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Hydrogeochemical Appraisal of Groundwater Quality and Its Suitability for Drinking and Irrigation Purposes in the West Central Senegal

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Abstract: Groundwater has been the main resource used for drinking, domestic and agricultural activities in West central Senegal for the past few decades. Thus, this study investigates the quality of groundwater and assesses its suitability for drinking and irrigation purposes. To this end, 42 samples were collected and analyzed for various chemical parameters (major ions, fluoride, pH, total dissolved solids (TDS)). Chemical data were interpreted using water quality indexes, Wilcox and USSL salinity diagrams, bivariate plots, ionic ratios and by comparing with the WHO standards. Results indicated that the groundwater is neutral to slightly alkaline with pH values between 7.1 and 8.2. Piper diagram shows that mixte-Ca-Na-Mg-HCO_3 is the dominant hydrochemical facies. TDS and water quality index (WQI) values indicated respectively that 69% and 64.3% of samples were suitable for drinking. Moreover, major ions concentrations were found below the desirable limits in most of groundwater samples. However, for fluoride, 69% of samples exceed the WHO guideline, limiting their use for drinking. The computed index of irrigation water quality and Wilcox diagram reveal that 87% and 78% of samples belong, respectively, to excellent to good category and excellent to good and good to permissible. Similarly, according to the US salinity classification, the majority of samples were acceptable for irrigation. Gibbs plots illustrate that water-rocks interaction with some extent evaporation is the main hydrochemical process controlling groundwater chemistry while bivariate plots and ionic ratios indicate that mineral dissolution and ion exchange play important role in groundwater chemistry.

Keywords: groundwater quality; irrigation and drinking water; hydrochemical process; WQI; west central Senegal

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1. Introduction

Groundwater is considered worldwide as a vital and essential water resource for drinking, domestic, industrial and agricultural activities due to non-perennial flow and poor quality of surface water [1]. In many countries, especially in rural and coastal areas of arid and semi-arid regions, groundwater is the main resource available to meet domestic, agricultural and industrial water needs. According to Nickson et al., 2005 [2] about one-third of the world's population use groundwater for drinking purpose with or without treatment. Central west of Senegal is concerned and affected by scarcity evolution, diminution of rainfalls, combined with rapid growth of population and industrial and agricultural activities; leading to overexploitation of groundwaters. Consequences are a considerable decline in groundwater levels and a progressive degradation of their chemical quality, as observed in others regions [3]. Groundwater quality depends on several factors such nature of recharge, hydrologic gradient, residence time of groundwater in the aquifer, pollution by anthropogenic activities and rock–water interactions beneath the surface [4]. Several past studies have been carried out to determine the quality of water and especially its suitability for domestic and agricultural use [3,5–7]. Our study is focused on groundwater characteristics to determine the quality of water and, in particular, its suitability for drinking, domestic or agricultural use. Previous works in the Senegalese sedimentary basin [8] and the Mbour area [9] showed strong mineralization of groundwater with occurrence of high fluoride content. Thus, to assess groundwater quality of the study area, hydrochemical and physical characteristics have been performed on 42 samples collected in order to estimate its quality for human uses: drinking and irrigation purposes. We used different international parameters and indicators as total dissolved solid, (TDS), total hardness (TH), water quality index (WQI), sodium adsorption ratio (SAR), residual sodium carbonate (RSC), sodium percent (%Na), permeability index (PI), Kelly ratio (KR), magnesium ratio (MR). Objectives are to determine the characteristics of the hydrogeochemistry groundwaters sampled, to estimate the ratio or percentage of waters suitable for drinking and irrigation purposes. One of the objectives of this work is to demonstrate that each index calculated and used is important and provides information on the quality of the water according to the uses envisaged and the targets concerned. This work is of importance because there are very few published studies on this region of central western Senegal. Thus, this study provides the scientific community and stakeholders with quantified elements (in the form of percentage of water suitable for human consumption or agriculture). Nevertheless, as with any study, this work describes a situation in a constant evolution, which requires monitoring in order to meet the challenges of climate and sustainable development.

