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Abstract

Purpose: This study assessed the suitability of groundwater in parts of Yaoundé city for drinking and domestic purposes, investigating the factors controlling its composition.

Materials and Methods: Water samples were collected during the dry season and analyzed for physicochemical parameters and major ions.

Findings: Results showed an acidic aquifer with generally fresh water, dominated by Ca-HCO_3, Na-Cl, Ca-$NaHCO_3$, and Ca-Cl water types. While most major ions were within WHO guidelines, nitrates exceeded safe limits in most samples, and some trace elements like aluminum, manganese, and iron were also above recommended levels.

Implications to Theory, Practice and Policy: The study concludes that groundwater quality is influenced by water-rock interaction, ion exchange, and anthropogenic activities, particularly nitrate and chloride pollution. Therefore, proper groundwater management strategies are crucial to ensure the sustainability and safety of this vital resource.

Keywords: *Groundwater, Yaoundé-Cameroon, Nitrate, Chloride, Pollution*

JEL Codes: Q25**,** O13, Q53

1.0 INTRODUCTION

Groundwater is a vital resource for the human population (Clark and Fritz, 1997; Wotany et al., 2013; Wirmvem et al., 2013; Bon et al., 2021; Menti et al., 2023), meeting nearly half of the global freshwater demand for domestic and agricultural purposes. Almost all communities in sub-Saharan Africa depend on groundwater for domestic use (Edet, 2008; Eneke et al., 2011, Ngai et al., 2023) due to its availability and relative cleanliness compared to surface water sources, which are easily polluted by domestic waste and runoff, especially during the rainy season (Yidana et al., 2010). The high demand for water necessitates hydrochemical and hydrological evaluations (IAEA, 2006), which are critical components of sustainable groundwater resource evaluation and management. Given the reliance on groundwater as a primary water source in Sub-Saharan Africa, hydrological and hydrochemical studies, though uncommon in most communities, are crucial (Adelana and MacDonald, 2008; Adelana et al., 2011). Several studies have shown that the quality of drinking water in Cameroon is influenced by major ions, silicate weathering (Ako et al., 2011 and 2012, Eneke et al., 2011, Wotany et al., 2013, 2014), and anthropogenic processes (Wotany et al.,2019; Kamtcheung et al., 2022).

Besides major ions, trace elements, which occur naturally in minute concentrations, provide important information about water quality. These elements include Se, Zn, V, Fe, Ni, Cr, Co, Cu, Mn, Pb, Th, U, As, Hg, and Ti. The distribution of trace elements in the environment is influenced by both natural and anthropogenic activities. They are considered environmentally hazardous substances due to their persistence, toxicity, and bioaccumulation potential, as they cannot be degraded or destroyed (Duribe et al., 2007). They have been reported to cause mutagenic, teratogenic, neurotoxic, and carcinogenic effects (Ngole and Ekosse, 2012).

In-situ sanitation in urban areas, particularly in developing countries, poses a significant risk to groundwater quality (Foster et al., 2010). This includes contamination of groundwater and surface water by NO3- and Cl- (Vengosh and Pankratov 1998; McArthur et al., 2012; Mtoni et al., 2013), as well as the potential presence of harmful trace elements (Asaah et al., 2006). Understanding the hydrochemical characteristics and variations in groundwater composition is crucial for the effective utilization of water resources and the identification of polluted sources (Mahesha and Nagaraja, 1996). Investigations in Cameroon have revealed that silicate weathering is the primary control on water chemistry, and the water quality is generally suitable for drinking (Njitchoua and Ngounou-Ngatcha, 1997; Fantong et al., 2009; Fantong et al., 2010; Eneke et al., 2011; Oyebog et al., 2012; Ako et al., 2012a,b; Takounjou et al., 2011; Fantong et al., 2013; Fantong et al., 2020).

Yaoundé's population has grown rapidly in the last 50 years, averaging 4% annually (Moffo et al., 2011). Studies have shown that groundwater in some communities exceeds permissible limits for iron, bicarbonate, and some trace metals, posing health risks (Teikeu et al., 2015). Fonkou et al. (2005) found heavy metals like cadmium, copper, zinc, and lead in the Olezoa wetland, with the highest concentrations in fish organs (Bon et al., 2021). Water from this wetland is used for urban agriculture and domestic purposes, and the contaminated fish are consumed. Chemical analyses indicate that River Mingoa, a major tributary to the Municipal Lake, is the primary collector of pollutants from activities on the sloping side of the river and the lake. Teikeu et al. (2015) reported that groundwater in Yaoundé ranges from weakly to moderately mineralized, with iron and bicarbonate exceeding permissible limits. Studies indicate pollution from waste dumps, urban agriculture, open drains, pit latrines, and septic tanks (Defo et al., 2015; Teikeu et al., 2015; Fongoh et al., 2023, 2024).

Recent studies have highlighted the constraints and opportunities for groundwater quality and supply in Yaoundé. Fongoh et al. (2023) used stable isotopes and hydrochemical parameters to reveal pollution constraints in urban groundwater and the importance of rock-water interaction and residence time in peri-urban groundwater. Another study by Fongoh et al. (2024) emphasized the influence of geomorphological settings on hydrogeology, urban occupation, and water exploitation and contamination, demonstrating the need to protect shallow groundwater resources. In some parts of Yaoundé, groundwater is cloudy with an unusual taste and smell due to indiscriminate waste disposal and sewage systems near drinking water sources. This poses a threat to the growing population, with recurring waterborne diseases like typhoid and cholera linked to groundwater pollution from wells by latrines and septic tanks (Mpakam et al., 2008)

Problem Statement

The increasing reliance on groundwater in Yaoundé, Cameroon, coupled with limited understanding of its quality and contamination sources, presents a significant problem. This lack of knowledge hinders effective management and protection of this vital resource, potentially jeopardizing the health and well-being of the population. The study aims to address this issue by conducting a comprehensive assessment of groundwater quality, focusing on major ions and trace elements. By identifying the sources and spatial distribution of pollutants, the research will provide crucial information for decision-makers and stakeholders to develop targeted interventions and ensure the long-term sustainability of groundwater resources in Yaoundé.

Geographic and Geologic Settings

Geographic Setting

Yaoundé is the political capital of Cameroon and the second most populated city in the country with more than 1.5 million inhabitants (Figure 1.). It is located in Tropical Africa between latitudes 3°47'–3°56' N and longitudes 11°10'–11°45' E, over a mean altitude of 710.8 m. (Moffo *et al.*, 2011). It has a surface area of 180 km^2 and forms part of the Pan–African Yaoundé series. The area is characterized by four seasons. They include a rainy season from March to June, a short dry season from July to August (transitional phase of the monsoon), a rainy season from September to November and a dry season from December to February (Sighomnou, 2004). In the dry season from December to February, rainfall depths are low compared to the rainy season. The low rainfall is because the southerly monsoon flow is weakened in this season. During this period, the entire area is alternatively influenced by north-easterly Harmattan winds (Thorncroft *et al.*, 2011).

Yaoundé is characterized by an arborescent hydrographic network (Ngon-Ngon *et al.*, 2009) and dense dendritic drainage systems. Yaoundé is drained by many rivers including Rivers Mfoundi, Mefou and Mfoulou (Kuitcha *et al.*, 2012).

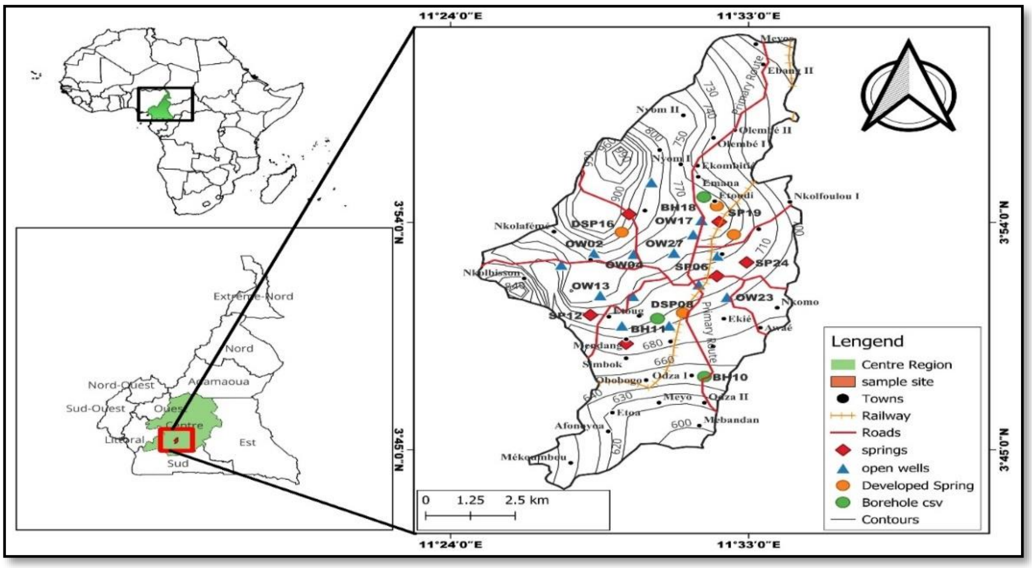


Figure 1: Location Map of the Study Area

This hydrographic network has developed flat valleys with different widths ranging from 50 to 150m (Ngon-Ngon *et al.*, 2009). The steep slopes in the city result in the rapid flow of run-off and streams with the subsequent development of wetlands in the lowlands (Temgoua *et al.*, 2005). In the Yaoundé crystalline basement area, despite strong rainfall, the groundwater wells for feeding populations are characterized by very low water flow rates which are not successful sometimes (Teikeu *et al.,* 2012a,b).

Geologic Setting

Geologically, the study area is part of the Pan-African Chain of Central Africa (Mvondo et al., 2003). Previous research has established the southward thrusting of the southern border of the Central African Fold Belt (CAFB) onto the northern edge of the Congo Craton (Poidevin 1983; Ball et al., 1984; Nedélec et al., 1986; Nzenti et al., 1988). This resulted in nappes extending from the Central African Republic (Rolin, 1992) to Cameroon (Yaoundé nappe) and continuing into northeastern Brazil (Davison and Dos Santos, 1989). In Cameroon, the nappe consists of the Neoproterozoic Yaoundé Group, thrust onto both the Congo Craton and the Nyong Group, and the Paleoproterozoic Bafia Group, thrust onto the Yaoundé Group to the north (Ball et al., 1984; Nédelec et al., 1986; Tchakounté 1999; Mvondo et al., 2003; Toteu et al., 2004). Garnet zoning profiles in Yaoundé granulites suggest that nappe emplacement occurred near or after the peak of granulite facies metamorphism, estimated to be no older than 620 ± 10 Ma (Nzenti et al., 1988; Penaye et al., 1993).

Yaoundé's geology (Figure 2) is characterized by metamorphic rocks, including migmatites, migmatitic gneisses, gneisses, and mica schists (Mvondo et al., 2003). The basement comprises migmatites and gneisses (Mvondo et al., 2007), which are not porous or soluble but have fissure permeability due to discontinuities like faults and joints. Metasedimentary rocks are the most common outcrop along riverbeds. The study area has undergone three ductile deformation phases, primarily E-W to NW-SE compressions (D1 and D3) alternating with an N-S to NE-SW extension (D2). D1 is associated with prograde metamorphism culminating in high-pressure granulite conditions, while D2 is a decompression phase linked to magmatic activity, foliation, and gneiss dome formation. The brittle D3 phase includes joints, veins, fractures, and faults. These deformations shape the topography and influence hydrography. Owona et al.

