

Research Article

Groundwater Quality Investigation in the Coastal Aquifer of Limbe, South West Cameroon

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Abstract

Coastal aquifers are vital fresh water reservoirs that could be affected by seawater intrusion, thereby polluting the water resources. This study investigated the current status of subsurface water in Limbe-Cameroon, focusing on aquifer hydrochemical characteristics. Groundwater samples were obtained from nine boreholes and measurements were conducted on the following physicochemical parameters; pH, electrical conductivity (EC), and total dissolved solids (TDS) and major ions (cations and anions). The results showed that most of the sampled boreholes were in the permissible limits of the World Health Organization (WHO) guidelines, except for a few samples. 11.11% of the pH values, 11.11% of the EC values and 11.11% of the TDS values the WHO recommended limits. Major ion concentrations were below WHO prescribed levels in all analysed samples. The water quality index (WQI) indicated that 44.44% of the samples were of good quality water with water quality values varying from 26-50, 11.11% were classified as poor-quality water and another 11.11% of the samples were unsuitable for drinking purposes. The hydrochemical facies were principally Ca-HCO₃ and Ca-Mg-Cl-SO₄ water types. Irrigation water quality indices such as sodium adsorption ratio (SAR), Magnesium Hazard (MH), soluble sodium percentage (SSP) indicated that groundwater in Limbe is suitable for irrigation. These higher values signify the possibility of salt water intrusion in the study area and highlights the critical need for sustainable groundwater management in Limbe to prevent further degradation from seawater intrusion and protect the freshwater resources in the region.

Keywords

Coastal Aquifers, Water Quality Index, Seawater Intrusion, Limbe-Cameroon

1. Introduction

Water supply is key to the development of resilient cities and communities, but global water supplies are dwindling. Currently, almost 50% of the global population lives in re-

gions where scarcity of water is experienced for at least one month annually [1]. The number of persons who experience water scarcity is expected to increase to 57% by 2050 [1].

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Water scarcity is driven by increase in water use due to population growth, increase in pollution of fresh water resources, and decrease in water resources [2, 3]. Water scarcity is already a major issue in developing countries. Future stress on water resources is expected to be higher in these countries due to rapid population growth [4, 5]. Self-supply of water plays a vital role in the water supply ecosystem of developing countries and has the potential to pivot the pace toward attainment of Sustainable Development Goals target 6.1 [6]. Self-supply comprises water sources (both groundwater and surface water) within the premises of individual households that are owned and managed by the households [7, 8]. Groundwater is the fastest growing means of meeting water demands in sub-Saharan African cities. Approximately 1.5 billion people worldwide depend on groundwater for their provisions [9, 10]. As is the case throughout the world, the majority of sub-Saharan African cities are located along the continental coastal belts, where groundwater resources are vulnerable to the influence of seawater intrusion, atmospheric sea aerosol deposition, and pollution due to population pressure [11].

Groundwater resource is one of the most challenging current and future issue of worldwide concern. The ever-increasing rate of population growth and the inherent water supply demand have led to intensive groundwater exploitation. Groundwater is of great importance for domestic, drinking, irrigation, and industry purposes especially where surface water resource availability is scarce [12-14]. This is because it is typically less polluted than surface water due to its self-cleaning ability and ease of treatment [15, 16]. In developing countries, inadequate access to clean drinking water adversely affects the population's general health and life expectancy [17, 18]. Clean surface water is relatively scarce, and people have deviated to groundwater sources [11].

Good quality water is strongly associated with good health comfort and social well-being of people. Because of this, target 6.1 of the Sustainable Development Goal (SDG) emphasizes on access to safe drinking water by the year 2030 [19]. The impacts on health depend on the concentration of the chemicals in polluted water and the time of exposure [20]. It has also been reported that about 3.1% of people die globally as a result of drinking contaminated water [21]. Some chemicals might produce immediate impacts on human health because of the nature of the hazardous chemicals [22, 23]. Severe human health implications, such as cardiovascular and skeletal diseases, infertility, neurotoxicity, are associated with heavy metal exposure [24].

Coastal aquifers are one of the most important water resources in the world. In addition, the natural discharge of freshwater to the sea as submarine groundwater discharge, plays an important role in the ecology of marine environments [25]. The dynamics of seawater and freshwater within coastal aquifers are highly sensitive to disturbances, and their inappropriate management may lead to the deterioration of water quality. Coastal aquifer systems are especially valuable as one of the primary contributors of freshwater, solutes and nutri-

ents from land to sea [26]. These pathways can also serve as an effective conduit for pollutants to reach coastal areas [27]. In many coastal aquifers, seawater intrusion has become a major constraint imposed on groundwater utilization [28]. Groundwater exploitation and climate variations create dynamic conditions, which can significantly increase seawater intrusion into aquifers and may result in the salinization of ground water resources [29].

Recent studies in Cameroon have showed that many semi-urban communities are water stressed, and are confronted with the issues of inadequate access and continuous availability of water supply for domestic water needs [30, 31]. Sustainable groundwater use requires an adequate understanding of the complexity of natural and anthropogenic processes and how they affect groundwater quality [32].

Groundwater quality studies have been conducted in the following localities in Cameroon; Douala, Yaounde, Ngaoundéré and Melong [33-36]. The aim of this study was to evaluate the groundwater quality and determine its suitability for drinking and irrigation in Limbe-Cameroon in order to provide valuable insights that can inform effective management strategies and safeguard freshwater resources for current and future generations. The specific objectives were to determine the physico-chemical properties of groundwater; the spatial distribution and the suitability of the water for different uses.

2. Study Area

The study was conducted in Limbe Metropolis, situated along the coast of the Atlantic Ocean in the South West Region of Cameroon, constituting part of the oceanic segment of the Cameroon Volcanic Line (CVL). It is located approximately between latitudes 3°00' and 4°05' N and longitudes 9°29' and 9°06' E (Figure 1). It is a low-lying area that covers approximately 671 km², with a population of about 140,000 [37]. Limbe has a subequatorial climate, consisting of two main seasons; a rainy season that spans from April to October and a dry season from November to March, with a mean annual precipitations about 3 750 mm [38]. The mean annual temperature is ~26 °C and shows only limited variations of 4 °C throughout the year [39]. Humidity is generally above 85%. The town is characterized by a low-lying coastal plain, rising to a chain of horseshoe shaped hills towards the northeast and east, with the highest point at 362 m above sea level. The topography is marked by ridges and deeply incised ravines, with a general W-E orientation, at high angle to the general NE-SW orientation of Mount Cameroon and gently sloping foot slopes of Mount-Cameroon. Individual ridges are separated by asymmetric V-shaped valleys occupied by perennial and ephemeral streams [40]. These rivers frequently overflow their banks in the rainy season causing floods in the low-lying areas that are only 1-2 m above sea level. These streams either discharge directly into the Atlantic Ocean or into the delta (Figure 2). The hydrogeology is characterized by unfossilif-

erous sandstone and gravel, weathered from underlying Pre-cambrian basement rock. It consists of coastal plain sands (CPS) and recent sediments. The CPS aquifer is the most productive and exploited aquifer in Limbe. The Limbe area is

made up mostly pyroclastic and weathered fractured and columnar basalt resulting in volcanic fractured rock aquifers. Limbe is a geohazard zone with past history of numerous volcanic activities, landslides and floods [41].