2. Materials and Methods

2.1. Study Area Description

2.1.1. Location and Climate

The study area is located in the central western part of Senegal and includes the departments of Mbour (Thiès region) and Fatick (Fatick region). It is located in the groundnut basin and also includes part of the districts of Sindia, Sessene, Tattaguine and Fimela. It covers an area of 971 km^2. It is bounded to the North by the districts of Notto and Fissel, to the East by those of Niakhar and Diakhao, to the Southeast by the bolongs which are part of the tributaries of the Saloum River and to the West by the Atlantic Ocean (Figure 1). Its climate is of the dry tropical type characterized by the alternating of two seasons: A short rainy season that lasts about 4 months (July to October) and a very long dry season (November to June) with the influence of two types of wind: the cool, humid and non-rainy maritime trade winds and the hot and dry Harmattan season. The rainfall data, acquired during the period from 1991 to 2020 and from 1990 to 2020 respectively in Mbour and Fatick, shows that the average annual rainfall is respectively 561 mm and 595 mm. The highest rainfall amounts are recorded during the months of August and September (Figure 2). The influence of dry season winds (maritime trade winds and Harmattan) leads to high evaporation in the area. In fact, the average potential evaporation is 1600 mm/year and 2200 mm/year in Mbour and Fatick respectively. The relative humidity in the study area is high during the rainy season and is generally above 65%. In Mbour, the average monthly maximum temperatures are observed during the months of July and November with a maximum of 28.7 °C recorded in October. From December to May, temperatures are quite low with a minimum of 25.4 °C in January. In Fatick, from March to October, average monthly temperatures vary between 29.3 °C and 30.5 °C. The lowest temperatures are recorded during December and January with 26.4 °C and 25.6 °C respectively.