(2011) and Mvondo et al. (2007) identified a fourth deformation phase (D4), attributed to lateral flows after crustal extensions.

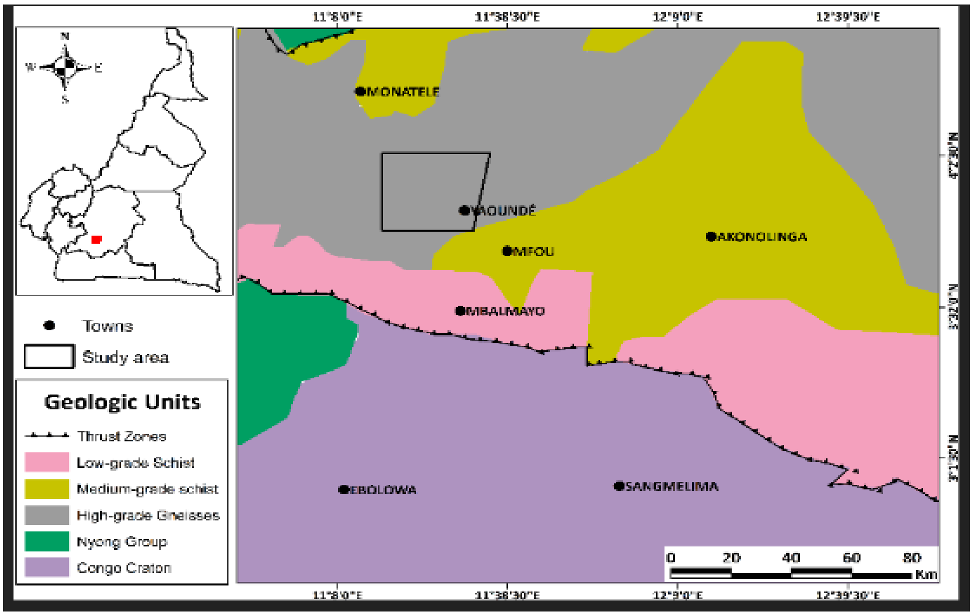


Figure 2: Geology Map of the Study Area (Modified after Toteu et al., 2004)

2.0 MATERIALS AND METHODS

Sampling, Sample Analysis and Quality Control

$$C_d = \sum_{i=1}^{n} C_{Fi} \quad (1)$$

Where, $C_{fI} = \frac{C_{Ai}}{C_{Ni}} - 1$Field campaigns involved sampling of 30 water points in the dry season (January) from 30 points in the urban city of Yaoundé. These included open wells (14), ‘boreholes’ (3) and springs (10) termed groundwater; streams (1), rivers (1), and lakes (1) termed surface water. The sample location points and altitudes were obtained in the field by using a Garmin Vista CX Geographic positioning system (GPS) and a sample location map was produced (Figure.1). Fieldwork preparation followed guidelines described in Karklins (1996). The meter was calibrated before and during the field campaign using buffer solutions recommended by the manufacturer. A bucket (collector) and the bottles used for sampling were rinsed at least 3 times with the same water that was sampled. Surface water was sampled as far as possible from the edges of the water bodies and as deep as possible along the flow path. Groundwater from active wells was collected into the collector using a rope tied to the bucket and/or permanently installed hand pumps (after several minutes of pumping) while springs were collected directly as they discharged under natural pressure.

The water collected in the bottle was labelled and stored in a cooler which had ice blocks. This was to enable preservation of the chemical Components of the water sample. These filtered samples were used for major ions and trace elements (acidified); and major anions (non-acidified) analyses. These chemical analyses of water samples were carried out after sampling in the Chemistry Laboratory of Tokai University, Japan. Major cations; sodium (Na^+), Potassium (K^+), magnesium (Mg^{2+}), and calcium (Ca^{2+}) were determined by a Flame Technique in a High-Resolution Continuum Source AAS (Atomic Absorption Spectrometry) ContrAA700. Samples with EC values >100µS/cm were diluted 5 or 10 times to acquire an absorbance within the range of the used standards for Na^+, K^+, Mg^{2+} and $Ca^{2+.}$ The anions:

fluoride (F^-), chloride (Cl^-), nitrate (NO_3^-), sulphate (SO_4^{2-}), phosphate (PO_4^{3-}), nitrite (NO_2^-), and bromide (Br^-)were determined by using Dionex ICS-900. Trace element concentrations were determined by inductively coupled plasma mass spectrometry (ICP-MS). Blanks were simultaneously run with samples to ensure that the analytical results were accurate.

Alkalinity/bicarbonate (HCO_3^-) was determined within 8 hours of sampling by acid titration from a volume of 0.02 M HCl, added to the sample and stirred with an automatic stirrer until the end-point, which was marked by a pH of 4.5.

Data Analysis

The application of the Cl-/Br- ratio was used to enable us to identify the main anthropogenic sources of groundwater contamination such as domestic wastewater, septic-tank effluent and animal waste for subsequent remediation Measures (Katz *et al.*, 2011; McArthur *et al.*, 2012). This is because both ions move conservatively in water, and have different abundances in natural fluids and solids (Davis *et al.*, 1998). Even though chloride generally is 40–8000 times more abundant in nature than Br, chloride has a slightly lower aqueous solubility than bromide (Davis *et al.*, 1998). As a result, plots of chloride concentrations and the mass (or molar) ratio of chloride to bromide (Cl/Br) have been used by several studies to distinguish pristine groundwater from wastewater sources and other anthropogenic and natural salinity sources such as road salt, seawater, and deep basin brines (Landon *et al.*, 2008; Brown *et al.*, 2009). The Cl/Br molar ratio can be obtained by multiplying the mass ratio by 2.254.

Gibb's ratio for ions was computed to provide information on which the mechanisms of precipitation, water-rock or evaporation control the chemical character of the water sources. This diagram was obtained by plotting these ions of groundwater and surface water samples against the respective values of TDS to determine the general environment of the chemical character of the groundwater (Mc Neil *et al.*, 2005; Yidana et al., 2008).

The classification of trace elements in water was done using the method of Ficklin et al. (1992) and modified by Caboi et al. (1999). The method plots metal load (mg/l) against pH. In this study, the metal load was computed by summing all the trace elements analyzed in the water samples.

Trace Element Distribution and Evaluation Indices

The Contamination Index (Cd)

This method involves the calculation of the degree of contamination (C_d) to evaluate the quality of water (eq 1). The C_d is computed separately for each sample of water analyzed, as a sum of the contamination factors of individual components exceeding the upper permissible value. Hence the C_d summarizes the combined effects of several quality parameters considered harmful to household water.

Cfi = contamination factor for the ith component

CAi = analytical value for the ith component

CNi = upper permissible concentration of the ith component (N denotes the 'normative value')

The resultant C_d value identifies areas of varying contamination levels which are grouped into three categories as follows: low (Cd <1), medium (Cd = 1–3) and high (Cd >3).

Trace Element Evaluation Index (TEI)

The TEI method gives an overall quality of the water concerning trace metals (Edet and Offiong, 2002).

It is given as;

$$TEI = \sum \frac{MC}{MAC} \quad (2)$$

Where;

Mc= Observed metal concentration

MAC= maximum allowable concentration of the metal in the water guideline (WHO water guideline).

Enrichment Factor (EF)

The computation of enrichment factor (EF) has been adopted to evaluate the impact of anthropogenic activities related to the metal abundance in water (Zhang *et al.*, 2007). The enrichment factor was to infer the most enriched trace metals within the study area.

$$\text{EF} = \frac{(C_x|C_{Fe})sample}{(C_x|C_{Fe})background} \quad (3)$$

Fe (iron) is chosen as a natural element of reference;

(C_X/C_{Fe}) sample is the ratio between the concentration of the element "X" and that of Fe in the water sample;

(C_X/C_{Fe}) background is the ratio between the concentration of the element "X" and that of Fe in the unpolluted reference baseline

Pollution Load Index (PI)

It involves the linear summation of contamination factors taking note of the differences in the toxicity of various metals in the water samples (Harikumar *et al.*, 2009).

$$\text{PLI}= (CF_1 x CF_2 \dots \dots \dots CF_n)\frac{1}{n} \quad (4)$$

Where n=number of metals and CF (contamination factor)

$$\text{CF} = \frac{metal\ concentration\ in\ sediments}{Background\ concentration\ of\ metal}$$

3.0 FINDINGS

Results of the physiochemical data of groundwater and surface water showed varied concentrations of individual elements suggesting varied controls on the water chemistry. Groundwater in the densely populated areas like Briqueterie, and Valle Nlongkak, have distinctively higher concentrations of ions relative to less dense areas in the outskirts of the city like Lycee Emana and Santa Babara. NO_3^- and Cl^- were distinctively higher in shallow wells suggesting the influence of human activities on groundwater (Table 1).

Table 1: Statistical Summary of Physiochemical Data of Groundwater and Surface Water in the Study Area

