. 3j) below the suitable limit of 3.0, suggesting no salinity concerns for irrigation use. This is a positive outcome compared to studies like Awad et al. (2022) and Al-Mashreki et al. (2023), who found a large number of samples to be unsuitable due to high PS.

The Corrosivity Ratio (CR) indicates the potential of the water to corrode metallic pipes and infrastructure. CR values ranged from 0.23 to 1.86. The data shows that 50% of samples exceeded the non-corrosive threshold of 1 (Fig. 3k), indicating a corrosive tendency. This is a practical concern for any irrigation system using metallic pipes, suggesting that non-metallic alternatives or protective measures may be necessary. This contrasts with Rawat et al. (2018), who found their groundwater safe, but aligns with Raju et al. (2011), who reported that 99% of their samples were corrosive.

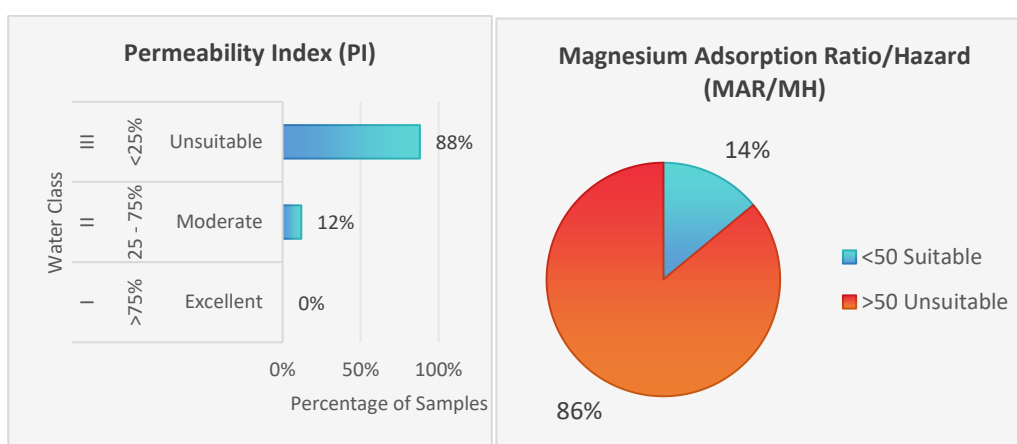
In synthesis, the groundwater in Epe presents a mixed profile for irrigation. Its most outstanding quality is its very low sodium hazard, as evidenced by excellent SAR, KR, %Na, and SSP values, a characteristic consistently observed in suitable waters globally. Furthermore, the negative RSC/BH and low PS indicate no alkalinity or salinity threats. However, the persistently low permeability index and high MAR/MH values across all locations represent a major limitation, a challenge possibly faced in several other international study areas. While the water can be used for irrigation, the magnesium hazard could lead to soil permeability problems over the long term, particularly in fine-textured soils. This risk must be managed through appropriate soil and water management practices, and the corrosivity of the water must be considered in the design of irrigation infrastructure.





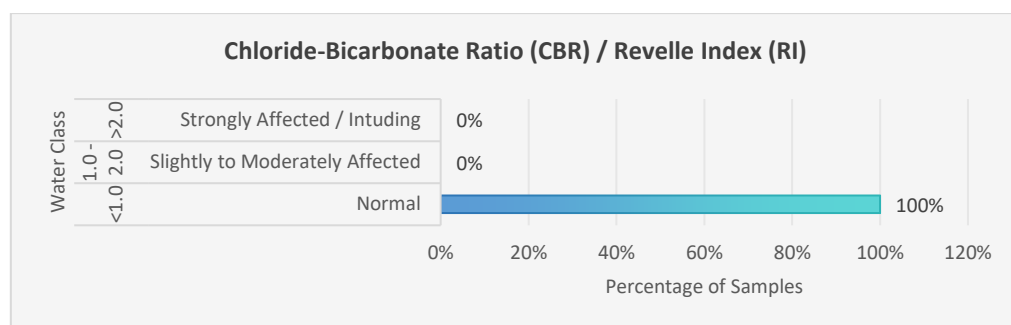
c.

d.