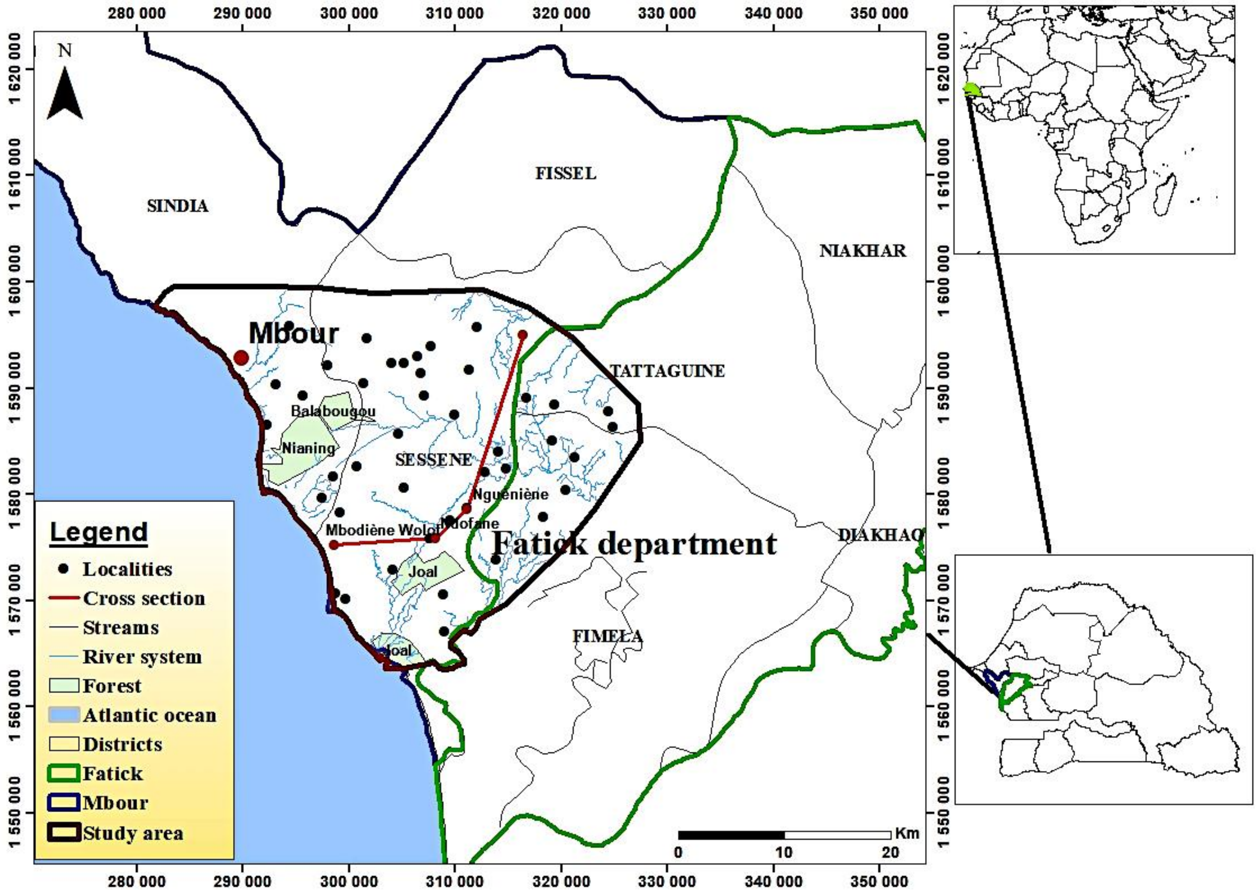

Figure 1. Location map showing the localization of the study area.

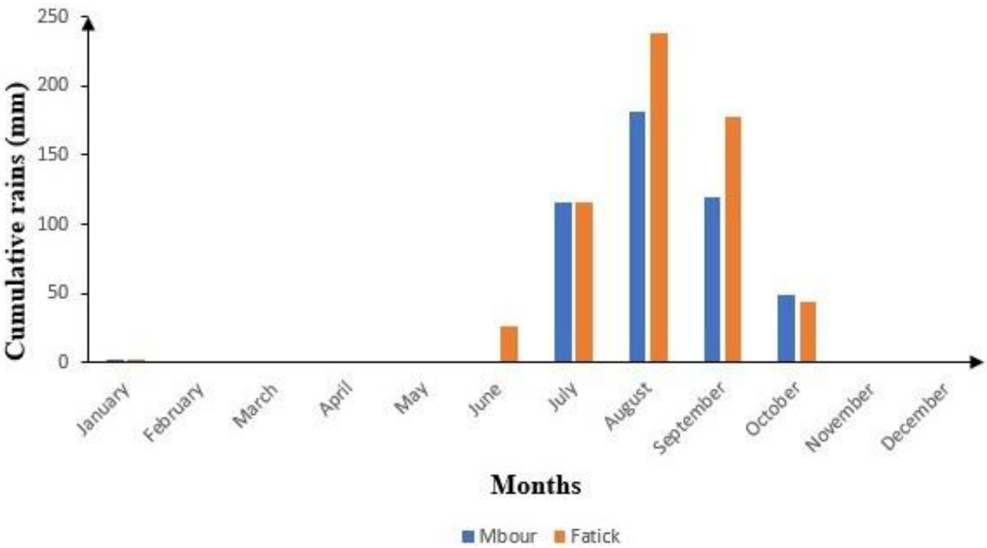

Figure 2. Average monthly rainfall from 1991 to 2020 at the Mbour and Fatick station.

2.1.2. Geology and Hydrogeology

The geology of the study area is particularly well known through the description of the outcrops and stratigraphic logs of the oil and hydraulic drillings. The lithological description of the formations indicates the presence of detrital soils with a predominance of clay and sand that constitute the geological layers of the Continental Terminal and Quaternary (Figure 3).

The Eocene epoch is also known in the area from boreholes that have crossed it at different depths. However, it has undergone strong erosion and is only represented in the area by its lower terms. It is particularly represented by:

(1) a level formed of clayey limestone, marls and phosphate or silicified clays observed at the contact with the Paleocene [10];
(2) a clayey or marly assemblage with some intercalations of limestone very frequent in the upper part;
(3) a calcareous and marly limestone horizon encountered especially in the Ngazobil area [8].