Water Source	Localities	Type	T(°C)	EC (µs/cm)	TDS (mg/l)	pH	Na^+ (mg/l)	K^+ (mg/l)	Ca^{2+} (mg/l)	Mg^{2+} (mg/l)	F- (mg/l)	Cl- (mg/l)	Br- (mg/l)	NO_3^- (mg/l)	SO_4^{2-} (mg/l)	HCO_3^- (mg/l)
BH10	Odza Auberge Bleu	Borehole	32	140	70	4.7	10.35	2.68	3.54	2.82	0.1	3.7	0.04	42.52	0.5	2.3
BH11	Efoulan	Borehole	29	492	247	4.9	39.8	6.09	13.54	13.12	0.3	51.3	0.07	82.89	1	29.1
BH18	Mosque Etoudi	Borehole	27	416	205	4.8	46.55	8.2	5.39	5.38	0.1	67.9	0.07	139.69	0.4	3.3
OW01	Nkolbisson	Open well	26	250	120	4.4	30.39	10.48	4.37	3.04	0.1	23.6	0	96.99	0	0
OW02	Oyom-Abang	Open well	25	250	110	4.1	28.26	5.57	2.78	1.61	0.1	26.7	0.05	64.19	0.1	0
OW04	Madagascar	Open well	26	579	288	5.1	22.92	25.3	54.82	6.74	0.1	31.8	0.19	77.75	26	76
OW05	Valle Nlongkak	Open well	26	460	230	5.1	44.2	8.46	20.78	9.72	0.1	63.1	0.16	146.7	4.1	4.8
OW07	Monte Zoe	Open well	27	660	320	5.2	25.54	11.08	12.73	4.67	0.4	77.7	0.1	217.92	0.7	2.5
OW09	Nsam	Open well	27	500	250	5.2	10.62	3.63	2.73	4.35	0	13	0	84.58	1.4	20.8
OW13	Akoa-Doe	Open well	26	520	260	5.3	17.38	15.1	1.5	1.03	0	22.9	0.11	116.24	2.9	61.1
OW15	Chapelle Obilli	Open well	26	230	110	5.6	10.33	9.22	0.84	1.21	0.2	13.5	0.02	69.22	0.7	1.3
OW17	Tongollo II	Open well	27	630	313	5.9	27.88	28.47	35.44	4.68	0.2	15.6	0.19	185.78	3.7	80.4
OW22	Lycee D'Emana	Open well	29	110	50	4.4	7.68	3.6	1.6	1.51	0.1	5.4	0	28.02	1.3	0
OW23	Kondegui	Open well	28	210	110	4.2	25.63	4.02	1.12	0.21	0.1	18.2	0.03	61.56	0	0
OW25	Quartier Fouda	Open well	28	380	190	4.6	39.55	4	3.09	2.97	0.1	29	0.02	116.19	0	1
OW27	Briquiterie	Open well	28	660	310	5.1	54.44	19.09	9.4	4.31	0.1	105.3	0.08	166.83	4.6	21.8
OW29	Tam-Tam	Open well	27	290	40	4.7	6.17	8.7	3.94	3.07	0	37	0.07	110.28	0.7	0.4
SP06	"Mvog-Ada, Cornee"	Spring	27	320	160	4.1	5.27	7.43	8.93	4.18	0.2	10.5	0.07	111.06	0.6	24
SP08	Mvan-Brasseries	Spring	26.5	370	190	5.2	10.35	10.84	24.55	2.77	0	35.5	0	104.34	9.1	1.5
SP12	Mendong	Spring	26.6	230	120	5.2	17.54	5.84	13.88	6	0.1	27.1	0.03	45.02	2.7	32.2
SP19	Manguier	Spring	27	330	160	4.2	33.41	8.28	10.33	6.07	0.1	35.9	0.04	120.65	1.6	0
SP24	Essos Hotel de Plateau	Spring	27.6	330	160	4.4	37.99	7.44	5.04	1.97	0.3	34.6	0.03	134.4	2.3	0
SP30	Damas	Spring	25	180	90	6.2	2.1	2.1	7.14	0.2	0.2	0	0.03	4.49	0.6	55.8
RW03	Carrefour Mecc	River Water	25	480	240	6.6	44.27	20.2	18.08	4.78	0.1	56.5	0.1	59.69	7.9	48.7
LK14	Municipal Lake	Lake	29	280	140	7.2	20.5	9.33	16.95	3.01	0.1	30.5	0.04	9.59	0.4	72.6
ST21	Lycee D'Emana	Stream	25	50	20	5.5	3.25	2.16	3.6	1.69	0.1	1.3	0	2.04	1	23.1

A statistical summary of the physio-chemical data is presented in Table 2 below with temperature values ranging between 23 - 32°C with a mean of 26.94°C. The lower mean groundwater temperatures in the study area (27.1°C) relative to the air temperatures suggest that depths of circulation (3-10m) are short (shallow flow path) and quick infiltration (proximity to recharge areas) (Chapman, 1996; Ako *et al.*, 2012b). The lower mean temperature in groundwater 22^0C sources is relatively close to the annual mean air temperature in the Yaoundé region of around 24.17^0C (Teikeu *et al.*, 2015). This explains that the study area is associated with unconfined aquifers and this is further supported by the evidence from field observations. Where the aquifers are typically shallow, unconfined and have characteristic depths of 3 to 20m.

Table 2: Statistical Summary of Physiochemical Data of Groundwater and Surface Water in Yaoundé

Parameters	Surface and groundwater (n=30)				Groundwater= n=27)				Surface water(n=3)			
`	Min	Max	Mean	STD	Min	Max	Mean	STD	Min	Max	Mean	STD
T^0C	23.00	32.00	26.94	1.67	23.00	32.00	27.01	1.63	25.00	29.00	26.33	2.31
pH	4.10	7.20	5.10	0.78	4.10	6.60	4.95	0.62	5.50	7.20	6.43	0.86
Ec (µs/Cm)	20.00	660.00	325.57	182.07	20.00	660.00	331.74	181.71	50.00	480.00	270.00	215.17
TDS(mg/l)	10.00	330.00	161.60	90.75	10.00	330.00	164.7	90.28	20.00	240.00	133.33	110.15
Na^+(mg/l)	2.10	54.44	22.58	14.83	2.10	54.44	22.57	14.58	3.25	44.27	25.23	15.03
K^+(mg/l)	1.19	28.47	8.63	6.81	1.19	28.47	8.42	6.70	2.16	20.20	10.56	9.08
Ca^{2+}(mg/l)	0.84	60.44	15.28	16.28	0.84	60.44	15.55	17.03	2.78	18.08	9.16	7.66
Mg^{2+} (mg/l)	0.06	13.12	3.77	2.96	0.06	13.12	4.01	3.08	1.69	4.78	3.16	1.55
HCO_3^-(mg/l)	0.00	80.44	19.75	25.84	0.00	80.44	16.60	24.38	23.10	72.6	48.13	24.75
NO_3^-(mg/l)	0.70	217.92	84.30	55.49	0.70	217.92	91.03	53.76	2.04	59.69	23.77	31.38
Cl^-(mg/l)	0.71	105.32	29.33	24.79	0.70	105.32	29.32	25.04	1.31	56.47	27.70	19.68
SO_4^{2-}(mg/l)	0.00	57.90	4.46	11.24	0.00	57.90	4.61	11.80	0.40	7.90	3.10	4.17

The pH values of groundwater reflect acidic sources (4.1 – 6.6). Similar pH values have been recorded by Teikeu et al. (2015). The author associates this pH considering the clayey and medium carbonate nature of the aquifer matrix. The slightly acidic nature of the water sources suggests groundwater reaction with human acids from the decomposition of organic matter in the infiltration zones leading to acidification from dissolved carbon dioxide (CO_2).

Electrical conductivity (EC) shows a wide range of values, from 20 to 660µs/cm. The EC for open wells were slightly higher than those for springs and boreholes, probably due to increased nitrate concentration (116.19mg/l) and also in some open wells like those in Tongolo II. Das et al., (1999) and Neve et al. (2000) believe there is a relationship existing between EC and nitrate as observed in the correlation matrix.

The water samples were generally fresh (slightly mineralized) given that their TDS were lower than 600 mg/l (Freeze and Cherry 1979; Davis and De Wiest 1966; Wirmvem *et al.*, 2013b; Menti et al., 2023). Both EC and TDS had high standard deviations compared to other parameters and suggest that water chemistry is not homogenous in the study area and is regulated by distinguished processes (Ako *et al.*, 2011).

The spatial distribution of the physio-chemical parameters (Figures 3a-d) and the meq/l mean concentrations of major ions are plotted on pie charts to distinguish the various ionic species in the different water sources (Figures 4 & 5). For open wells, $Na^+ > Ca^{2+} > K^+ > Mg^{2+}$ and $NO_3^- > Cl^- > HCO_3^- > SO_4^{2-}$ (Fig 4a). For springs, $Na^+ > Ca^{2+} > K^+ = Mg^{2+}$ and $NO_3^- > Cl^- > HCO_3^- > SO_4^{2-}$ (Fig 4b). For developed springs, $Na^+ > Ca^{2+} = Mg^{2+} > K^+$ and $NO_3^- > Cl^- > SO_4^{2-} > HCO_3^-$ (Figure 4c). For boreholes $Na^+ > Mg^{2+} > Ca^{2+} > K^+$ and $NO_3^- > Cl^- > HCO_3^- > SO_4^{2-}$ (Figure 4d). From these illustrations, Na^+ is the dominant cation, while NO_3^- is the dominant anion for all groundwater sources. For surface water sources, $Na^+ > Ca^{2+} > K^+ > Mg^{2+}$ and $Cl^- > NO_3^- > HCO_3^- > SO_4^{2-}$ for river (Figure 5a.) for lake $Na^+ > Ca^{2+} > K^+ = Mg^{2+}$ and $HCO_3^- > Cl^- > NO_3^- > SO_4^{2-}$ (Figure 6b). For streams $Ca^{2+} > Na^+ = Mg^{2+} > K^+$ and $HCO_3^- > SO_4^{2-} > Cl^- > NO_3^-$ (Figure 6c). Similar to groundwater sources Na^+ is the dominant cation and HCO_3^- is the dominant anion except Ca^{2+} and Cl^- which are the dominant ions in streams and rivers, respectively.

The low K^+ in groundwater may be due to its low geochemical mobility (Hem, 1989; Srinivasamorthy *et al.*, 2008) while low Mg^{2+} is possibly due it's to low content in rocks within the study area. Correlation coefficients are one of the indices to assess the strength of a relationship between different variables (Kim *et al.*, 2007). Low concentrations of F^- in groundwater of the study area may be due to the acidic nature of the groundwater (pH <5.9), which renders F^- immobile (Hem, 1989; Edmunds and Smedley, 1996) because of its high electronegativity, hence, forming strong solute complexes with most cations (Hem, 1989). For example, the highest value of F- (0.4mg/l) was identified in a well (OW07) with a pH of 5.2 (Table 1).