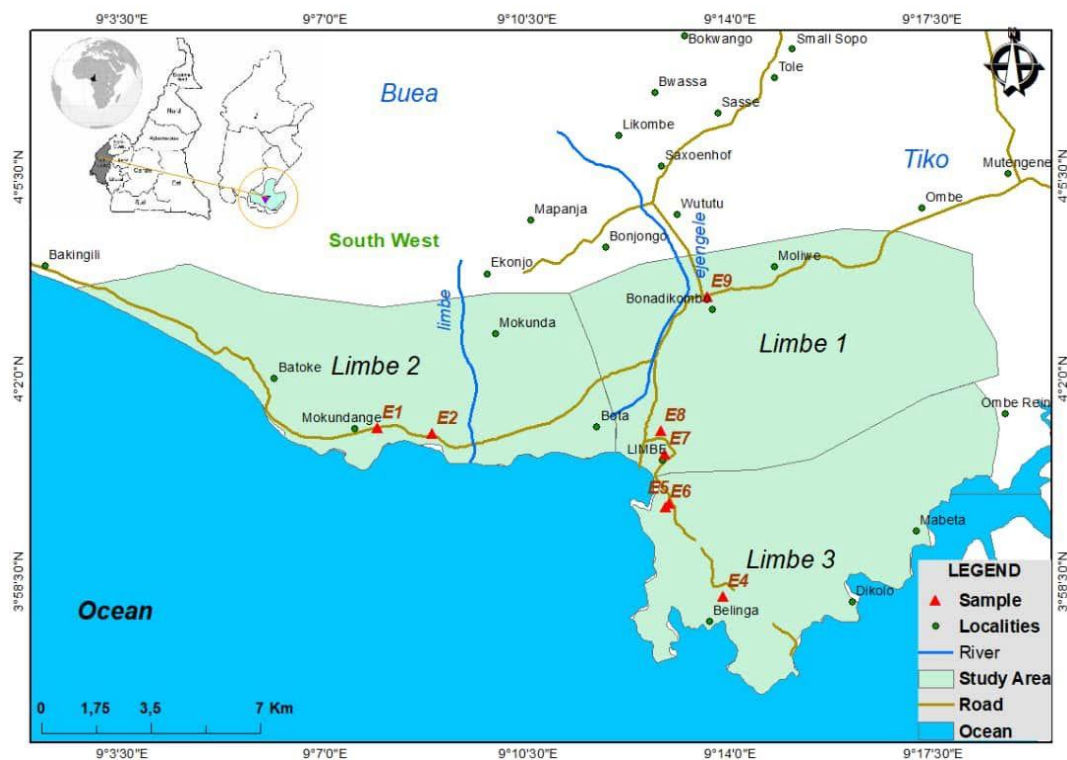


Figure 1. Location of the study area, with locations of sampling points.

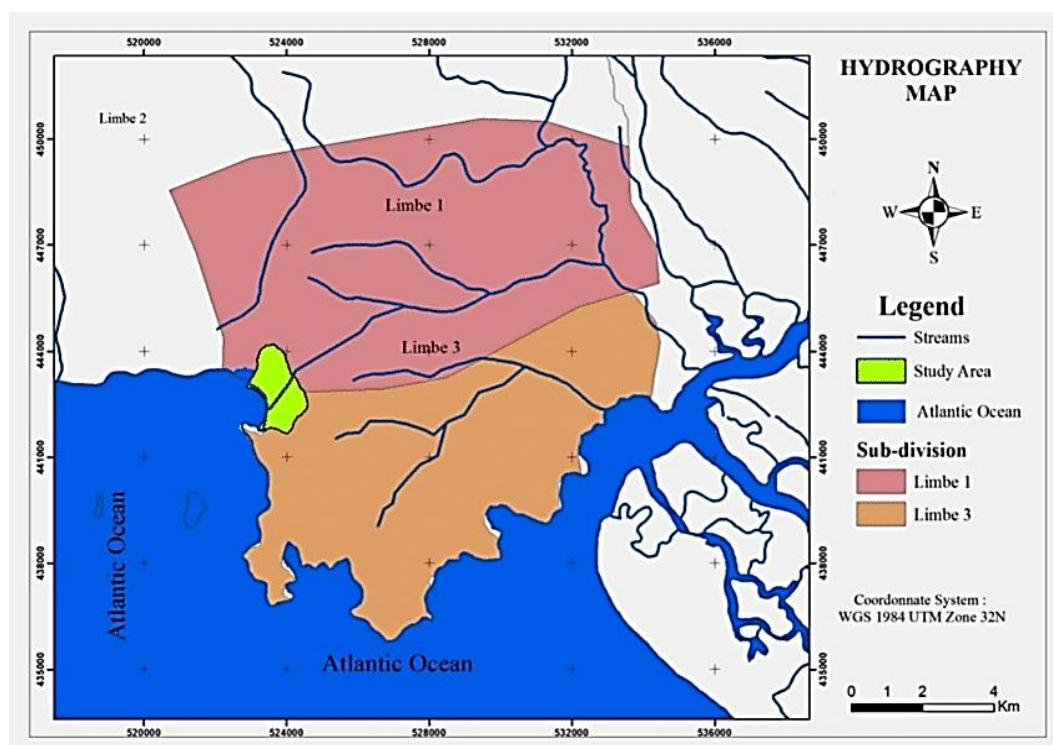


Figure 2. Hydrography map of Limbe [39].

3. Materials and Methods

3.1. Field Procedures and Sample Collection

Water samples were collected from nine boreholes in Limbe I, Limbe II, and Limbe III and labeled E1 to E9. Coordinates of the sampling points were determined with the aid of a global positioning system [42]. A water sampler marked, Gallenkamp 1000 ml was utilised to obtain water samples from the boreholes. In order to obtain a representative sample, stagnant water in the boreholes was removed before a sample was taken, a process termed purging. Samples were collected for about 5 to 10 minutes of continuous flow from the boreholes so as to include changes in water quality parameters in the water column. Samples were randomly collected, taking into consideration the spatial distribution, depth of the borehole, proximity to the sea and land use. The following parameters were measured in the field: pH, total dissolved solids (TDS), electrical conductivity (EC) using a portable multi-parameter probe Hanna HI 98127/HI98107. The sample bottles were washed thoroughly with 10% nitric acid and rinsed with distilled water and finally with the water to be sampled to prevent any eventual contamination. After collection, water samples destined for laboratory analyses were carefully transferred into 500 ml polystyrene sampling bottles avoiding any spillage in pre-cleaned sterilized bottles and stored in an ice box specifically designed for water sampling that maintains the temperature at about 4 °C. This helped preserve sample integrity during transportation to the laboratory. The bottles were sequentially securely capped to prevent leakage and contamination during transportation and labeled with the sample ID.

3.2. Laboratory Analyses

Chemical water quality characteristics were determined following the scientific methods of the American Public Health Association [42] immediately the samples were taken to the laboratory of the Cameroon Baptist Convention Health Services (CBCHS) in Mutengene, Cameroon. Major cations in mg/l in the sampled water, such as calcium (Ca^{2+}), magnesium (Mg^{2+}) and sodium (Na^+), likewise major anions such as bicarbonate (HCO_3^-), chloride (Cl^-) and sulphate (SO_4^{2-}) were determined by ion chromatography and spectrophotometric methods as described by [43, 44]. The samples were injected into an ion chromatograph, equipped with cation and anion exchange columns. Cations and anions were separated based on their interactions with the stationary phase and eluted from the column at different times. Detection was typically done using conductivity detectors for ions like calcium, magnesium, sodium, bicarbonate, chloride, and sulphate. Then the concentration of each ion was quantified based on the peak area or height in the chromatogram, calibrated using standard solutions of known concentration [44]. A spectrophotometric

method was also employed for confirmation purposes. Ca^{2+} and Mg^{2+} were determined using complexometric titration methods or colorimetric assays based on the formation of coloured complexes with specific reagents. Na^+ was analysed using flame photometry or atomic absorption spectroscopy (AAS), which measures the absorption of light by the atoms at specific wavelengths. HCO_3^- , Cl^- and SO_4^{2-} ions were gotten by titration method. A combination of these two methods provided a comprehensive and accurate analysis of major cations and anions of the sampled groundwater [42].