The lower Eocene base consists of gray marl and clay with intercalation of flint [11]. However, the Eocene clays show, at the base of the formation, a predominance of attapulgite associated with sepiolite and a disappearance of smectites present in the upper part [8]. In the study area, the Paleocene formations, with an average thickness of 100 m, sink towards the East and South-East under the Eocene, Terminal Continental and Quaternary formations. They are supported by the clayey-sandstone formations of the Maastrichtian. However, it outcrops in the Mbour area. It is formed of homogeneous facies of limestone and marly limestone often shells [11].

The shell limestones, with little marl, are karstified or fissured and often consists of sandstone. They occupy the middle and upper horizons of the Paleocene [11]. At its bottom, the Paleocene is made up of frank limestone and grey marly limestone which can be sandstone.

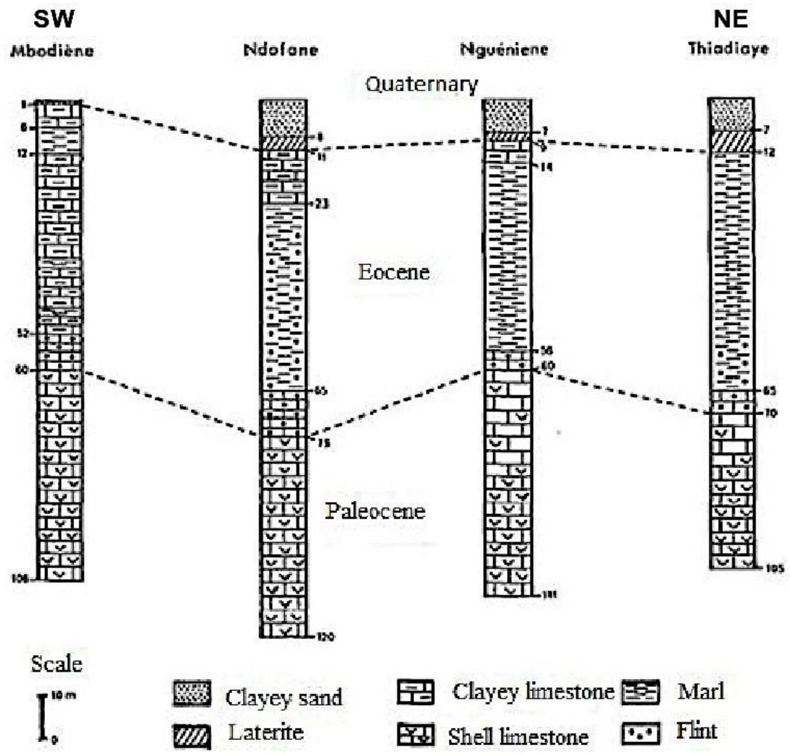

Figure 3. Lithology and stratigraphic correlation at the Mbodiène, Ndofane, Nguéniene and Thiadiaye boreholes [11].

The hydrogeology of the study area is characterized by the presence of several types of aquifers of which the most exploited are the superficial and the deep aquifers. The superficial aquifer system is made up of Mio-Pliocene, Quaternary and upper Ypresian aquifers. The latter is formed by marly limestone, while the Mio-Pliocene and Quaternary aquifers are formed by clayey sand. The aquifers of the superficial system are mainly exploited by traditional wells to satisfy domestic water needs and for market gardening. The Eocene limestone aquifer is distinct or associated with the Miocene-Quaternary aquifer.

When the two aquifers are distinct, the percolation of water through the marlstones is difficult. These two aquifers are often exploited together. The deep aquifer system consists of the Lower Eocene, Paleocene and Maastrichtian aquifers. This deep aquifer system is generally exploited by boreholes and modern wells. The Paleocene aquifer is relatively thin and lies on the sandstone-clay sediments of the Maastrichtian. It consists of limestone, argillaceous limestone and marl with flint, glauconite and phosphate [11]. Its bottom is mainly made of marlstone, which as a result of a change of facies, is replaced by shell limestone in the west, and by marlstone in the North-West, East and South [9]. The Paleocene aquifer is currently the most exploited due to the depletion or salinization in some areas of the superficial aquifers.