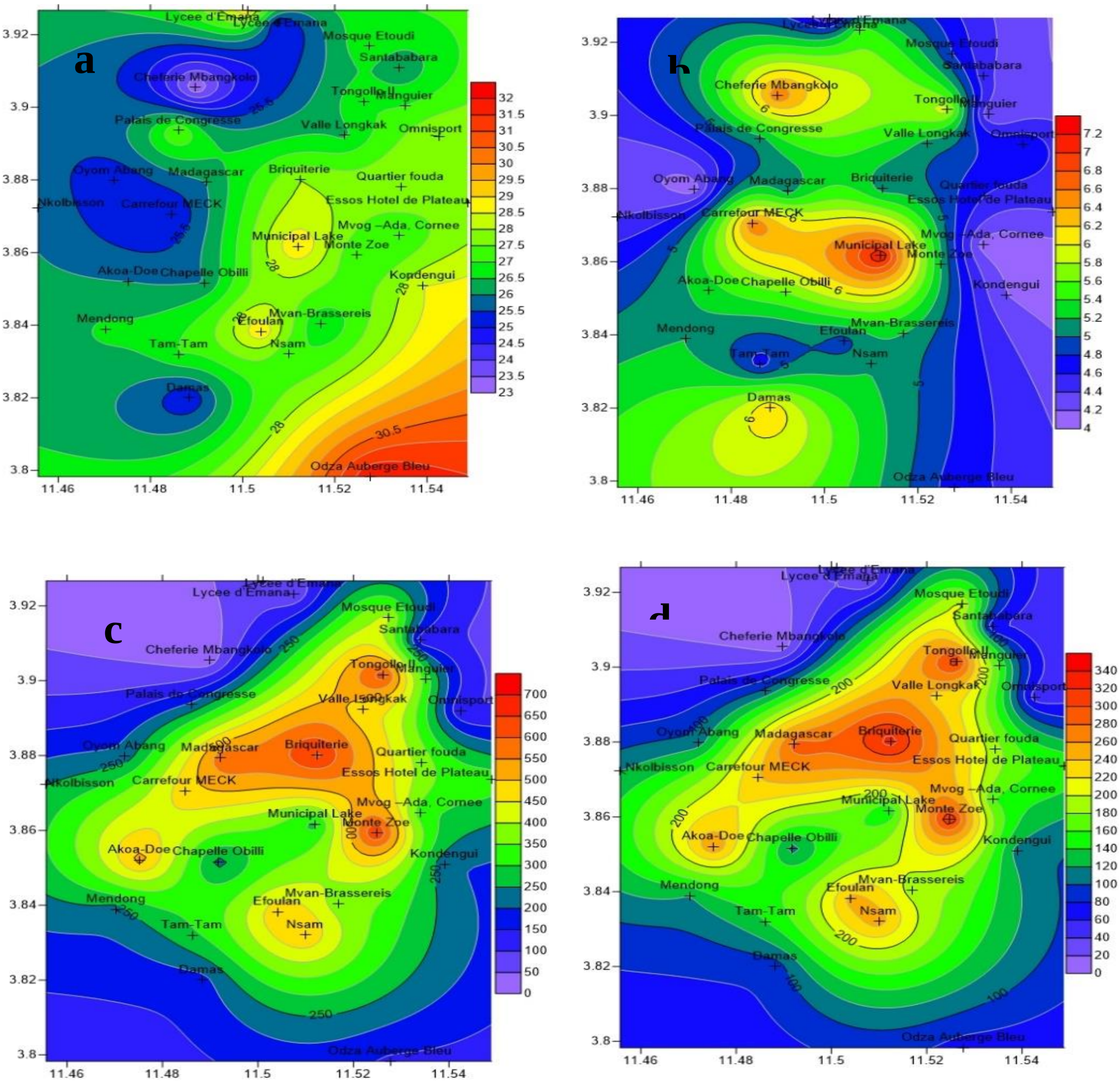
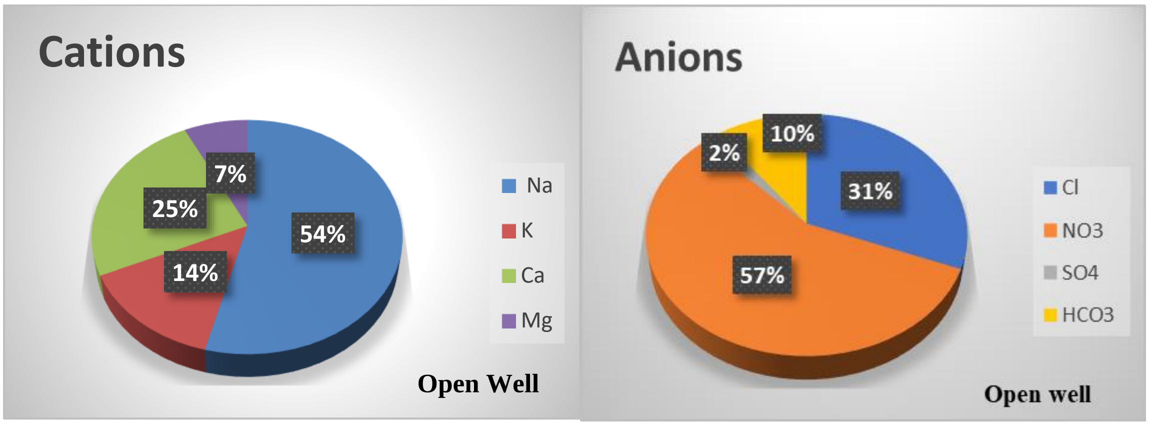
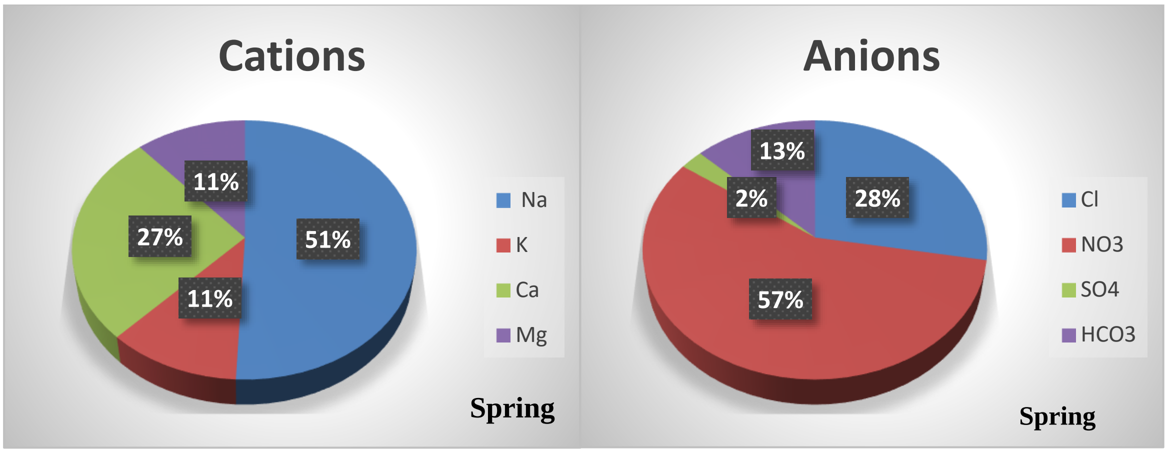


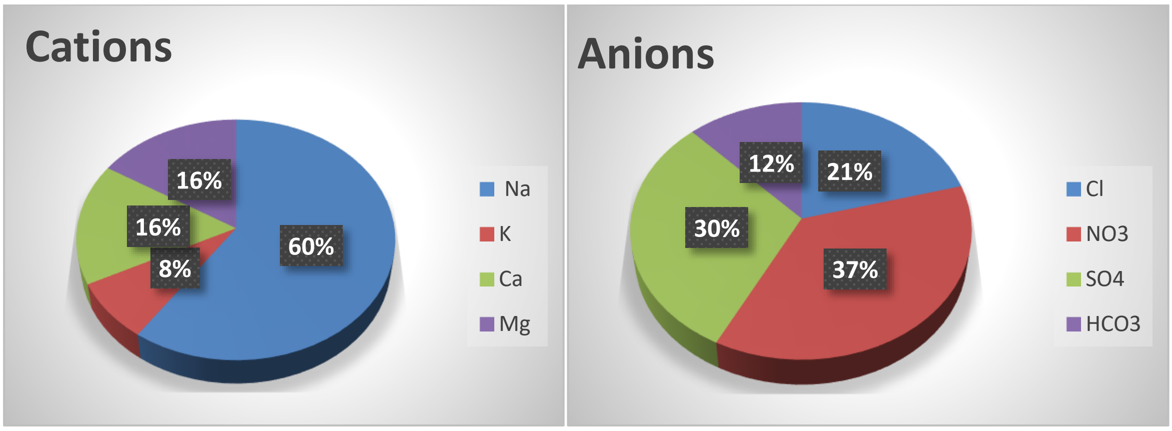
Figure 3: Spatial Distribution of Physio-Chemical Parameters