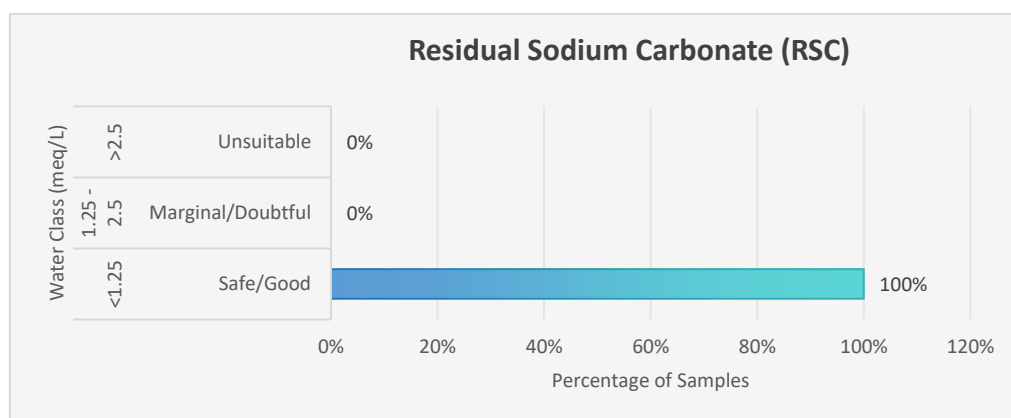


e.

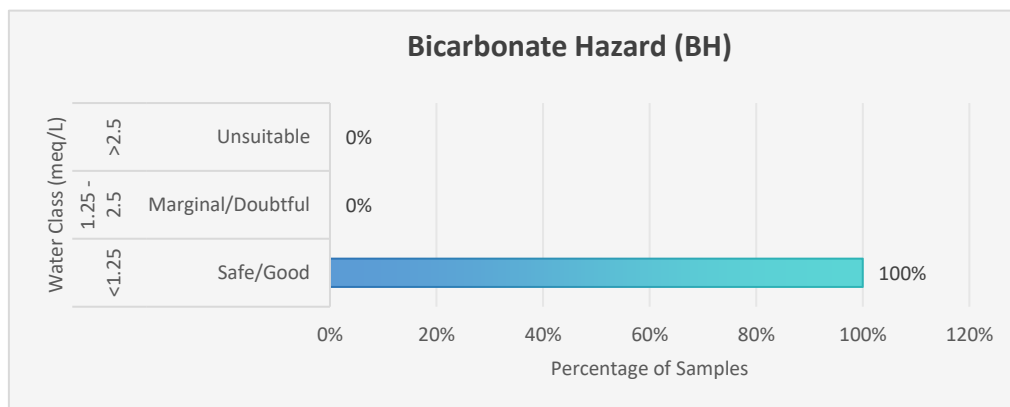
f.



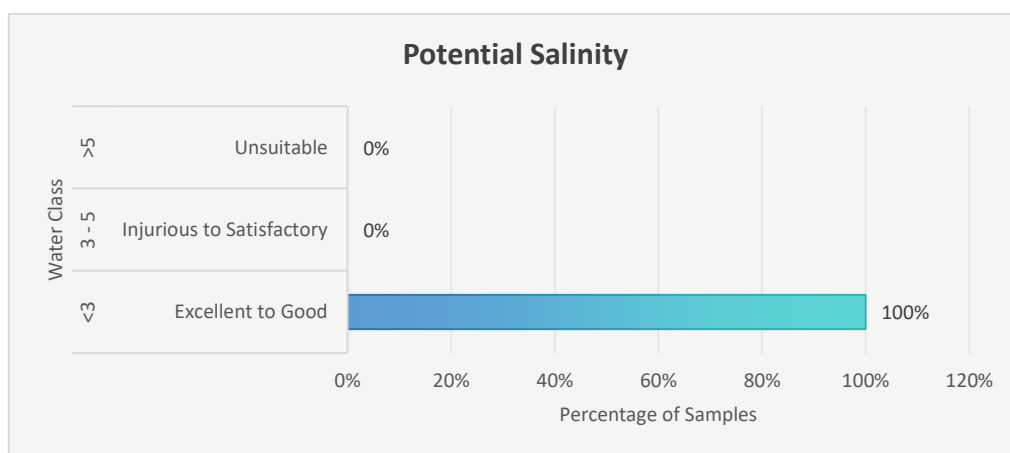
g.