2.1.3. Hydrographic Network of the Study Area

The fairly dense pattern of the drainage system indicates that it was very important during wet periods. The present drainage pattern consists of thalwegs that are dry for a long period of the year (Figure 4). Its functioning depends on the amount of annual rainfall. This hydrographic network is divided into two groups: the small marigots that flow towards the ocean (Baling, Warang, Nianing and Mbodiène) and the tributaries of the Saloum. The latter (Foua, Balabougou and Nguénième marigots) collect all of the water from the thalwegs and drain it into the tannes. This water is then discharged into the mouths of the Saloum and then into the sea to the west.

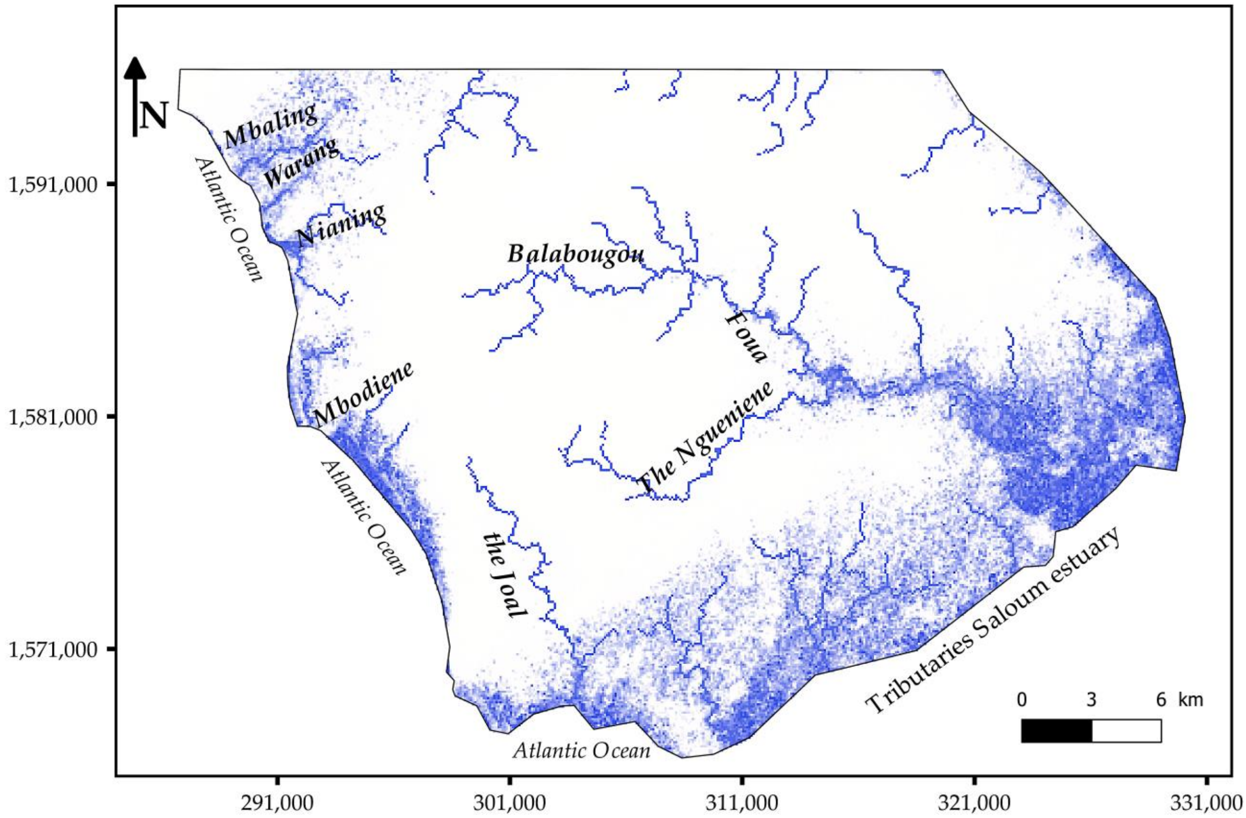

Figure 4. Hydrographic surface network of the study area.