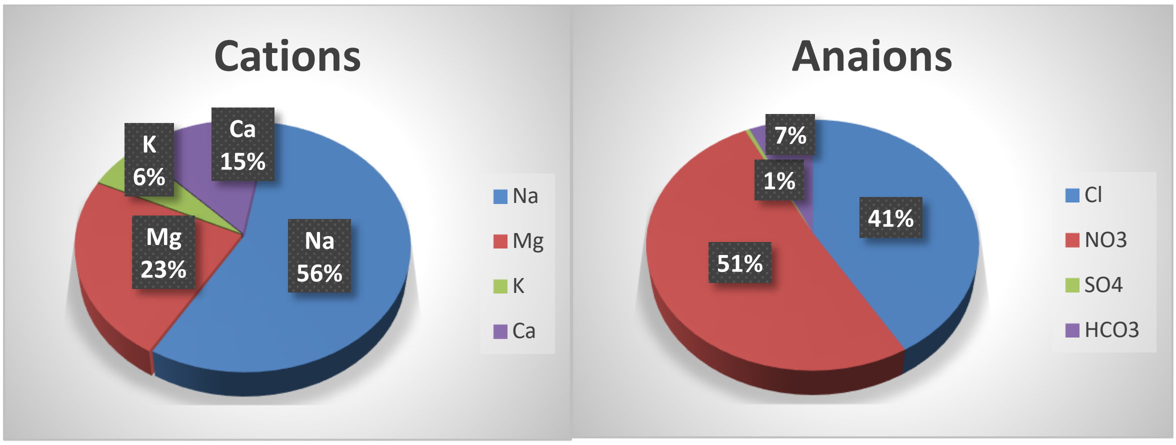
a) Opens wells



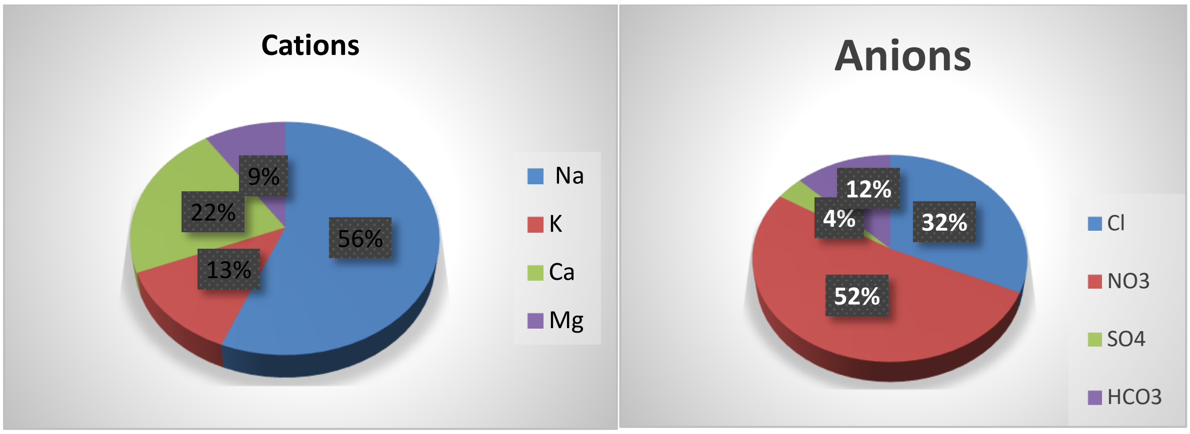
b) springs



c) Developed springs

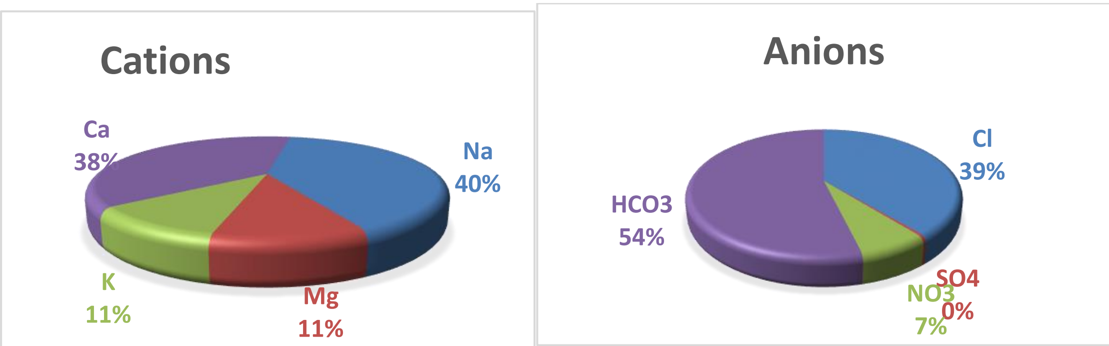


d) Borehole

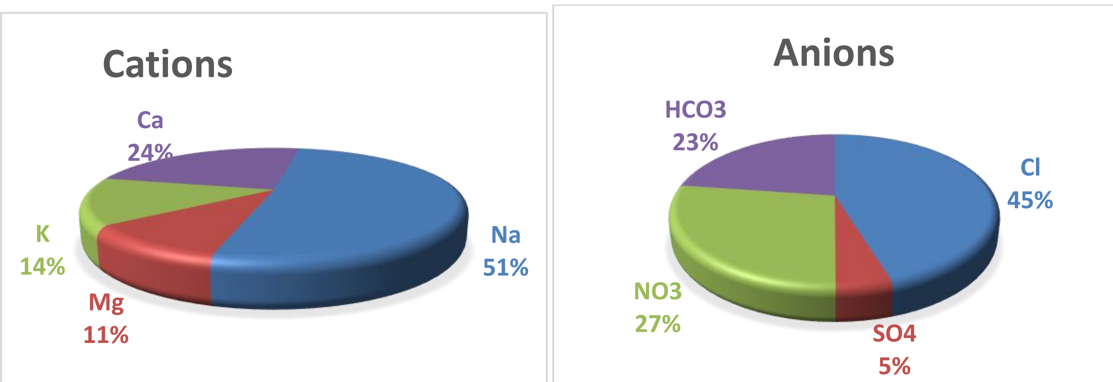


e) Summary of mean constituents for major ions

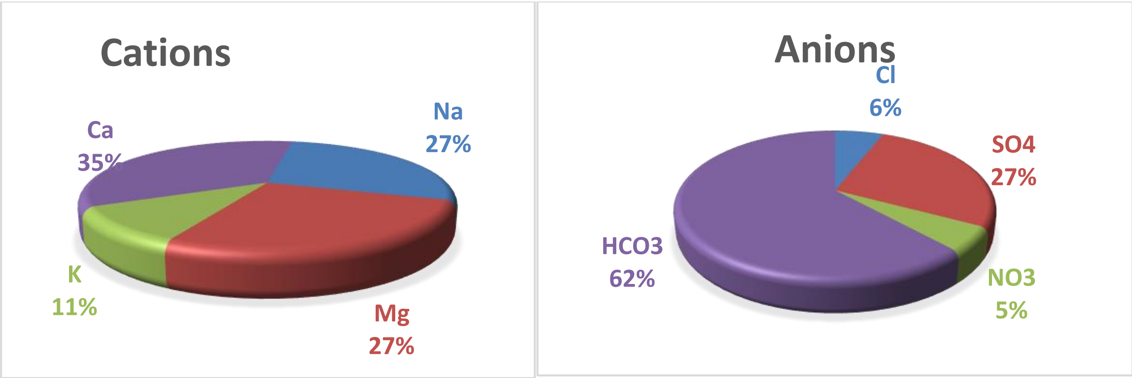
Figure 4: Pie Charts of Mean Concentrations of Ions (meq/l) (a) Open Wells (b) Springs (c) Developed Springs (d) Bole Hole (e) Summary of Mean Constituents of Major Ions Showing Na^{+} *and* NO_3^{-} *in Groundwater Sources*



a. Lake



b. River water



c. Stream water

Figure 5: Pie Charts of Mean Concentrations of Ions (meq/l) (a) Lake (b) River water (c) Stream

Determination of Water Types, Sources of Ions and Hydrochemical Processes

To identify and understand the chemical facies of groundwater in the study area, groundwater samples and surface water samples were plotted on a Piper diagram using Rockware software (Piper 1944; Figure 6). The water samples plot mainly in facies I, II, III and IV

I= Ca-HCO_3=20%

II=NaCl= 54%

III= CaCl=10%

IV=Ca-Na. HCO_3=16%

Ca-HCO_3 water type indicates shallow fresh groundwater While Ca-Na-HCO_3 water type indicates deeper fresh water. Similar water types have been reported in the Rio del Rey Basin (Wotany *et al.*, 2013) and from springs in Mount Cameroon (Ako *et al.*, 2012a). The Na-Cl facies suggest pollution due to anthropogenic activities in the area.

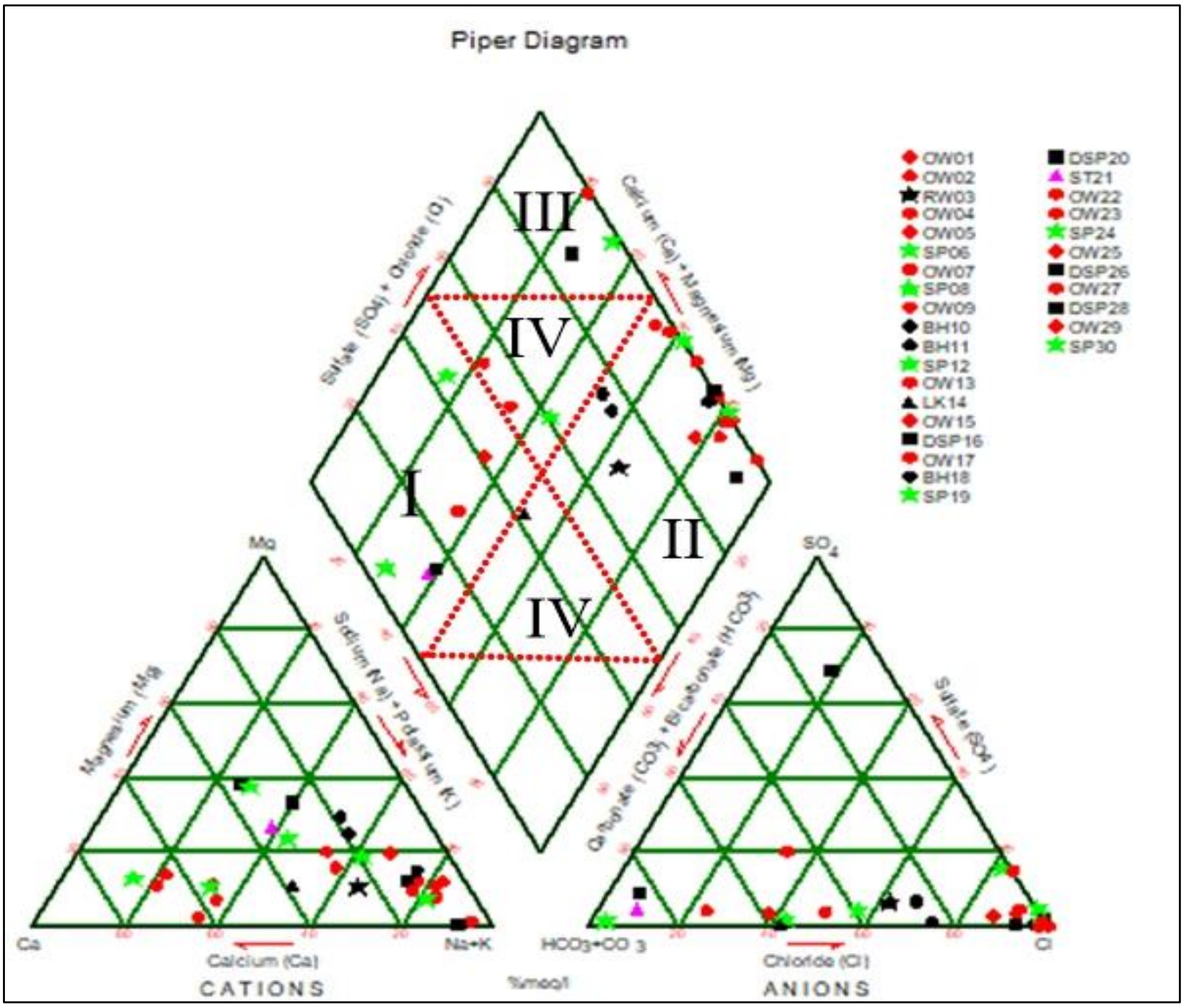


Figure 6: Piper Diagram Showing the Water Types with Their Proportions in the Study Area

The calculated values of the **(**Cl^-/Br^-) mass ratio were plotted against the log values of the chloride ions of water samples in the study area (Figure 7). The results show that most samples (80%) plotted close to the septic leachate. This shows clear evidence of human pollution of the shallow aquifer in Yaoundé. Similar studies have been reported in the urban city of Douala, Cameroon (Wirmvem *et al.*, 2017 and the urban cities in the USA (Katz *et al.*, 2010).13.33% of the samples plotted in the bulk precipitation zone and 6.67% plotted in the zone of dilute water. Shallow groundwater beneath septic tanks can be elevated in nitrate, orthophosphate, chloride, sodium, calcium, potassium, dissolved organic carbon, and boron; depleted in dissolved oxygen (Panno *et al.*, 2006, 2007). Also, elevated concentrations of trace metals (Fe, Al, Mn, and Cr) can develop under anoxic conditions in plumes down gradient from septic systems (Robertson and Blowes, 1995).

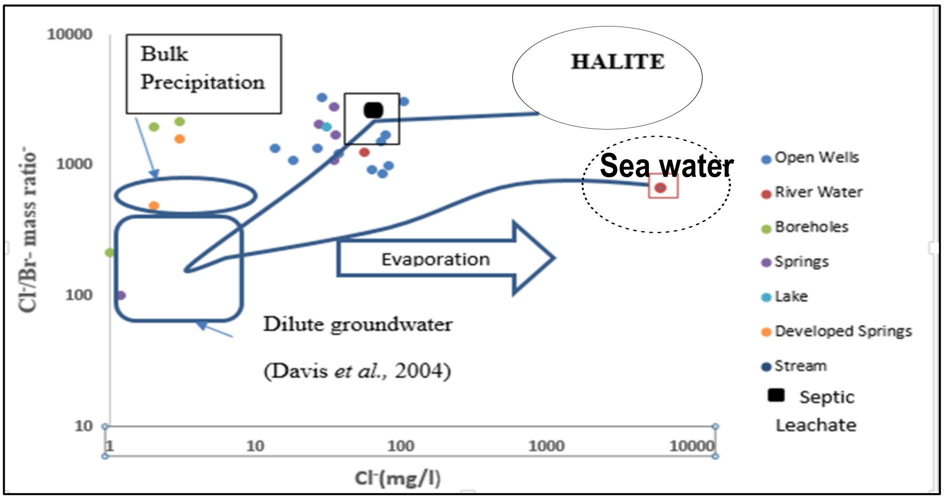


Figure 7: Relation between Cl^-/Br^- and Cl^- of Groundwater and Surface Water in Yaoundé.