3.3. Water Quality Index (WQI)

In this research, the Weighted Arithmetic Water Quality Index (WA-WQI) was determined for a better appraisal of groundwater quality. This method assigns weights to different water quality parameters based on their importance and then calculates an overall index. The WA-WQI assesses the fitness of water meant for drinking. It is defined as a rating that reflects the composite influence of different water quality parameters on the overall quality of water. It indicates the quality of an index number, which represents the overall quality of water for any intended use [45]. It was calculated on nine (09) water quality parameters (pH, EC, TDS, Mg^{2+} , Ca^{2+} , Na^+ , Cl^- , HCO_3^- , SO_4^{2-}) to ascertain the suitability of groundwater in the study area for drinking purposes.

The stages of calculating the WA-WQI are as follows (Equations 1-4):

$$q_n = 100 \frac{V_n - V_{10}}{S_n - V_n} \quad (1)$$

Where: q_n = quality rating for the n^{th} water quality parameter, n = the water quality parameter and quality rating or sub index (q_n) corresponding to n^{th} parameter, that is, a number reflecting the relative value of this parameter with respect to its standard (maximum permissible value); V_n = estimated value of the n^{th} parameter at a given sampling point;

S_n = standard permissible value of the n^{th} parameter.

V_{10} = ideal value of n^{th} parameter in pure water, that is, 0 for all other parameters except pH and dissolved oxygen (7.0 and 14.6 mg/l respectively).

The unit weight of the n^{th} parameter (W_n) was calculated by a value inversely proportional to the recommended standard value (S_n) of the corresponding parameter.

$$W_n = \frac{K}{S_n} \quad (2)$$

Where: S_n = standard value for the n^{th} parameters; K = proportionality constant

$$K = \frac{1}{\sum (\frac{1}{S_n})} \quad (3)$$

The WQI was then calculated using Equation

$$WQI = \frac{\sum q_n w_n}{\sum w_n} \quad (4)$$

Table 1 shows the classification of water based on the WA-WQI from the view point of potability [46].

Table 1. Water quality index classification and status of water quality class [46, 47].

WQI range	Rating	Use
0-25	Excellent water quality	Drinking, irrigation, industrial use
26-50	Good water quality	Drinking, irrigation, industrial use
51-75	Poor water quality	Irrigation, industrial use
76-100	Very poor water quality	Irrigation
>100	Unsuitable	Unsuitable for use

3.4. Suitability of Groundwater for Irrigation

Additionally, the agricultural suitability of groundwater in the study area was evaluated using the sodium adsorption ratio (SAR), soluble sodium percentage (SSP) and magnesium hazard (MH) (equations 5-7).

$$SAR = \left[\frac{(Na^+)}{\sqrt{(Ca^{2+} + Mg^{2+}) / 2}} \right] \quad (5)$$

Where Na, Ca and Mg are the concentrations of Na^+ , Ca^{2+} and Mg^{2+} respectively, in meq/L.

Likewise, soluble sodium percentage (SSP) was determined using the measured concentrations of Na^+ , Ca^{2+} , and Mg^{2+} , expressed in meq/L as in Equation 6.

$$SSP = \left[\frac{(Na^+)}{(Ca^{2+} + Mg^{2+} + Na^+)} \right] * 100 \quad (6)$$

Magnesium Hazard (MH)

In general, Ca^{2+} and Mg^{2+} maintain a state of equilibrium in most waters. In addition, high concentrations of Ca^{2+} and Mg^{2+} in groundwater can degrade soil quality, which adversely affects crop yield [48]. In order to evaluate the fitness of water for irrigation, the Magnesium Hazard (MH) ratio is very helpful [49]. A MH ratio of more than 50% is regarded as being unsuitable for irrigation. It is computed utilizing Equation 7.

$$MH = Mg / (Ca^{2+} + Mg^{2+}) * 100 \quad (7)$$

3.5. Evaluation of the Groundwater Sources for Industrial Use

The Langelier Saturation index (LSI) was used for this evaluation. It is an equilibrium model derived from the theoretical concept of saturation and provides an indicator of the degree of saturation of water with respect to calcium carbonate. It can be shown that the LSI approximates the base 10 logarithm of the calcite saturation level. The Langelier saturation level approaches the concept of saturation using pH as a main variable. The LSI can be interpreted as the pH change required to bring water to equilibrium [50]. The LSI was calculated as follows:

$$LSI = pH - pH_s \quad (8)$$

Where:

pH is the measured water pH

pH_s is the pH at saturation in calcite or calcium carbonate and is defined as:

$$pH_s = (9.3 + A + B) - (C + D) \quad (9)$$

Where:

$$A = (\log_{10} [TDS] - 1) / 10$$

$$B = -13.12 \times \log_{10} (^{\circ}C + 273) + 34.55$$

$$C = \log_{10} [Ca^{2+} \text{ as } CaCO_3] - 0.4$$

$$D = \log_{10} [\text{alkalinity as } CaCO_3]$$

If LSI is negative: No potential to scale, the water will dissolve $CaCO_3$.

If LSI is positive: Scale can form and $CaCO_3$ precipitation may occur.

If LSI is close to zero: Borderline scale potential. Water quality or changes in temperature, or evaporation could change the index.

The data obtained was exported to an ArcGIS 10.8 software to generate maps of their spatial distribution in the study area.

4. Results and Discussions

Data obtained from the analysed groundwater samples from nine boreholes in the Limbe Metropolis are summarised in Table 2.

4.1. Physical Characteristics

The pH fluctuated from 6.43 to 8.14 with a mean of value of 7.21 and a standard deviation of 0.56. It controls the chemical state of many nutrients, including dissolved oxygen, phosphate and nitrate [51]. According to WHO recommendations [19], the pH of the groundwater conforms to standards for drinking water quality. Electrical conductivity (EC) is the ability of water to convey an electric current and signifies the total number of dissolved acids [52]. Conductivity is a good indicator of mineralization [53]. The EC values ranged from

60 $\mu\text{S}/\text{cm}$ to 1004 $\mu\text{S}/\text{cm}$ with an average of 319.44 $\mu\text{S}/\text{cm}$, and a standard deviation of 285.35 (Table 2). Similar results have been reported by [32] in hard rock aquifers of Yaounde but differ from the works of [54] and other researchers that had worked in southern part of Cameroon where water circulates in plutono-metamorphic basement [56] and other residual aquifers in Africa [55]. TDS is a reflection of the extent of dissolved ions in a water source and provide guide-

lines on the use of water for different purposes. The TDS values varied from 35 mg/l to 675 mg/l with a mean of 213.56 mg/l and a standard deviation of 192.30 mg/L. All TDS values were within the prescribed limit of WHO except 11.11% of the sample. Similarly, low EC and TDS values have been recorded in other parts of Cameroon by [56] in Santchou; [57] Dschang; [58] in Awing) and [59].

Table 2. Summary statistics of groundwater quality parameters in Limbe.