2.2. Groundwater Samples Collection and Analysis

During September 2019, a total of 42 groundwater samples were collected from dug wells and boreholes in cleaned polyethylene bottles at different sampling points of the study area (Figure 5). The locations of sampling points were determined in the field using the GARMIN (GPSMAP-64s, GARMIN France SAS, Nanterre, France) global positioning system (GPS). Physical parameters such as temperature, electrical conductivity (EC) and pH were measured in the field using a portable multiparameter meters (WTW-multi 350i).

Before sampling, polyethylene bottles were rinsed several times with the water to be sampled. At each sampling point, two groundwater samples were collected for cation and anion analysis. After sampling, the groundwater samples were labeled, stored in an ice box and transported to the laboratory for chemical analysis. The water samples were analysed at the Chrono environment Laboratory of the UFR Sciences and techniques at the University of Bourgogne Franche-Comte, Besançon, France. In the laboratory, collected groundwater samples were filtrated using cellulose nitrate membrane (0.22 μm pore size) and divided into two groups. One group was used for anions analysis and the second group (50 mL) was treated with HNO_3 for cations and metal analysis. However, before filtration, the bicarbonate concentration was measured by titration. Anions analysis were performed using a Dionex-100 ion chromatography whereas cations and metals of the water samples were determined using Inductively Coupled Plasma-Mass Spectrometry (ICP-MS). The charge balance error (CBE) was calculated to check the accuracy of analysis using the Equation (1). The majority of groundwater samples have an ion balance error within the allowed limit of ±5% [12].

$$\% \, CBE = \frac{\sum cations - \sum anions}{\sum cations + \sum anions} * 100 \quad (1)$$

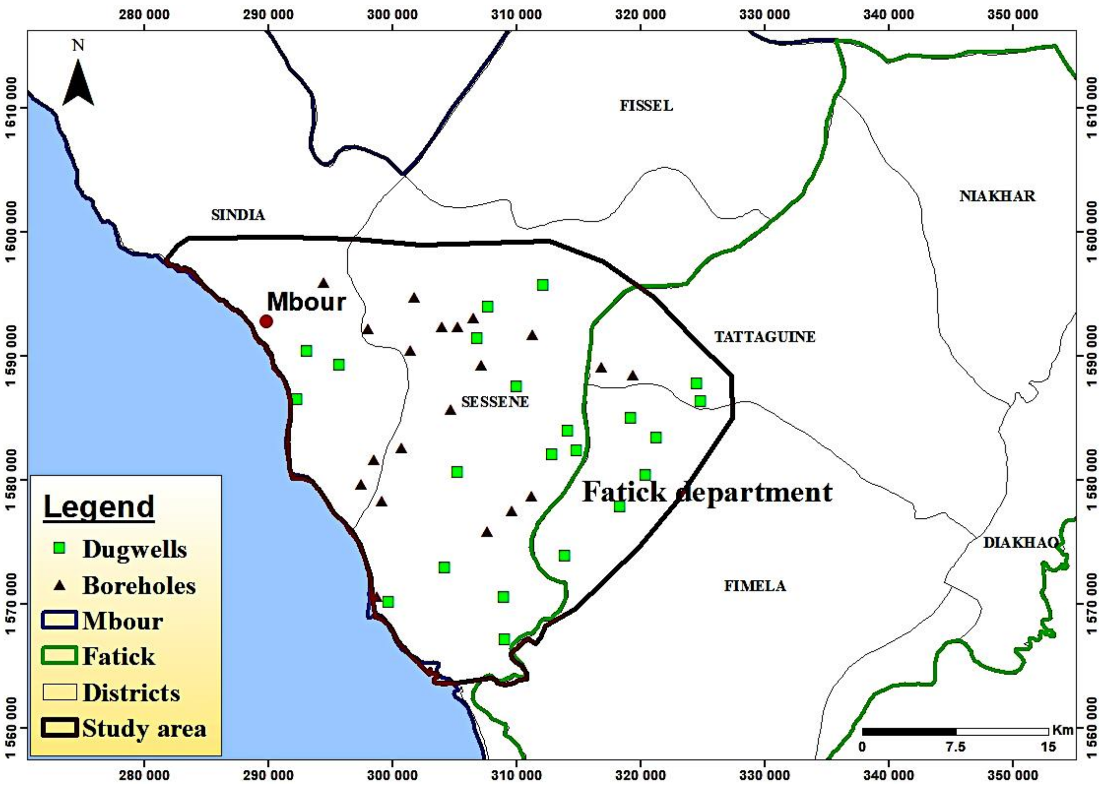

Figure 5. Location of sampling points in the study area.