The calculated values of the Na/Cl molar ratios indicate that 80% of the water samples had molar ratios greater than 1 and 20% had molar ratios lesser than 1 (Figure 8). Meybeck (1987) used Na/Cl molar ratios to study silicate weathering reactions and showed that Na/Cl molar ratio >1 reflects Na^+ released from silicate weathering. 80% of groundwater and surface water samples were greater than that of seawater (0.86) which reflects silicate weathering reactions (Cendon *et al.*, 2010, Wotany *et al.*, 2013., Fongoh *et al.*, 2024). Values of Na/Cl molar ratios <1 (0.84mg/l) imply another source is contributing chloride to the groundwater (Edet *et al.*, 2011). Wirmvem et al. 2017 in their research in Douala suggested an additional source of Cl^- likely from human activities.

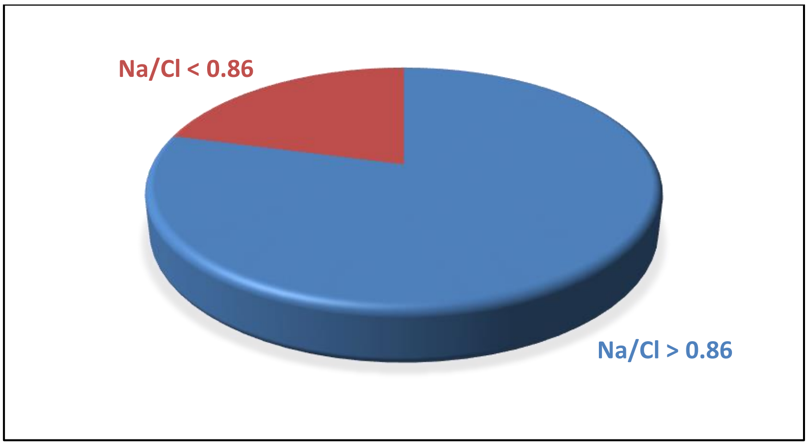


Figure 8: Pie Chart Showing Na/Cl Molar Ratios for Water Sources in the Study Area

A strong positive correlation existed between NO_3^- and Cl^- (R^2 = 0.61) in the water samples in the study area (Figure 9). The high population density poor access to sanitation facilities, and human activities in the study area could affect the groundwater quality together with agro-industrial activities. This can be related to the significant overall correlation between NO_3^- and Cl^-. Demlie et al., 2007 illustrated that a strong positive correlation between NO_3^- and Cl^- is a diagnostic indicator of anthropogenic activity. In this study, a strong positive correlation between NO_3^- and Cl^- (R^2 = 0.6077) exists and is a diagnostic indicator of anthropogenic activity on groundwater quality in the study area.

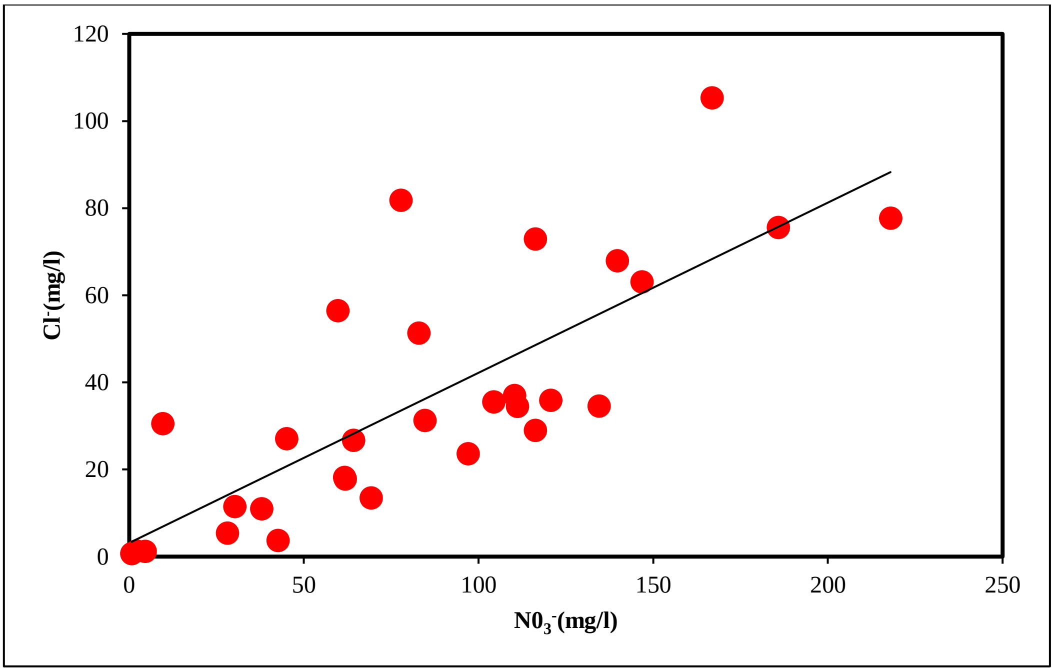


Figure 9: Scatter Plot of Cl^- versus NO_3^- in Groundwater and Surface Water Sources in the Study Area

There was an inverse relationship between NO_3^- against depth. As the number of nitrates is significantly higher in the first 22m of the aquifers and decreases with depth (Figure 10). This indicates that nitrate species in most of the considered groundwater are of superficial origin (anthropogenic). The significant concentrations of NO_3^- in groundwater are indicative of the unconfined nature of the system. Shallow groundwater resources (open wells and springs) are more vulnerable to nitrate contamination due to natural N-fixing under aerobic conditions, while denitrification in reducing conditions is the probable cause of low nitrate concentrations in waters from boreholes of the study area (Ako *et al.*, 2011).

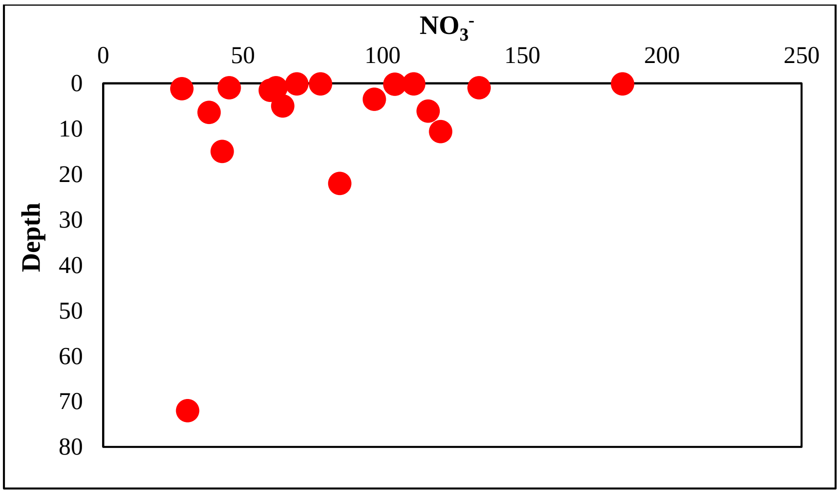


Figure 10: Plot of Depth of Wells and Boreholes versus Nitrate Concentrations of Groundwater and Surface Water Sources in the Study Area

Gibbs plot (Figure 11) shows that 90% of water samples plot in the Rock-dominance zone and 10% in the precipitation-dominance zone. No sample fell under evaporation- dominance zone. Weathering of the aquifer matrix is the primary dominant process in the acquisition of ions while atmospheric precipitation is the secondary process controlling the hydrogeochemistry in Yaoundé Similar works have been recorded by Akoachere et al., (2019) in Yaoundé.

Trace Elements Composition of the Studied Groundwater

Ten water samples were analyzed for trace metals that showed higher concentrations of Aluminum, Iron and Manganese relative to the other elements in the groundwater (Table 3).

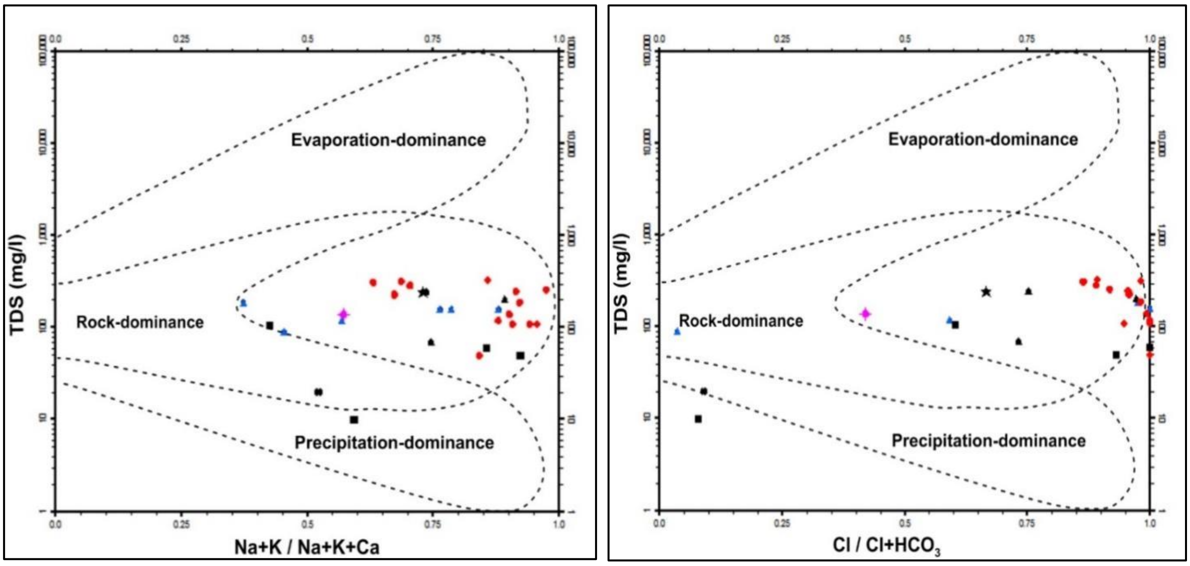


Figure 11: Mechanisms Controlling the Chemistry of Groundwater (After Gibbs, 1970)

Table 3: Trace Element Results (ppm)

Locations	Water Sources	Al	Mn	^{57}Fe	Be	Cr	Co	Ni	Cu	Zn	Ga	As	^{77}Se	^{82}Se
Nkolbisson	Open Well	0.23900	0.70000	0.27200	0.00019	0.00069	0.00843	0.00846	0.00169	0.02296	0.00276	0.00097	0.00305	0.00188
Valle Longkak	Open Well	0.24000	1.22800	0.56800	0.00006	0.00012	0.00165	0.00099	0.00094	0.00082	0.00125	0.00024	0.00160	0.00155
Nsam	Open Well	0.15600	0.08400	0.28400	0.00014	0.00034	0.00501	0.00421	0.00067	0.01295	0.00082	0.00024	0.00084	0.00109
Odza	Borehole	0.11700	0.14300	0.22300	0.00026	0.00013	0.00352	0.00670	0.00259	0.02219	0.00055	0.00016	0.00106	0.00166
Efoulan	Borehole	0.13600	0.06000	0.22500	0.00007	0.00305	0.00094	0.00158	0.00670	0.00952	0.00034	0.00014	0.00023	0.00099
Mendong	Spring	0.07800	0.25200	0.22800	0.00007	0.00017	0.00584	0.00219	0.00046	0.00207	0.00020	0.00009	0.00011	0.00106
Mosque Etoudi	Borehole	0.28200	0.45200	0.29200	0.00021	0.00029	0.01090	0.00637	0.00327	0.14071	0.00160	0.00836	0.00311	0.00276
Manguier	Spring	0.35900	0.47100	0.30800	0.00032	0.00057	0.01154	0.00702	0.00185	0.03573	0.00460	0.00052	0.00593	0.00242
Kondengui	Open Well	0.26600	0.07300	0.24800	0.00016	0.00025	0.00098	0.00101	0.00048	0.00348	0.00325	0.00025	0.00338	0.00172
Omnisport	Developed spring	0.20700	0.13500	0.28600	0.00011	0.00022	0.00338	0.00114	0.00057	0.00270	0.00146	0.00035	0.00100	0.00105
Minimum		0.07800	0.06000	0.22300	0.00006	0.00012	0.00094	0.00099	0.00046	0.00082	0.00020	0.00009	0.00011	0.00099
Maximum		0.35900	1.22800	0.56800	0.00032	0.00305	0.01154	0.00846	0.00670	0.14071	0.00460	0.00836	0.00593	0.00276
Mean		0.20800	0.35980	0.29340	0.00016	0.00058	0.00522	0.00397	0.00192	0.02531	0.00168	0.00113	0.00203	0.00162
Standard deviation		0.08608	0.37234	0.101212	8.7E-05	0.00088	0.00391	0.00293	0.00193	0.04212	0.00143	0.00255	0.00181	0.00060