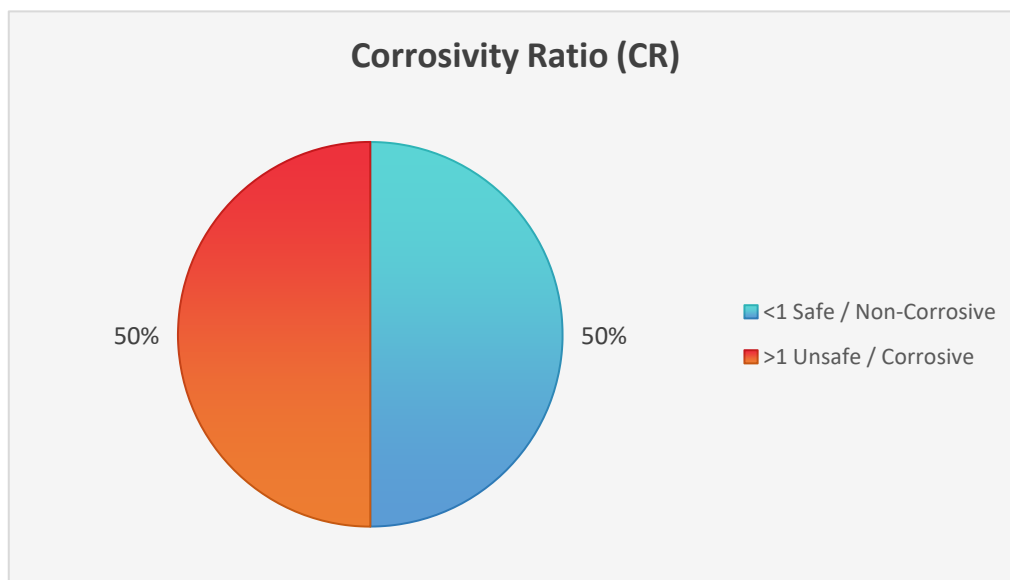
h.



i.



j.



k.

Fig. 3: Hydrogeochemical irrigation suitability indices a. KR, b. SAR, c. %Na, d. SSP, e. PI, f. MAR, g. CBR/RI, h. RSC, i. BH, j. PS, k. CR of groundwater in Epe
Source: Field Survey, 2025

Hydrogeochemical Facies Inferences

Piper Diagram

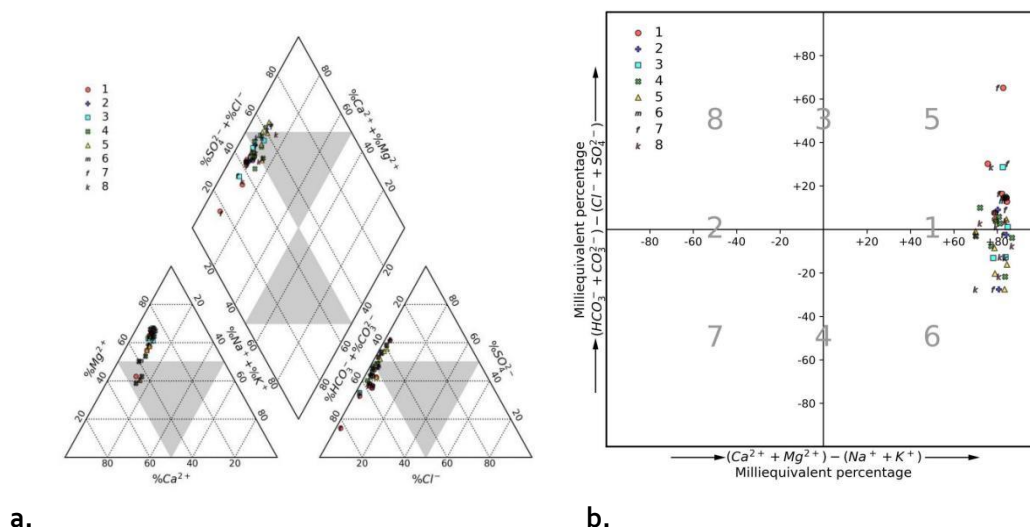
In the central diamond shape (Fig. 4a), majority of the samples fell in the calcium magnesium bicarbonate segment while a few fell into the calcium magnesium sulphate segment. In the left cation triangle, majority of the samples fell into the magnesium sub-triangle while some fell into the no dominant ion type sub-triangle. The some that fell into the no dominant ion type is a signal of ion exchange processes. In the right anion triangle, the vast majority fell into the bicarbonate type sub-triangle while a few fell into the sulphate type sub-triangle with a very few in no dominant type sub-triangle. Putting the results together, it is safe to conclude that the water in the study area is predominantly calcium magnesium bicarbonate with a few tending towards calcium magnesium sulphate type.