Parameter	Unit	Min.	Max	Mean	Std	WHO 2017 standard
pH	-	6.43	8.14	7.21	0.28	6.5-8.5
EC	$\mu\text{S}/\text{cm}$	60.00	1004.00	319.44	285.35	<1000
TDS	mg/L	35	675.00	213.56	192.30	500
Na^+	mg/L	0	0.40	0.18	0.15	200
Ca^{2+}	mg/L	0	40.88	15.50	14.71	75
Mg^{2+}	mg/L	1.46	4.38	2.54	1.08	200
HCO_3^-	mg/L	0	94.08	31.36	35.68	120
SO_4^{2-}	mg/L	8.01	98.09	49.38	32.95	250

4.2. Chemical Characteristics

4.2.1. Major Cations

The ionic concentrations in this study revealed Ca^{2+} as the dominant cation (Figure 3) while HCO_3^- was the dominant anion (Figure 4). Ionic loads in the studied samples were in the order of $\text{Ca}^{2+} > \text{Mg}^{2+} > \text{Na}^+$ for cations meanwhile anions were in the order $\text{HCO}_3^- > \text{SO}_4^{2-} > \text{Cl}^-$ (Table 2). Ca^{2+} varied between 0 to 40.88 mg/l (Table 2) with a mean of 15.50 mg/l and standard deviation of 14.71 mg/l. Ca^{2+} plays a vital role in bone structure, muscle contraction, nerve impulse transmission, and blood clotting. Low intake of Ca^{2+} has been reported to cause osteoporosis, rickets, and hypertension [60]. Mg^{2+} was the second most abundant cation in the samples, varying between 1.46 and 4.38 mg/l (Table 2) with a standard deviation of 1.08 mg/l. Na^+ was the least cation in all the samples and varied between 0 to 0.34 mg/l (Table 2) with a mean of 0.18 mg/l and standard deviation of 0.15 mg/l. Magnesium is one of the earth's most common elements and forms highly soluble salts. The high concentration of Mg^{2+} is undesirable in potable water because it causes scale formation, cathartic and diuretic effects. Though magnesium is an essential co-factor for more than 350 enzyme systems, it is also responsible for energy metabolism, nucleic acid synthesis, and cellular balance, cardiovascular and hormonal functions [61]. Low magnesium intake is responsible for osteoporosis, increased

calcium balance, insulin resistance, metabolic syndrome, increased oxidant stress and increased risk of cardiovascular disease [61]. Na^+ was the least cation in the studied sources fluctuating from 0 mg/l to 0.40 mg/l. All recorded values were far below the [19] recommended levels of 200 mg/l.

High sodium loads in the drinking water supply is a major health concern for most people with heart disease, hypertension, kidney disease, and circulatory illness. High intake of Na^+ can also result in heart failure, gastrointestinal infections [62].

4.2.2. Major Anions

For the major anions, HCO_3^- was the most abundant anion in all the samples and varied between 0 mg/l to 94.08 mg/l (Table 2) with a mean of 31.36 mg/l and a standard deviation of 35.68 mg/l. Bicarbonate ions in groundwater could possibly originate when carbon dioxide dissolved in rain water precipitated as bicarbonate ions [63] as well as the dissolution of carbonate minerals [64]. However, the concentration of bicarbonate ion conforms with WHO recommendations of 120 mg/l and suggests a relatively lower influence of SWI on this specific parameter. In fact, bicarbonate is the principal anion that contributes to the alkaline nature of water. High concentrations of bicarbonate ion were recorded in E5 and E6 and may indicative of marine influence on water chemistry. SO_4^{2-} was the second most abundant anion in the studied samples and varied between 8.01 to 98.09 mg/l (Table 2) with

a mean of 49.38 mg/l and a standard deviation of 32.95 mg/l. In all the samples, the WHO limit of 500 mg/l was not exceeded (Figure 4). Higher sulphate ion concentrations, particularly observed in samples E2 (98.09 mg/L), E5 (68.06 mg/L), and E6 (74.07 mg/L), could indicate potential sea-

water intrusion. Sulphate ions observed in the sample water may be due to human activities, for instance, use of chemical fertilizers for agriculture, industrial and domestic effluents [70] (Yu et al., 2020). The Cl⁻ was not detected during the research period.

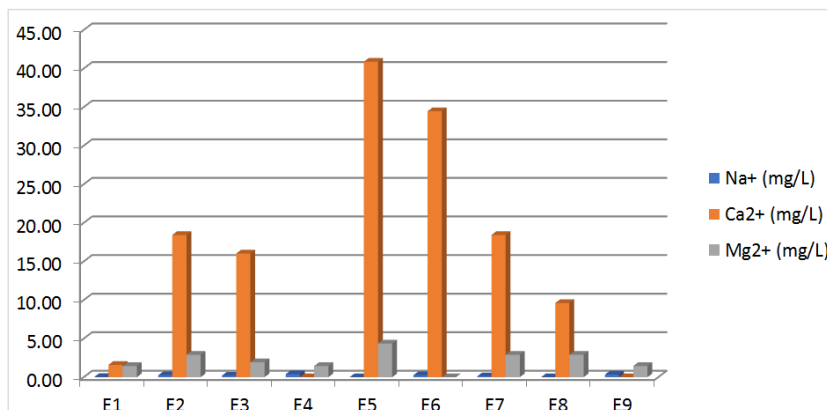


Figure 3. Variation of major cations of groundwater in Limbe.

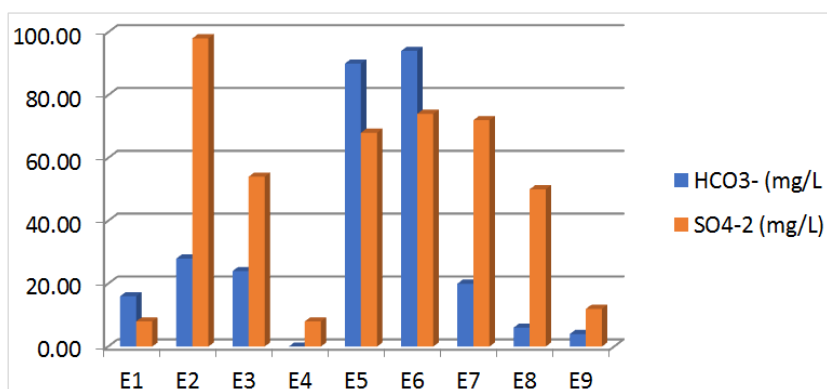


Figure 4. Variation of major anions of groundwater in Limbe.

4.3. Spatial Distribution of Ions

4.3.1. Cations

The spatial distribution of Ca²⁺ ions demonstrates a high concentration at Upper Mitondo (E5), mildly distributed around Bobende (E2), Gardens (E7) and sparsely distributed around Bonadikumbo (E6), Mokundange (E1), Mabeta (E4) as seen on Figure 5. The spatial distribution of Mg²⁺ ions is similar to that of Ca²⁺ ions (Figure 6). The concentration of Na⁺ (Figure 7) is higher at Mitondo (E4), mild at Wututu (E8), Bonadikumbo (E6), Bobende (E2), Gardens (E7) and sparsely distributed at Mokundange (E1). The increased concentration of calcium ions in the groundwater, along with a decrease in sodium ions, can serve as indicators of seawater intrusion. During seawater-freshwater interactions in coastal aquifers, Na⁺ is lost to the aquifer matrix and replaced by Ca²⁺. The

enrichment of calcium has been used as seawater intrusion indicator for mapping seawater intruded areas in arid and semi-arid regions [65-67].