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Table 3: Continued

Locations	Water Sources	Sr	Ag	Cd	Cs	Rb	Tl	Pb	Th	U
Nkolbisson	Open Well	0.04970	0.000207	0.0001	0.00037	0.01470	0.00035	0.03467	0.00165	0.00027
Valle Longkak	Open Well	0.08330	0.0001210	0.0000	0.00025	0.00530	0.00009	0.00021	0.00105	0.00023
Nsam	Open Well	0.02820	0.0001570	0.0000	0.00037	0.00530	0.00021	0.00103	0.00065	0.00020
Odza	Borehole	0.02910	0.0001590	0.0001	0.00018	0.00810	0.00009	0.00098	0.00173	0.00019
Efoulan	Borehole	0.08030	-0.0000200	0.0000	0.00011	0.00370	0.00006	0.00019	0.00068	0.00020
Mendong	Spring	0.07440	0.0000310	0.0000	0.00007	0.01660	0.00010	0.00010	0.00080	0.00019
Mosque Etoudi	Borehole	0.07050	0.0002300	0.0001	0.00072	0.02260	0.00071	0.00409	0.00557	0.00024
Manguier	Spring	0.08600	0.0001230	0.0001	0.00068	0.01280	0.00014	0.00387	0.00157	0.00024
Kondengui	Open Well	0.00630	0.0000740	0.0000	0.00046	0.00460	0.00008	0.00226	0.00031	0.00032
Omnisport	Developed spring	0.00770	0.00032	0.0000	0.00071	0.00430	0.00016	0.00195	0.00127	0.00024
Minimum		0.00630	-0.00002	0.00002	0.00007	0.00370	0.00006	0.00010	0.00031	0.00019
Maximum		0.08600	0.00032	0.00012	0.00072	0.02260	0.00071	0.03467	0.00557	0.00032
Mean		0.05155	0.00014	0.00006	0.00039	0.00980	0.00020	0.00494	0.00153	0.00023
Standard deviation		0.031492	9.795E-05	3.87E-1	0.000246	0.006506	0.000199	0.010547	0.001498	4.08E-05

The mean concentration of uranium in groundwater was 0.00980ppm (Figure 12). The highest concentration of uranium was registered in the borehole at Mosque Etoudia and the least was registered in the borehole at Efoulan (Table 3).

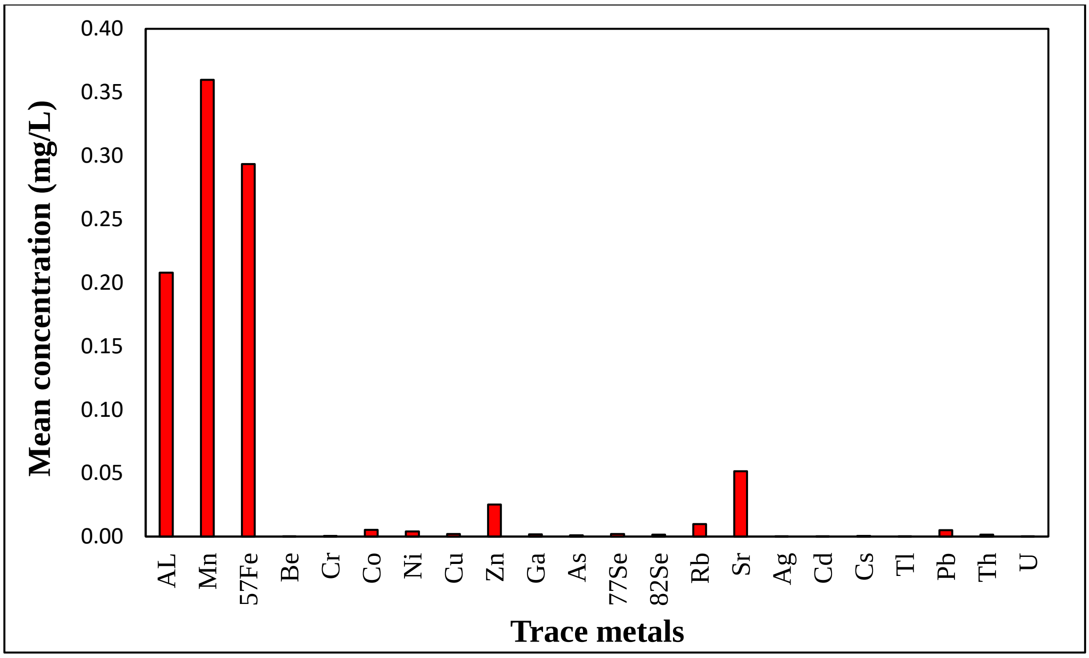

Figure 12: Bar Graph Showing Variation in the Mean Concentrations for Trace Metals in Groundwater in the Study Area

Thirty per cent (30%), forty per cent (40%), and ten per cent (10%) of aluminium, Manganese and iron were above the desirable limit of drinking water standards, respectively (WHO, 2011). Thirty per cent (30%), one hundred per cent (100%), and ten per cent (10%) of aluminium, Manganese and iron were above the desirable limit of drinking water standards, respectively (US.EPA, 2009). The remaining elements were within the desirable limits of drinking water guidelines (WHO, 2011, US.EPA, 2009).

The concentration of iron in water was in the range of 0.22300mg/l to 0.56800mg/l, which is above the desirable limit and at some locations it was above the permissible limit (Valle NLongkak). Thus, iron toxicity is possible in that area (Taqveem, 2011). Iron is the most abundant metal on earth, but its deficiency occurs worldwide. It is so because humans have a mechanism that prevents excess iron absorption. Humans are generally well protected from oral overdose; however, children between 1 and to 2years old are particularly vulnerable to iron toxicity from the ingestion of iron supplements that have been commercially prepared for adults (Fairbanks et *al.*, 1971). The high concentration of Fe and Mn in water is attributed to high suspended solids (Edet and Offiong 1998a, b). The presence of Fe is very significant in this area as the water has a reddish-brown colour.

Contamination Index (C_d) and the Trace Element Potential Index (TEI)

Cd and TEI were evaluated for their suitability for contamination monitoring of groundwater (Table 4). Results show that despite the significant correlation between the data generated from these indices. The final classification gave two extreme results (Figure 13). The values for TEI and C_d exhibited more or less similar distribution patterns with both having their highest concentration at OW01 (open well at Nkolbisson (Figure 13 a & b).

Following the approach of Edet and Effiong (2002), the samples fall within the zone of low contamination (Table 4). This has also been reported by studies carried out in Ekondo-Titi Onshore Rio del Rey Basin Cameroon (Akoachere *et al.*, 2019). The strong correlation between trace elements indicates these metals are probably from the same sources. The TEI and Cd exhibit more or less similar distribution patterns with both having their highest concentration the OW05 (open well at Valle NLongkak). These suggest similar point sources. Similar studies have been carried out in the Akpabuyo-Odukpani area, Lower Cross River Basin (southeastern Nigeria) ((Edet and Offiong 1998a, b).

Table 4: Computed Values for TEI and C_d

Locations	Code	Water sources	TEI	C_d
Nkolbisson	OW01	Open Well	7.38	-5.62
Valle Longkak	OW05	Open well	5.71	-7.2
Nsam	OW09	Open well	2.16	-10.8
Odza	BH10	Borehole	1.94	-11.06
Efoulan	BH11	Borehole	1.72	-11.28
Mendong	SP12	Spring	1.75	-11.25
Mosque Etoudi	BH18	Borehole	4.87	-8.13
Manguier	SP19	Spring	4.57	-8.43
Kondengui	OW23	Open well	2.72	-10.28
Omnisport	DSP26	Developed spring	2.58	-10.42
Minimum			1.72	-11.28
Maximum			7.38	-5.62
Mean			3.54	-9.42
Standard Dev.			1.97	1.97

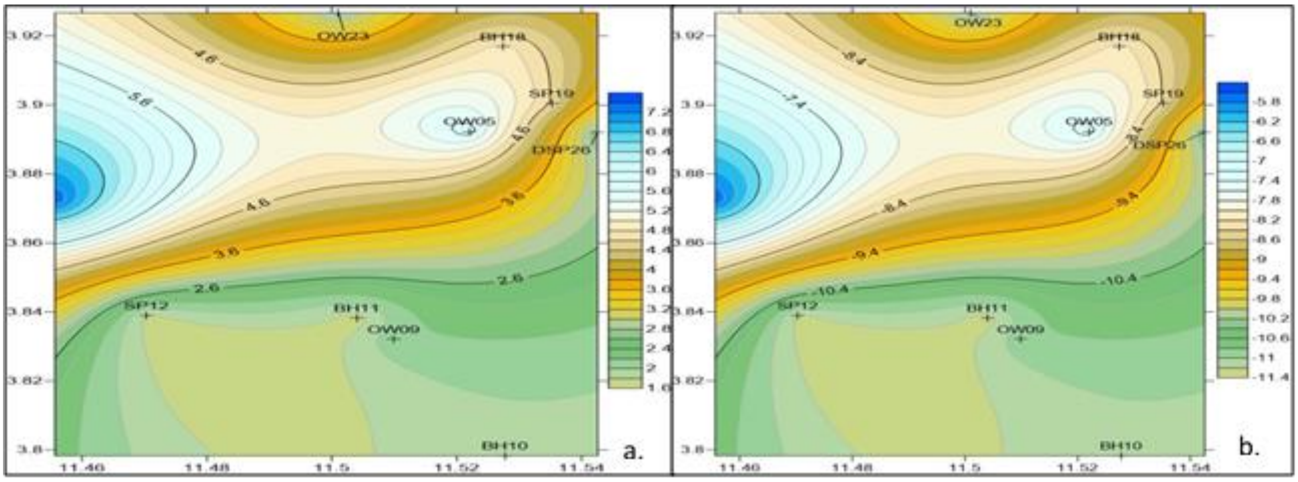

Figure 13. Spatial Variation Map (a) TEI and (b) C_d.