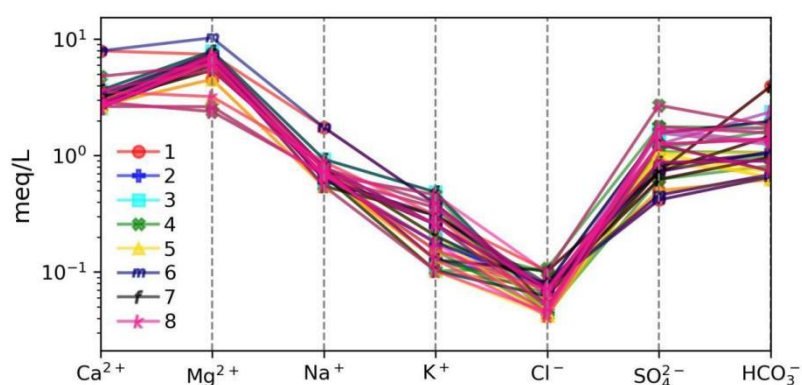
Chadha Diagram

This diagram (Fig. 4b) confirmed the results of the Piper Diagram. However, the distribution of samples between the first and second quadrant seemed to be even signally both a calcium magnesium bicarbonate water type and calcium magnesium sulphate chloride water type. It can be inferred that the water in the study area is calcium magnesium bicarbonate water type but with some infractions from sulphate pollutants probably from intensive use of fertilizer and pesticides on agricultural fields

Schoeller Diagram

This shows (Fig. 4c) the dominance of magnesium among the cations and bicarbonate among the anions. The levels of calcium and sulphate are almost respectively at par with magnesium and bicarbonate. It can be inferred that the source of sulphate is from anthropogenic additions from intensive agriculture.





c.

Where: 1 = Ayetoro, 2 = Iraye, 3 = Odomola, 4 = Mojoda, 5 = Ilara, 6 = Poka, 7 = Odo-Iragushi, 8 = Eredo

Fig. 4: Diagrams of a. Piper, b. Chadha and c. Schoeller showing the relative cation and anion composition of water samples (n=50)

Source: Field Survey, 2025

Chloroalkaline Indices

The Chloroalkaline Indices I (CA I) and II (CA II) are used to assess the nature of water-rock interactions, specifically ion exchange. In this study, CA I value (Table S8 in Supplementary Information) were consistently negative, ranging from -21.01 (AY 8) to -1.30 (ER 7), and CA II values were also negative, from -0.67 (PK 3) to -0.03 (ER 7). The overwhelmingly negative values for both indices across all samples indicate that ion exchange is the dominant geochemical process. This phenomenon, where sodium (Na^+) and potassium (K^+) ions adsorbed on clay minerals are released into the groundwater, exchanging with calcium (Ca^{2+}) and magnesium (Mg^{2+}) ions, is common in clay-rich aquifers like the Benin Formation. This finding aligns with global observations in similar geological settings. Studies by Singh et al. (2020) in India and Mussa and Mjemah (2023) in Tanzania also reported predominantly negative CA indices, confirming exchange as a key process controlling groundwater chemistry. Similarly, Li et al. (2016) in China and Ratri et al. (2021) in Indonesia identified this process in their respective aquifers, underscoring its prevalence in diverse hydrogeological environments. It is however important to note that despite the cation exchange the levels of Na and K were much lower than those of Ca and Mg. The probable cause is the low cation exchange capacity (CEC) of the quartz-sandy aquifer (Balogun et al., 2019), which completely exhausts its minor monovalent ions early in the season (Yusuf and Abiye, 2019), combined with accelerated dry-season weathering of silicate and carbonate minerals that continuously pumps calcium and magnesium into stagnant groundwater (Omeru et al., 2018; Lehmann et al., 2023; Mafimisebi, 2024).