4.3.2. Anions

SO₄²⁻ (Figure 8) is highly distributed at Bobende (E2), and mildly distributed at Mabeta (E3), Mitondo (E5), Gardens (E7) and sparsely distributed at Bonadikumbo (E6) and Mokundange (E1) while HCO₃⁻ (Figure 9) is greater at Mitondo (E5) and Bonadikumbo (E6) and mildly distributed at Bobende (E2), Mabeta (E4), Gardens (E7), (Mokunda) E3, and Wututu (E8) and sparsely distributed at Bonadikumbo (E6). Sulphate (SO₄²⁻) and bicarbonates (HCO₃⁻) are the dominant anions in continental freshwater [68] while low concentrations are seen in seawater.

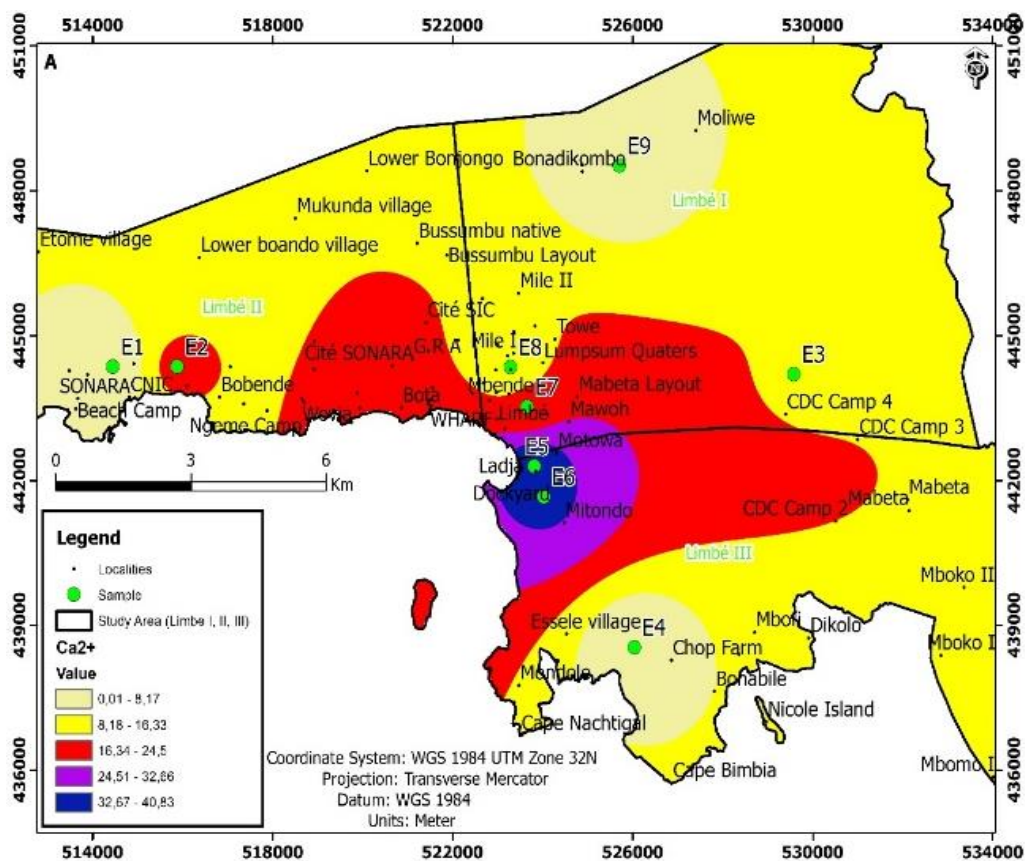


Figure 5. Distribution of Ca^{2+} ions in groundwater in Limbe.