2.3. Drinking Water Quality

Water quality is an important factor in assessing the suitability for multiple uses but especially for human consumption. In this study, the evaluation of the quality for drinking water is done by comparing the concentrations of chemical elements in groundwater with those of the WHO standards limits [13,14] and calculating the water quality index. Furthermore, other water quality parameters such as (TDS) and (TH), which are widely used in the assessment of water quality for human consumption, are also used in this study. The water quality index is an important water quality parameter which is widely used by several researchers worldwide in order to evaluate the quality of water for drinking purposes [3,7,15–20]. It is considered as an effective tool to estimate the overall groundwater quality for drinking purposes by examining the individual water quality parameters pH, TDS, TH, Ca^{2+}, Mg^{2+}, Na^+, K^+, HCO_3^-, SO_4^{2-}, NO_3^-, F^- and Cl^- [7]. WQI was computed by assigning weight (w_i) to the physicochemical parameters according to its importance in the overall quality of water for human consumption (Table 1). The assigned weight ranges from 1 to 5. The maximum weight of 5 was assigned to the water quality parameters such as nitrate (NO_3^-), Fluoride (F^-), due to their major significance in water quality assessment [18,21]. A minimum weight of 1 have been assigned to bicarbonate since it plays an insignificant role in the water quality assessment [16,22–24] and does not contribute to groundwater contamination [25]. The other water quality parameters such as pH, TH, Ca^{2+}, Mg^{2+}, Na^+, K^+, SO_4^{2-} and Cl^- were assigned a weight between 2 and 4 depending on their importance in the overall water quality assessment for drinking purposes. The relative weight is computed using Equation (2).

$$W_i = \frac{w_i}{\sum_{i=1}^{n} w_i} \tag{2}$$

where W_i is the relative weight, w_i is the weight of each parameter, n is the number of parameters. The weight (w_i), the calculated relative weight (W_i) values and the WHO standards [13,14] for each parameter are given in Table 1.

Table 1. Relative weight of chemical parameters.

Chemical Parameters	WHO Standard [13,14]	Weight (w_i)	Relative Weight (W_i) $W_i = \frac{w_i}{\sum_{i=1}^{n} w_i}$
pH (-)	6.5–8.5	3	0.073
TDS (mg/L)	1000	5	0.122
TH (mg/L)	500	4	0.098
Ca^{2+} (mg/L)	75	3	0.073
Mg^{2+} (mg/L)	50	3	0.073
Na^+ (mg/L)	200	2	0.049
K^+ (mg/L)	12	2	0.049
HCO_3^- (mg/L)	500	1	0.024
SO_4^{2-} (mg/L)	250	4	0.098
Cl^- (mg/L)	250	4	0.098
NO_3^- (mg/L)	50	5	0.122
F^- (mg/L)	1.5	5	0.122
		$\sum w_i = 41$	$\sum W_i = 1$

The quality rating scale (q_i) for each quality parameter is computed using Equation (3) based on the WHO standard for each parameter

$$q_i = \frac{C_i}{S_i} * 100 \tag{3}$$

where q_i is the quality rating, C_i is the concentration, in milligrams per liter, of each chemical parameter and S_i is the WHO standard of each chemical parameter in milligrams per liter according to the guidelines of the [14]. Before computing WQI, the SI_i, of each chemical parameter is first calculated using Equation (4). Finally, the WQI is calculated by summing the SI_i Equation (5).

$$SI_i = W_i * q_i \tag{4}$$

$$WQI = \sum_{i=1}^{n} SI_i \tag{5}$$

where SI_i is the Sub-index of each parameter, q_i is the rating based on concentration of each parameter, n is the number of parameters.