Gibbs Diagram

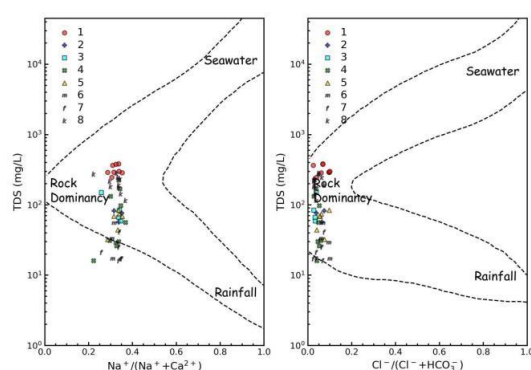
This shows (Fig. 5a) that the water quality is majorly affected by rock dominance with a minor contribution from rainfall or saturation. This signifies that rock water interaction is responsible for the ions in water.

Gaillardet Diagram

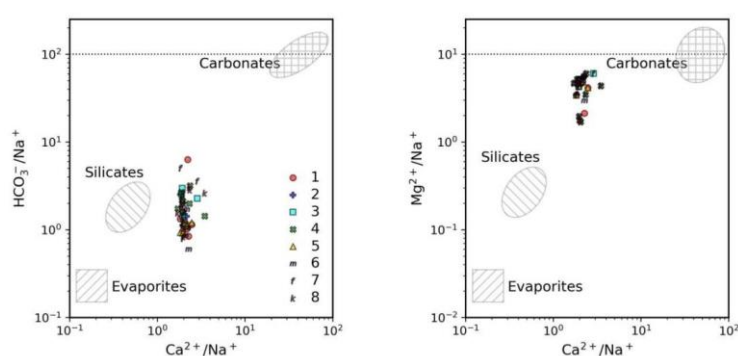
This shows (Fig. 5b) that the origin of the water is from the weathering of mixed carbonate and silicate rocks.

Hydrochemical Facies Evolution Diagram (HFED)

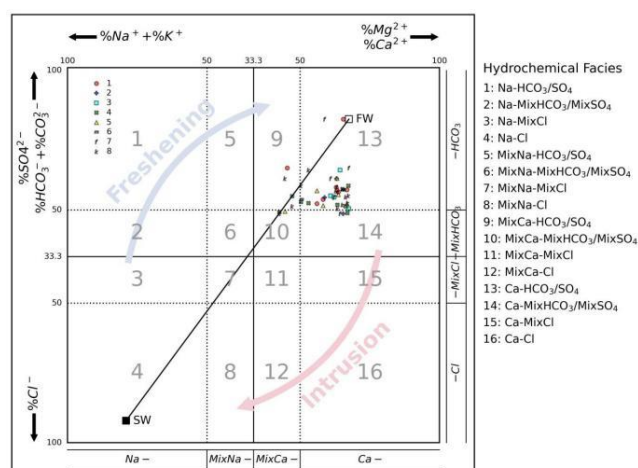
Samples fell majorly in quadrant 13 (Fig. 5c) and substantially in quadrant 9 which respectively represent mixed calcium bicarbonate/sulphate and calcium bicarbonate/sulphate water type. There are a few sample outliers on the border lines of 10 and 14 which represent mixed-calcium-mixed-bicarbonate-mixed-sulphate and calcium-mixed-bicarbonate-mixed-sulphate water types.



a.



b.



c.

Where: 1 = Ayetoro, 2 = Iraye, 3 = Odomola, 4 = Mojoda, 5 = Ilara, 6 = Poka, 7 = Odo-Iragushi, 8 = Eredo

Fig. 5 Diagrams of a. Gibbs, b. Gaillardet, c. Hydrochemical facies evolution respectively showing processes influencing water ion chemistry, dominant ion patterns, origin of water ions and the evolution path of water (n=50) in the study area

Source: Field Survey, 2025

Principal Component Analysis (PCA)

The Principal Component Analysis (PCA) of the groundwater quality data in Epe provides a robust statistical method to identify the dominant processes controlling hydrogeochemistry by reducing the dimensionality of the dataset. The first seven principal components (PCs) with eigenvalues greater than 1 were retained according to the Kaiser criterion (Table S9 in Supplementary Information). The first four PCs (**Fig. 6**) were the most important, collectively explaining 99% of the total variance in the data (PC1: 57.33%, PC2: 17.35%, PC3: 15.94%; PC4: 8.38%). The classification scheme of Ali et al. (2024) was utilized for the interpretation in which loadings > 0.75 were considered strong, 0.50-0.75 moderate, and 0.30-0.50 weak.