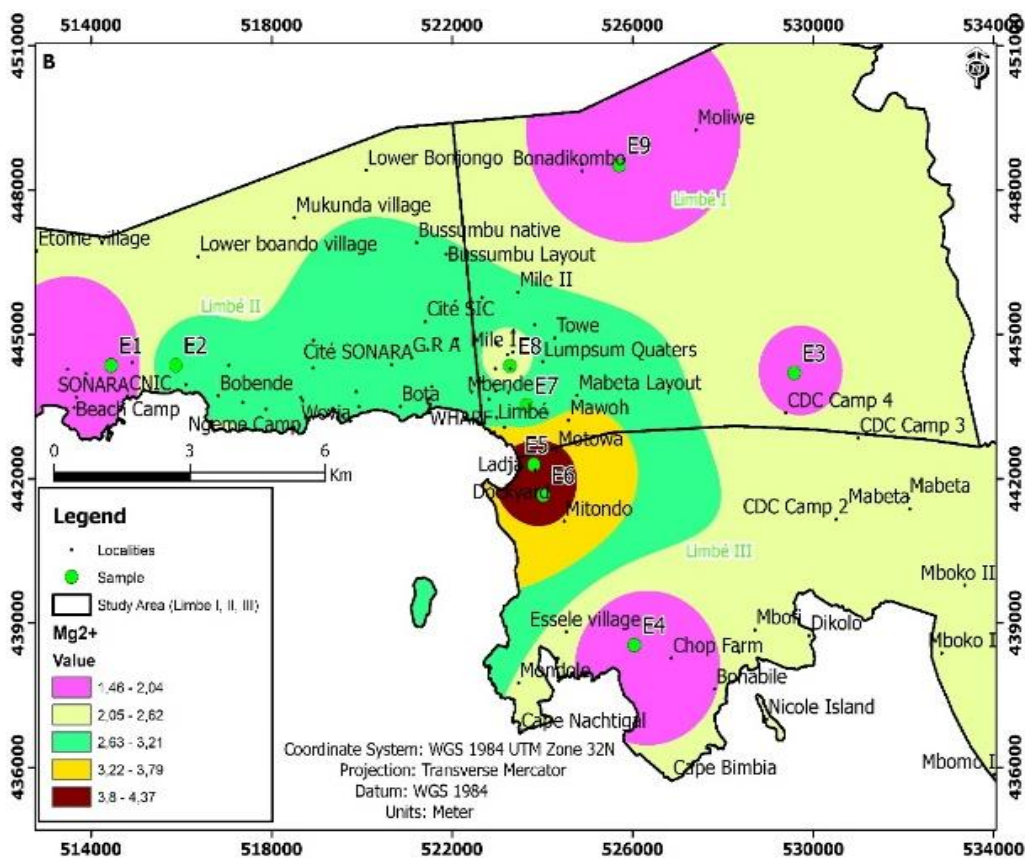
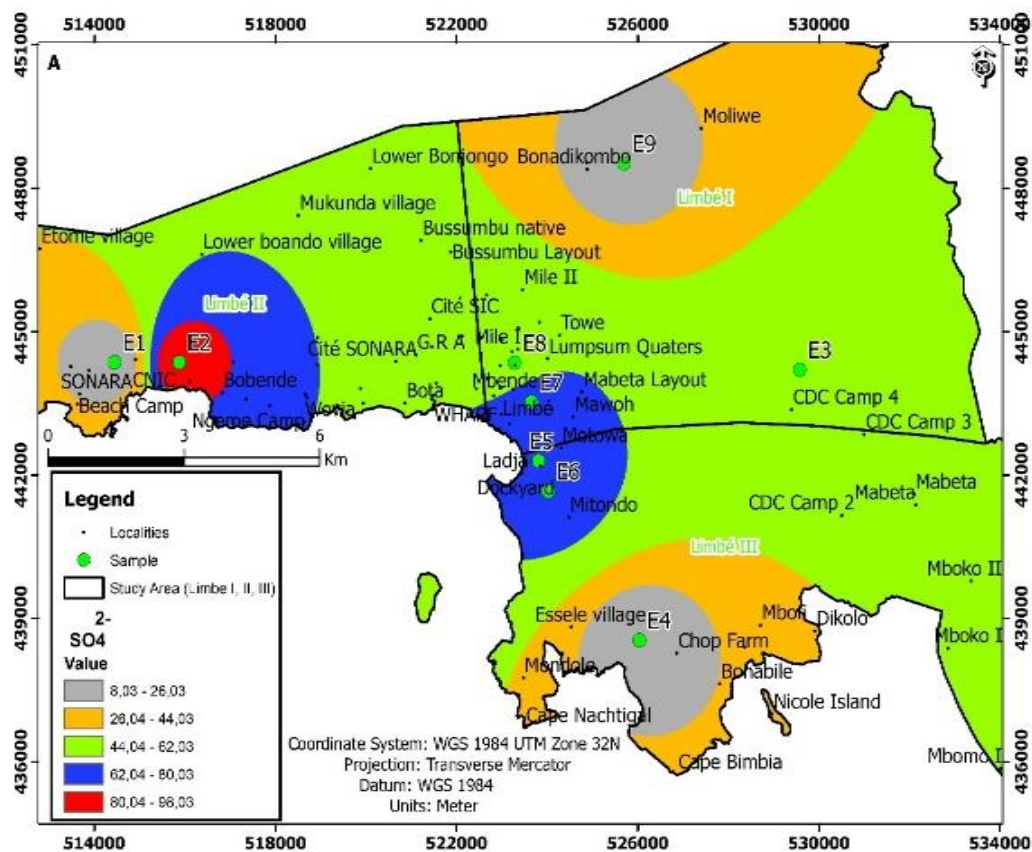
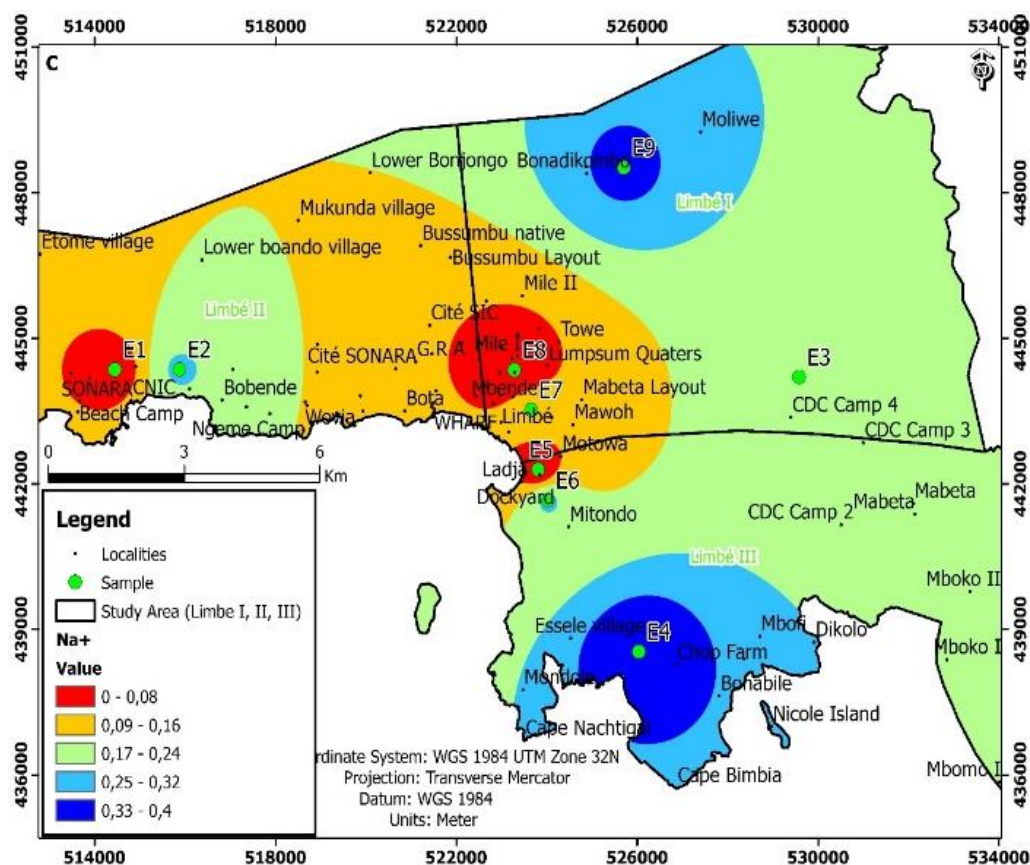


Figure 6. Distribution of Mg^{2+} ions in groundwater in Limbe.



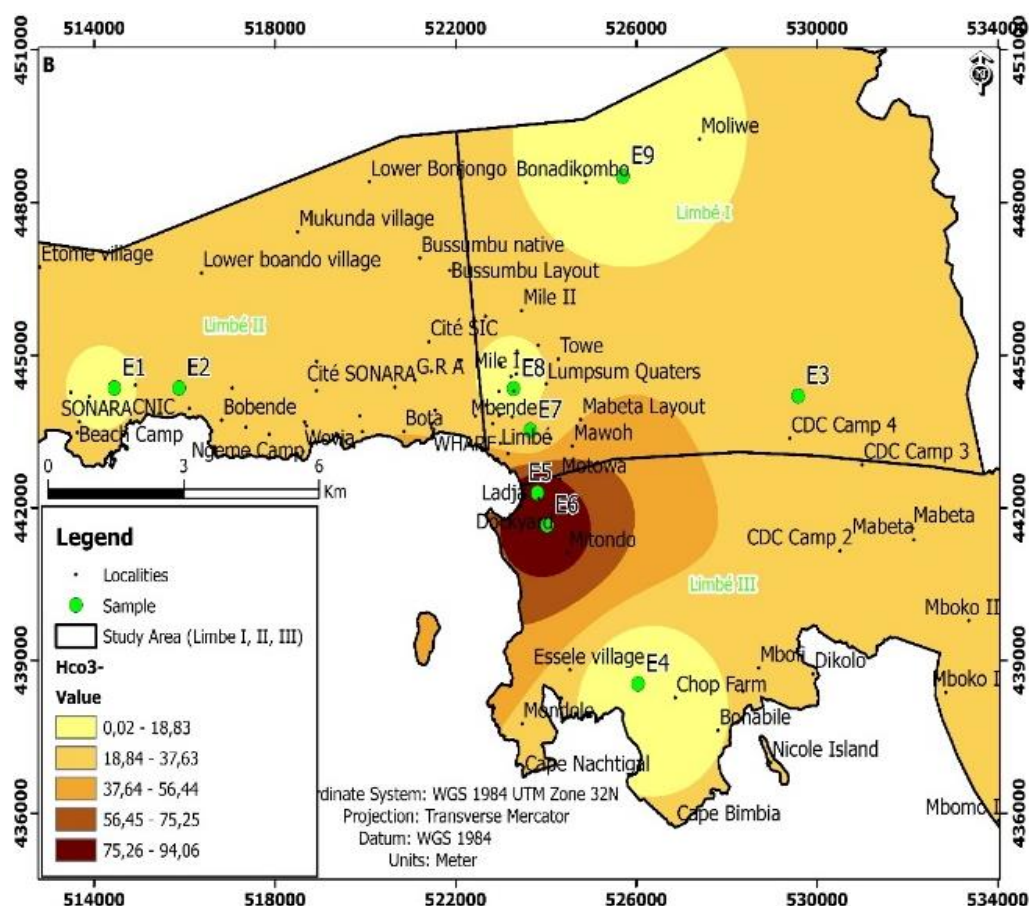


Figure 9. Distribution of HCO_3^- ions in groundwater in Limbe.