Enrichment Factor (EF)

The value of EF shows (Table 5) values between 0.00-3.83. According to Sutherland (2000), the values fall in the interval (1≤EF<3). The EF factor for all samples shows a similar distribution pattern superposing on each other. The open well at Nkolbisson recorded the element with the highest enrichment factor which corresponds to Lead (Pb) (Figure 14). Enrichment factor for all trace elements was computed (Table 5) and values were represented on a scatter plot. The sequence of EF in the water sources were Pb>Al>Mn>As>^{77}Se>Ni>Zn>Cr>^{88}Se>Cd>U EF<1 indicates the metals originate mainly from crustal materials or natural processes (Liaghati et *al.,* 2003).

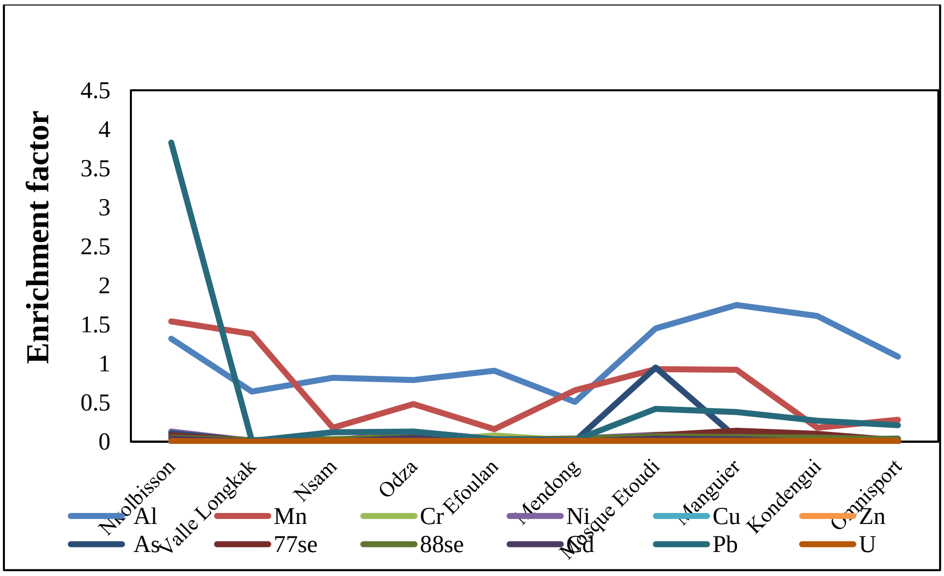

Figure 14: Variation of Enrichment Factor for Trace Elements in Groundwater

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Table 5: Computed Values for the Enrichment Factor

Locations	Water Sources	Al	Mn	Cr	Ni	Cu	Zn	As	77se	88se	Cd	Pb	U
Nkolbisson	Open Well	1.32	1.54	0.01	0.13	0.00	0.01	0.11	0.08	0.05	0.04	3.83	0.01
Valle Nlongkak	Open Well	0.64	1.38	0.00	0.01	0.00	0.00	0.01	0.02	0.02	0.00	0.01	0.00
Nsam	Open Well	0.82	0.18	0.00	0.01	0.00	0.01	0.03	0.02	0.03	0.00	0.12	0.01
Odza	Borehole	0.79	0.48	0.00	0.13	0.00	0.10	0.02	0.04	0.06	0.05	0.13	0.01
Efoulan	Borehole	0.91	0.16	0.08	0.03	0.01	0.00	0.02	0.01	0.03	0.00	0.03	0.01
Mendong	Spring	0.51	0.66	0.01	0.04	0.00	0.00	0.01	0	0.04	0.00	0.02	0.01
Mosque Etoudi	Borehole	1.45	0.93	0.01	0.09	0.00	0.05	0.95	0.08	0.07	0.04	0.42	0.01
Manguier	Spring	1.75	0.92	0.01	0.1	0.00	0.01	0.05	0.14	0.06	0.03	0.38	0.01
Kondengui	Open Well	1.61	0.18	0.01	0.02	0.00	0.00	0.03	0.1	0.05	0.00	0.27	0.01
Omnisport	Developed spring	1.09	0.28	0.01	0.02	0.00	0.00	0.04	0.02	0.03	0.00	0.21	0.01
Minimum		0.51	0.16	0.00	0.01	0.00	0.00	0.01	0.00	0.02	0.00	0.01	0.00
Maximum		1.75	1.54	0.08	0.13	0.01	0.1	0.95	0.14	0.07	0.05	3.83	0.01
Mean		1.089	0.671	0.014	0.058	0.001	0.018	0.127	0.051	0.044	0.016	0.542	0.01
STD		0.43	0.51	0.02	0.05	0.00	0.03	0.29	0.05	0.02	0.02	1.16	0.00

Pollution Load Index (PLI)

Pollution values (Table 6) ranged between 8.05788E-26 (spring at Mendong) to 2.07844E-15 (Borehole at Mosque Etoudi). All samples have PLI values <1. Pollution load index < 1 indicates no risk of pollution in Yaoundé (Adebowale *et al.*, 2009).

Table 6: Computed Values of Pollution Index

Location	Code	Water sources	PLI
Nkolbisson	OW01	Open well	5.4604E-16
Valle Longkak	OW05	Open well	1.121E-22
Nsam	OW09	Open well	7.0962E-22
Odza	BH10	Borehole	7.4716E-21
Foulan	BH11	Borehole	1.1593E-22
Mendong	SP12	Spring	8.0579E-26
Mosque Etoudi	BH18	Borehole	2.0784E-15
Manguier	SP19	Borehole	7.2858E-17
Kondengui	OW23	Open well	5.4307E-22
Omnisport	DSP26	Developed Spring	1.3496E-22
Min			8.05788E-26
Max			2.07844E-15
Mean			2.69735E-16
Standard			6.57927E-16

Classification of Trace Elements in Water

From the chart (Ficklin *et al.*, 1992), 30% of the water samples are classified as acid high metals and 70% are acid low metals (Figure 15). The acidic nature of groundwater is due to leaching of altered rocks by rainwater (Edet *et al.*, 2002).

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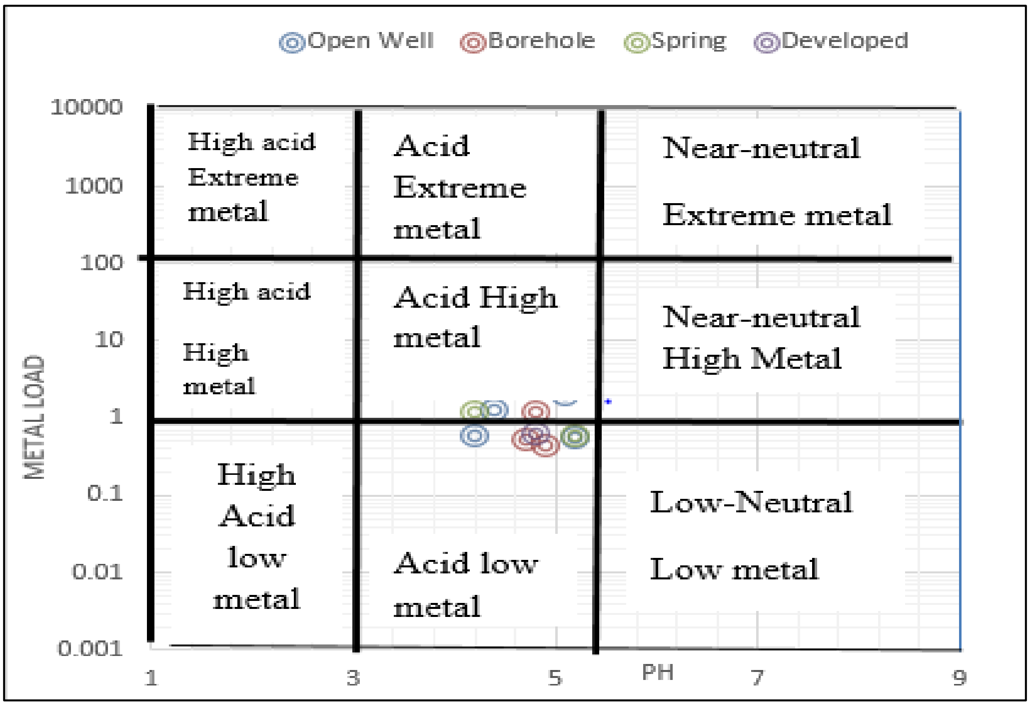

Figure 15: Classification of Water Samples Based on the Plot of Metal Load and pH

4.0 CONCLUSION AND RECOMMENDATIONS

The pH and TDS values of the groundwater sources indicate the water sources are acidic and are generally fresh and experienced slight mineralization. The primary source of NO_3^- and Cl^- contamination in the shallow wells was linked to leaching from the pit latrines and septic tanks. The highest concentrations of these contaminants were located in densely populated areas of the city. Nitrate pollution occurs between 0 to 22m in the aquifers. Cl^-/Br^- indicates pollution of these water sources was linked to septic leachate and pit latrines. Shallow groundwater in densely populated areas of Yaoundé is not a good source of drinking water. The groundwater facies included; Ca-HCO_3 (20%) Na-Cl (54%), Ca-Na-HCO_3 (16%) and Ca-Cl (10%) rich waters with its chemistry strongly influenced by rock water interactions, silicate weathering and anthropogenic processes. The mean concentration of trace metals in groundwater was in the order; Mn> Fe> Al> Sr> Zn > Co> Pb > Ni> 77Se >Th>82Se >As >Rb> Cr > Cs >U >Ti >Be >Ag. These elements were below the WHO (2011) guidelines values except Al (30%), Mn (40) and Fe (10%) and this occurs in densely populated areas of the study area; hence, indicating human pollution. The degree of contamination (Cd), trace element evaluation index (TEI), Enrichment factor (EF) and pollution load index (PLI) show low enrichment and contamination of the trace elements.

The presence of nitrate and chloride contamination indicates the need for proper sanitation practice, constant monitoring of wells and proper groundwater strategies necessary for the development and sustainability of the water resources. What are the implications of the study?

The implications of this study are significant for both the local population of Yaoundé and the broader scientific community:

Public Health Risk: The high levels of nitrate and some trace elements (Al, Mn, Fe) in the groundwater pose a potential health risk to the population relying on these sources for drinking and domestic use. This necessitates immediate action to provide alternative safe water sources and implement measures to mitigate contamination.

Sanitation and Waste Management: The study highlights the direct link between poor sanitation practices (pit latrines, septic tanks) and groundwater pollution. This underscores the urgent need for improved sanitation infrastructure and waste management practices in Yaoundé to protect groundwater quality.

Groundwater Management: The findings emphasize the importance of developing and implementing effective groundwater management strategies in Yaoundé. This includes regular monitoring of water quality, identifying and protecting recharge areas, and promoting sustainable extraction practices.

Urban Planning: The study's results can inform urban planning decisions in Yaoundé, ensuring that future development takes into account the vulnerability of groundwater resources and implements measures to minimize pollution risks.

Scientific Understanding: The research contributes to a better understanding of the hydrogeochemical processes and pollution dynamics in urban groundwater systems in developing countries. This knowledge can be applied to similar contexts worldwide to improve groundwater management and protection.

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Statement and Declarations

Conflict of interest: The authors declare no conflict of interest

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