PC1 (**Fig. 7a**; Table S10 in Supplementary Information), was characterized by an extremely strong positive loading on bicarbonate ($\text{HCO}_3^- = 0.97$) while PC2 (**Fig. 7b**; Table S10) had a very strong positive loading for Calcium ($\text{Ca}^{2+} = 0.82$) but a weak loading for magnesium ($\text{Mg}^{2+} = 0.49$). Both PCs signify that the natural dissolution of calcium, magnesium and bicarbonate minerals in the aquifer is the primary driver of water quality. This finding supports the inference got from the Gaillardet diagram about the origin of the water being from weathering of mixed carbonate-silicate rocks. PC3 (**Fig. 7c**; Table S10) exhibited an extremely strong positive loading on sulphate ($\text{SO}_4^{2-} = 0.95$) while PC4 (**Fig. 7d**; Table S10) had very strong positive loading on magnesium ($\text{Mg}^{2+} = 0.86$) and moderate negative loading on calcium ($\text{Ca}^{2+} = -0.50$). These components indicate gypsum/anhydrite dissolution or anthropogenic input as well as ion exchange. However, since there are no records of

gypsum among the mineral resources of Epe, these components definitely indicate anthropogenic input and ion exchange processes.

The remaining components explained minor variances and highlighted more specific interactions: PC5 had an extremely strong positive loading on the total depth of the wells (TD = 0.94) and a weak loading on the static water level (SWL = 0.32). This suggests a physical control where well depth influences the concentration of certain ions and actual water level (pressure head) doesn't dictate the chemistry as much as the physical bottom of the well does. PCs 6 and 7 were marked by extremely strong positive loadings on potassium ($K^+ = 0.95$) and sodium ($Na^+ = 0.93$) suggesting weathering of silicate minerals like feldspars within the Dahomey Basin sands, rather than marine sources and anthropogenic influences from sewage (septic tanks) or NPK fertilizers from local farming.

The minimal influence of Na^+ and Cl^- across all components powerfully reinforces that seawater intrusion is not a major factor, a crucial distinction from studies in other coastal areas like Badmus et al. (2020) in Ogun Waterside and Nkpoidet et al. (2025) in Eastern Obolo, where salinity-related parameters dominated the PCA.