4.4. Relationship Between Chemical Water Parameters as Indicators of Salt Water Intrusion

Saltwater intrusion is a natural phenomenon, likely to occur in coastal regions but it becomes an environmental challenge when fresh water is over pumped from an aquifer [69] due to population growth and urbanisation. The ultimate effect of over pumping of groundwater aggravates the effect of salt water intrusion into fresh water aquifers. It has been shown that ratios of cations/anions such as Na/Cl , Ca/Mg and $\text{Ca}/(\text{HCO}_3 \text{ and } \text{SO}_4)$ can serve as indicators of sea water encroachment into fresh water aquifers. If Na/Cl ratio, is less than 0.86, it means that the groundwater has been contaminated by seawater; meanwhile, if the ratio is >1 , it suggests that groundwater is contaminated by anthropogenic source. In a situation where the ratios of Ca/Mg and $\text{Ca}/(\text{HCO}_3 \text{ and } \text{SO}_4)$ are >1 , it signifies that sea water is intruding fresh water aquifer [70]. In this study the ratio of Ca/Mg varied from 0 to 9.33 with 77.78% of the sampling points with values greater than 1, signifying the possibility of salt water intrusion. The ratio of $\text{Ca}/(\text{HCO}_3 \text{ and } \text{SO}_4)$ on the other hand ranged from 0 to 0.26. Base on this ratio therefore, groundwater of the study area is not under the threat of SWI. The rate and degree of the

sea water intrusion (SWI) are controlled by a number of factors, including variations in the hydrological cycle components and the quality and quantity of the system inflows and outflows. The natural factors associated with climate change and anthropogenic factors due to coastal urbanization and human activities are the main components that exacerbate the SWI issues.

Correlation matrix of groundwater parameters of Limbe

A Pearson correlation matrix is a table that shows the linear relationship between variables in a dataset. Table 3 shows the relationships between physical and chemical parameters. This statistical tool was used to correlate the studied groundwater samples. Associations within and between these parameters were identified using a Pearson correlation (r). There is a strong positive association when $r > 0.7$; a moderate correlation when r is between 0.5 and 0.7 [71] and no correlation when r is 0.00. Conversely, a correlation is deemed weak when $|r|$ is between 0 and 0.4 [72]. Correlation matrix describes the inter-relation among the variables to identify the source of contaminates in the groundwater. Positive correlation is observed between pH, EC, TDS, Na, and HCO_3 . Table 3 revealed strong positive correlation between Na^+ and EC (0.77); Na^+ and TDS (0.77); Ca^{2+} and Mg^{2+} (0.93); Ca^{2+} and SO_4^{2-} (0.65); Mg^{2+} and HCO_3^- (0.87) and Mg^{2+} and SO_4^{2-} (0.65). There was moderate correlation between EC and pH

(0.50); TDS and pH (0.50) and mild correlation between HCO_3^- and SO_4^{2-} (0.44); HCO_3^- and pH (0.40); Na^+ and pH (0.23); Mg^{2+} and pH (0.17); Ca^{2+} and pH (0.17). Mild negative correlation was seen between Ca^{2+} and T (-0.47); HCO_3^- and T (-0.40); pH and T (-0.35); Na^+ and Mg^{2+} (-0.33); Mg^{2+} and T

(-0.33); Na^+ and HCO_3^- (-0.21); TDS and T (-0.21); EC and T (-0.20); Na^+ and SO_4^{2-} (-0.16); Na^+ and T (-0.15); Mg^{2+} and EC (-0.14); Mg^{2+} and TDS (-0.14); Ca^{2+} and EC (-0.11); Ca^{2+} and TDS (-0.47); SO_4^{2-} and EC (-0.02); HCO_3^- and EC (-0.02).

Table 3. Correlation Matrix of groundwater parameters of Limbe.

	Na^+	Ca^{2+}	Mg^{2+}	HCO_3^-	SO_4^{2-}	EC	TDS	pH
Na^+	1							
Ca^{2+}	-0,21	1						
Mg^{2+}	-0,33	0,93	1					
HCO_3^-	-0,21	0,93	0,87	1				
SO_4^{2-}	-0,16	0,65	0,73	0,44	1			
EC	0,77	-0,11	-0,14	-0,02	-0,37	1		
TDS	0,77	-0,11	-0,14	-0,02	-0,36	0,99	1	
pH	0,23	0,17	0,17	0,40	-0,35	0,50	0,49	1

5. Hydrochemical Facies

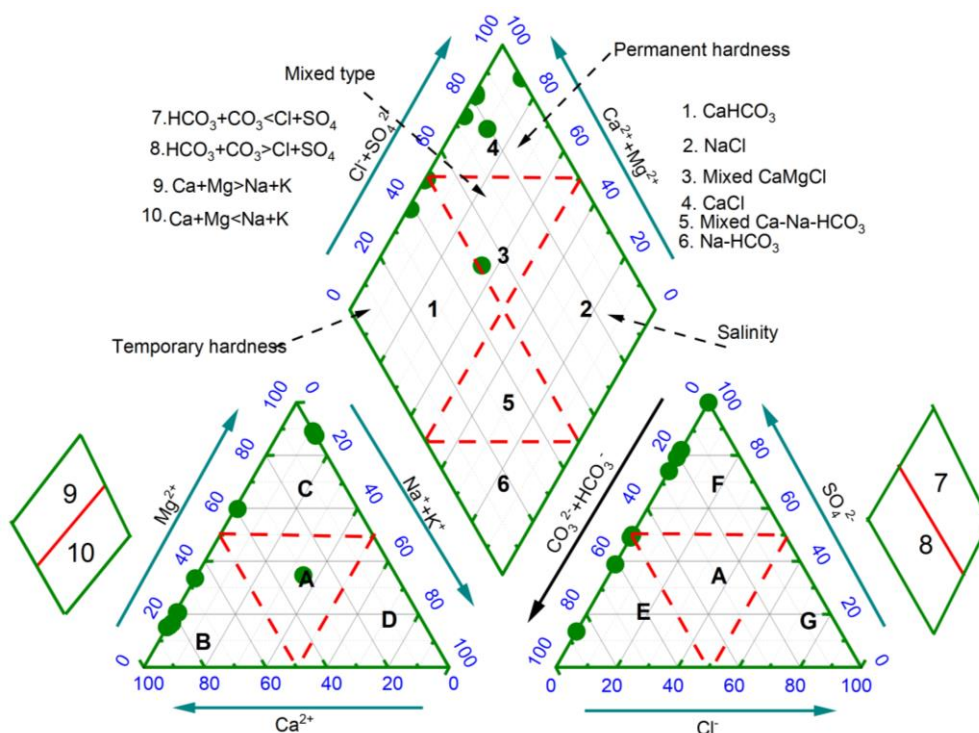


Figure 10. Piper plot showing hydrochemical facies with cations and anions in Limbe.

The Piper trilinear plot [73] provides information on the different chemical facies of the analysed water. From Figure 10, it can be noted that the principal types of underground

water are calcium and magnesium types that affect the groundwater quality of the area. Some of the samples (42%) plotted into the CaHCO_3 field, indicating a prevalence of

calcium and bicarbonate ions in the groundwater chemistry (Figure 10). Additionally, 25% of the samples exhibited characteristics of the Ca-Mg-Cl water type, while the remaining samples (33%) fell into the Ca^{2+} - SO_4 - HCO_3 and Ca-Mg-Cl types. Figure 10 equally revealed the dominance of alkali-earth elements ($\text{Ca}^{2+} + \text{Mg}^{2+}$) over alkali elements ($\text{Na}^+ + \text{K}^+$) and the weak acidic anion (HCO_3^-) over strong acidic anions ($\text{Cl}^- + \text{SO}_4^{2-}$). The major ions were plotted on the Piper trilinear diagram to investigate the water types found and the processes controlling them. The major facies are CaCl water type and CaHCO_3 water type with some samples plotting under mix CaMgCl water types. The dominance of CaHCO_3 and CaCl water types is an indication of mineral dissolution, particularly silicate minerals, mixing process and cation exchange processes with strong anthropogenic imprint. [32] reported similar results in hard rock aquifers of Yaounde. The findings of this study align with previous research on groundwater hydrochemistry in similar geological settings by [74].

1. Evaluation of groundwater quality for drinking water purposes

Table 4. Groundwater quality in Limbe in compliance with WHO [75] drinking water standard.

Parameter	Range in study area	WHO limit 2004
pH	6.43-8.14*	6.5-8.5
EC ($\mu\text{S}/\text{cm}$)	60-1004*	750
Ca^{2+} (mg/L)	0-40.88	75
Mg^{2+} (mg/L)	1.46-4.38	30
Cl^- (mg/L)	0	250
SO_4^{2-} (mg/L)	8.01-98.09	250
HCO_3^- (mg/L)	0-94.08	200

*values above WHO [75] limit pH values for the study area ranged from 6.43 to 8.14 with sample E3 out of the recommended guidelines by WHO. EC on its part was within WHO recommendations but for sampling point E4 with a value of 1004 ($\mu\text{S}/\text{cm}$). The concentrations of Ca^{2+} , Mg^{2+} , HCO_3^- , SO_4^{2-} in the analyzed groundwater were below the limits required by WHO (2004) for drinking water.

Water meant for drinking is an application that requires

more stringent standards of water. In order to evaluate the aptness of Limbe groundwater sources, the physicochemical characteristics of the groundwater were compared with the [75] requirements and those of the Ministry of Water Resources and Energy. The analytical results were evaluated to ascertain the suitability of groundwater in the study area for drinking purpose based on [75] recommendation as well as the calculated water quality index (WQI) (Table 4).

Water Quality Index (WQI)

Following the classification of WQI by [47] in Table 1, the WQI in Limbe metropolis varied from 22.40 to 101.59. Thus, 33.33% of the studied samples can be categorised as excellent water quality ($\text{WQI}=0-25$), 44.44% was in the category of good water quality (26-50), 11.11% was in the class of poor water quality (76-100) and while another 11.11% of the samples (E4) were unsuitable for use. This classification system provides a clear and concise framework for interpreting water quality based on WQI values, aiding in the assessment and management of water resources.

2. Evaluation of groundwater quality for agricultural purposes

Evaluating the quality of water for irrigation is important because poor quality irrigation water adversely affect soil structure, thereby, affecting crop yield. Thus, irrigation water quality in Limbe was assessed using indices such as EC, SAR and MH. According to [76] classification, EC and SAR values for irrigation water are categorized into four groups viz: low ($\text{EC} < 250 \mu\text{S}/\text{cm}$, $\text{SAR} < 10$), medium (250-750 $\mu\text{S}/\text{cm}$, SAR , 10-18), high (750-2250 $\mu\text{S}/\text{cm}$, SAR , 18-26), and very high (2250-5000 $\mu\text{S}/\text{cm}$, $\text{SAR} > 26$). The sampled groundwater in the study area recorded EC values in the range of 60-1004 $\mu\text{S}/\text{cm}$ and SAR values were in the range of 0-0.47 (Table 5). Based on this classification, all SAR values indicated low values and therefore would not pose a threat when used for agricultural purposes. Concerning values of EC, 66.67% of the analysed points indicated low values, 22.22% revealed medium values while 11.11% registered high EC values. Thus, all the samples are of the low to medium salinity apart from sampling point E4 whose salinity was slightly above recommended limits of [76]. Studies have shown that a high salt concentration in irrigation water leads to the formation of saline soil while a high sodium concentration leads to the development of alkaline soil. As such, the groundwater is generally suitable for irrigation purpose based on their EC and SAR. MH ratio varied from 10.08 to 100% with 7 out of the 9 sampling points registering values of less than 50% indicating good quality of water for irrigation.

Table 5. Irrigation water quality indices of Limbe groundwater.

Borehole location	E1	E2	E3	E4	E5	E6	E7	E8	E9
SAR	0.03	0.08	0.07	0.47	0	0.06	0.04	0	0.40
$\text{EC}_{\mu\text{S}/\text{cm}}$	60	246	206	1004	319	504	171	140	225

Borehole location	E1	E2	E3	E4	E5	E6	E7	E8	E9
SSP	1.29	1.17	1.38	21.52	0	0.67	0.61	0	18.90
MH (%)	47.65	13.66	10.82	100	9.67	10.08	13.66	23.29	100

3. Evaluation of groundwater quality for industrial purposes

Using the LSI method, the values ranged from -6.0 to 0.08, with 8 out of 9 (88.89%) borehole samples falling below 0. This water is under-saturated with respect to calcium carbonate. Under-saturated water has a tendency to remove existing calcium carbonate protective coatings in pipelines and equipment thereby not fit to be used for industrial purposes.

6. Conclusion

In conclusion, the investigation into the physiochemical parameters of borehole water in Limbe provided valuable insights into the quality and characteristics of groundwater within the coastal aquifers of the region. Through the analysis of both physical and chemical parameters, important observations and trends have emerged, shedding light on the underlying factors influencing groundwater quality and potential risks of seawater intrusion. The results reveal significant variations in physiochemical parameters among the boreholes, indicating spatial heterogeneity in groundwater composition and quality. Factors such as conductivity, total dissolved solids (TDS), pH, and ion concentrations exhibit considerable variability, reflecting differences in hydrogeological conditions, anthropogenic activities, and potential seawater intrusion impacts. The ion concentrations in groundwater in Limbe are as follows: cations: $\text{Na}^+ > \text{Ca}^{2+} > \text{Mg}^{2+} > \text{K}^+$, anions: $\text{HCO}_3^- > \text{SO}_4^{2-} > \text{Cl}^-$. The hydrogeochemical processes taking place in the numerous boreholes are depicted in Piper's diagram, which feature the existence of natural silicate weathering processes combined with low anthropogenic activity. Overall, the investigation into the physiochemical parameters of borehole water in Limbe provides a foundational understanding of groundwater quality dynamics and informs decision-making processes aimed at ensuring the sustainable use and protection of freshwater resources in the region. Continued research and collaboration among stakeholders are critical for addressing emerging challenges and implementing adaptive management strategies to address the risks associated with seawater intrusion in coastal aquifers. Further testing on organic chemicals and emerging pollutants could be done in the future to ensure the suitability of the groundwater sources to become drinking water.

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Author Contributions

Ewanoge Mesumbe: Conceptualization, resources, methodology, field investigation, data curation, visualization and writing of original draft.

Alice Magha Mufur: writing - review & editing.

Mathias Fru Fonteh: conception, reviewing and editing of manuscript.

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Data Availability

The data is available from the corresponding author upon reasonable request.

Conflicts of Interest

The authors declare no conflicts of interest.

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