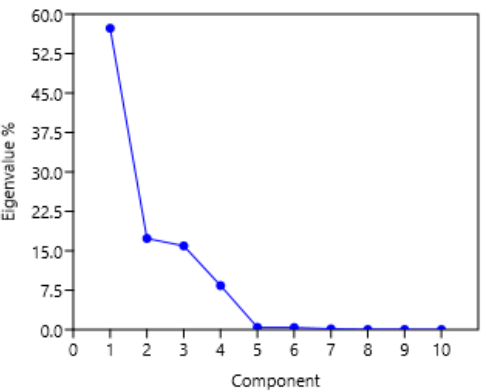
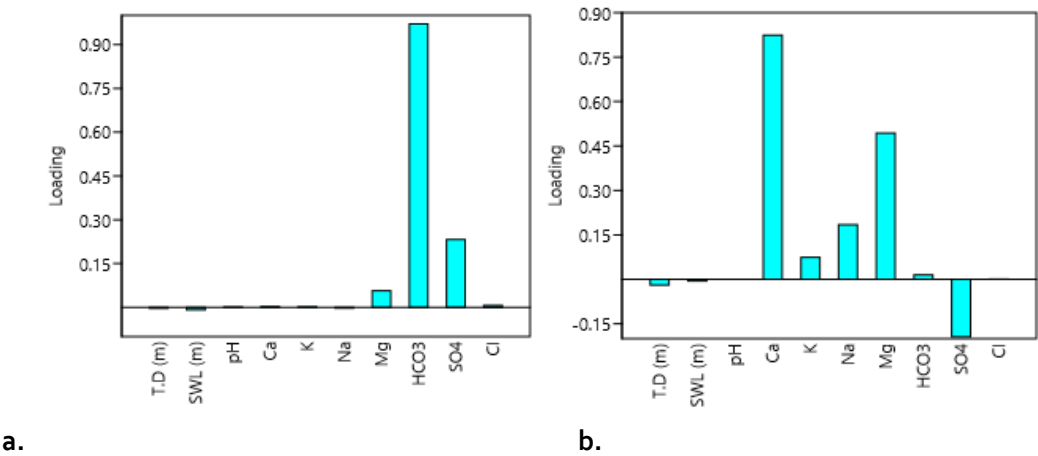
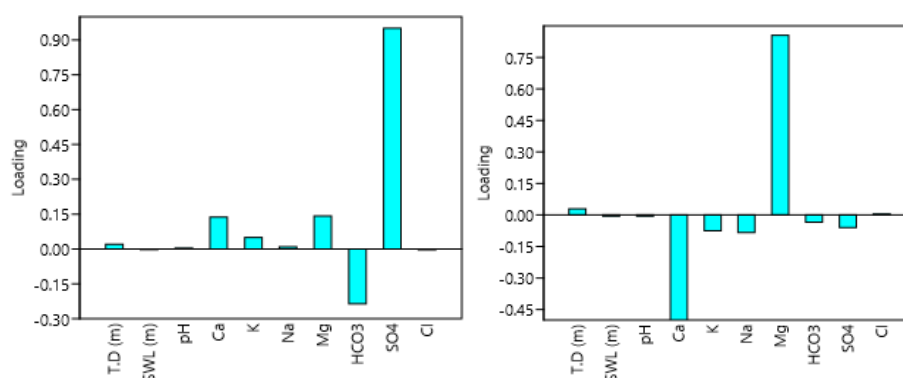


Fig. 6: Scree Plot showing parameters with Eigenvalue %

Source: Field Survey, 2025





c.

d.

Where: TD = Total depth, SWL = Static water level, pH = Hydrogen ion concentration, the next are cations and anions.

Fig. 7: Loading plot of **a.** principal component 1, **b.** principal component 2, **c.** principal component 3, and **d.** principal component 4 of Groundwater in Epe

Source: Field Survey, 2025

In synthesis, the PCA robustly confirms that the groundwater chemistry in Epe is predominantly controlled by natural geogenic processes, though structured by a clear hierarchy of mineral interactions. The overarching mechanism is driven by carbonate dissolution (PC1), which accounts for over half of the total variance and establishes the basic hydrogeochemical framework. This is supplemented by the weathering of calcium-rich minerals (PC2) and a distinct sulphate source (PC3), likely derived from anthropogenic additions. The chemical signature is further refined by a specific cation exchange process (PC4), where dry-season evaporative concentration and mineral weathering cause dissolved magnesium (Mg^{2+}) to numerically overwhelm the system, electrostatically displacing bound calcium (Ca^{2+}) from the clay matrix into the aqueous phase while the excess calcium precipitates out as calcium carbonate. This signature is concurrently shaped by aquifer stratification (PC5), indicating that overall mineralization increases with well depth. The isolation of potassium (PC6) and sodium (PC7) suggests these cations also originate from the weathering of silicate minerals like feldspars within the Dahomey Basin sands, rather than marine sources. Finally, the minimal influence of Chloride across all components and its failure to load with Sodium strongly reinforces that seawater intrusion is not a major factor in this groundwater system. This lack of a saline signature, alongside the dominant geogenic loadings, aligns with the findings from the hydrochemical facies and ionic plots, characterizing the system as one dominated by terrestrial rock-water interaction.

Limitations of the Study

This study has three principal limitations. Temporally, the single sampling campaign in March (dry season) provides only a seasonal snapshot, as wet-season recharge can substantially alter groundwater chemistry. Spatially, uneven sample distribution across

communities (3–10 samples per locality) introduces potential bias and limits the robustness of inter-site comparisons. Compositionally, the analysis was restricted to major ions and did not include nitrate, heavy metals, or microbiological parameters, although these have been addressed in complementary regional studies (Gbadebo *et al.*, 2026d, 2026e). The absence of integrated multi-contaminant data within a unified framework precludes a holistic assessment of synergistic risks. Future studies incorporating wet-season monitoring, balanced sampling, and full contaminant profiling are recommended to validate and extend these findings.

Conclusion

This comprehensive hydrogeochemical assessment of groundwater in Epe provides critical insights into its quality, the dominant geochemical processes controlling its composition, and its overall suitability for drinking and irrigation purposes. The study conclusively identifies that the groundwater is predominantly of the Ca-Mg-HCO₃ type, with a cationic order of Mg²⁺ > Ca²⁺ > Na⁺ > K⁺. This unique magnesium-dominated character is the central theme governing both the water's potential benefits and its limitations. The integration of multiple analytical tools including hydrochemical diagrams (Piper, Gibbs, Gaillardet) and multivariate statistics (PCA) consistently points to silicate and carbonate weathering as the primary geogenic process, supplemented by ion exchange. The Hydrochemical Facies Evolution Diagram further indicates mixed facies, suggesting an overprint of anthropogenic activities on the natural geochemical baseline. Principal Component Analysis quantitatively confirmed that natural geogenic processes are the principal factors governing water chemistry with slight anthropogenic contributions.

From a public health perspective, the assessment yielded positive results. The Water Quality Index (WQI) classified the water as 8% "excellent," 76% "good," and 16% "poor" while the Pollution Index of Groundwater (PIG) ranked all samples as having insignificant pollution (0.39 - 0.85). The principal parameter that contributed most to the WQI and PIG scores was magnesium which was the only parameter that consistently exceeded the Nigerian Standard for Drinking Water Quality. Although this poses no toxicity risk and even offers an important dietary contribution of magnesium in specific locations like Poka, it underscores that the water requires treatment before consumption to be deemed potable. For agricultural use, the groundwater presented a clear dichotomy. Its suitability is "excellent" regarding sodium hazard, as evidenced by low SAR, %Na, KR, and negative RSC values, indicating a very low risk of sodicity. However, this advantage was counterbalanced by widespread permeability risk (PI < 25% in 88% of samples) and magnesium hazard (MAR > 50% in 86% of samples), which poses a long-term risk to soil permeability and structure, particularly in clay-rich soils. Furthermore, the identified corrosivity of the water (CR > 1 in 50% of samples) presents a tangible threat to metallic irrigation and water supply infrastructure.

Overall, the groundwater in Epe is a valuable but vulnerable resource. Its chemical character is defined by the subsurface geology, rendering it safe from sodium-related issues but

challenging due to magnesium dominance. Proactive, science-based management is crucial to ensure this resource continues to support the health and livelihoods of the Epe community.

Recommendations

To safeguard and sustainably manage Epe's vital groundwater resources, the following measures are recommended:

1. **Agricultural Management:** Farmers should be made aware of the magnesium hazard and encouraged to adopt appropriate soil management practices, such as the application of organic amendments, to mitigate potential soil permeability issues.
2. **Infrastructure Planning:** For any new water supply or irrigation schemes, the use of corrosion-resistant pipes (e.g., PVC) is essential to prevent pipe degradation and water quality deterioration.
3. **Sustained Monitoring:** A robust and continuous groundwater quality monitoring program is imperative to track any changes, especially the potential escalation of anthropogenic pollution from agricultural and domestic sources.

Declarations

All authors have read, understood, and have complied as applicable with the statement on "Ethical responsibilities of Authors" as found in the Instructions for Authors.

Ethics approval

Not Applicable

Consent to participate

Not Applicable

Consent for publication

Not Applicable

Availability of Data and Materials

The datasets generated and analysed during the current study are available in the body of the article and as supplementary files

Clinical trial number

Not Applicable.

Competing Interests

The authors declare no conflict of interest.

Informed Consent

Not applicable

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Author Contributions

Adewole Michael Gbadebo: Visualization, Validation, Supervision, Resources, Methodology, Project administration, Conceptualization. Kudirat Korede Otubu: Visualization, Validation, Resources, Methodology, Investigation, Benjamin Onozeyi Dimowo: Conceptualization, writing – original draft, Writing – review & editing, Visualization, Resources, Investigation, Formal analysis, Data curation, Oluwajumilo Oluwadara Gbadebo: Writing – review & editing, Visualization, Formal analysis.

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