2.4. Irrigation Water Quality

In areas where agricultural activity is an important factor in development, assessment of water quality and suitability for irrigation is an essential step to ensure sufficient production and sustainable development. The irrigation suitability of groundwater was assessed using several parameters (such as Sodium Adsorption Ratio SAR), Sodium percent %Na, Residual Sodium Carbonate (RSC), Permeability Index (PI), Kelly Ratio (KR) and Magnesium Ratio (MR). These water quality parameters were derived from Equations (6) to (11), respectively, where all ion concentrations are expressed in milliequivalents per liter (meq/L).

$$\mathrm{SAR} = \frac{\mathrm{Na}}{\sqrt{\frac{\mathrm{Ca} + \mathrm{Mg}}{2}}} \tag{6}$$

$$\%\,\mathrm{Na} = \frac{(\mathrm{Na} + \mathrm{K})}{(\mathrm{Ca} + \mathrm{Mg} + \mathrm{Na} + \mathrm{K})} * 100 \tag{7}$$

$$\mathrm{RSC} = (\mathrm{HCO_3} + \mathrm{CO_3}) - (\mathrm{Ca} + \mathrm{Mg}) \tag{8}$$

$$\mathrm{PI} = \frac{\mathrm{Na} + \sqrt{\mathrm{HCO_3}}}{\mathrm{Ca} + \mathrm{Mg} + \mathrm{Na}} * 100 \tag{9}$$

$$\mathrm{KR} = \frac{\mathrm{Na}}{(\mathrm{Ca} + \mathrm{Mg})} \tag{10}$$

$$\mathrm{MR} = \frac{\mathrm{Mg}}{(\mathrm{Ca} + \mathrm{Mg})} * 100 \tag{11}$$

Furthermore, the diagram of Wilcox, 1955 [26], where %Na is plotted against EC, and the US salinity diagram (SAR versus EC plot) are used to evaluate the suitability of groundwater for irrigation purpose.

3. Results and Discussion

3.1. Hydrogeochemical Characteristics of Groundwater

Chemical quality of water, especially groundwater, is an important factor that determines its use in various human activities such as human consumption, agriculture, industry. Therefore, the assessment of its chemical composition can decide the type of use. Descriptive statistics analysis such as maximum, minimum, mean, median and standard deviation of the physicochemical characteristics of groundwater samples is presented in Table 2.

Table 2. Descriptive statistics and comparison with WHO values.

Water Quality Parameters	Min.	Max.	Mean	Median	Standard Deviation	WHO Standard Limit [14]	Number of Samples Exceeding Allowable Limits	Percentage of Samples Exceeding Allowable Limits
pH (-)	7.1	8.2	7.6	7.6	0.2	6.5–8.5	0	0
EC (µS/cm)	167	8880	1518	1065	1421	1500	13	31
TDS (mg/L)	112	5950	1017	714	952	500	35	83
Ca^{2+} (mg/L)	18	562	103	71	90	75	20	48
Mg^{2+} (mg/L)	2.7	168	46	44	35	50	16	39
Na^{+} (mg/L)	8.1	1106	142	72	202	200	6	14
K^{+} (mg/L)	0.3	10.7	3.2	2.3	2.7	12	0	0
Cl^{-} (mg/L)	12	2627	280	133	436	250	15	36
NO_3^{-} (mg/L)	0.1	432	45	14	89	50	5	13
SO_4^{2-} (mg/L)	1.2	528	71	30	113	250	3	7.1
F^{-} (mg/L)	0.1	9.4	3.2	2.7	2.5	1.5	29	69
HCO_3^{-} (mg/L)	9.4	541	297	345	152	500	4	10

In water, the pH provides vital information in many types of geochemical equilibrium or solubility calculations [27]. It indicates also the strength of the water to react with the acidic or alkaline material present in water. The combination of CO_2 with water forms carbonic acid, which affects the pH of the water. The pH values of groundwater samples in the study area ranged from 7.1 to 8.2 with an average value of 7.6 indicating that groundwater is neutral to slightly alkaline. The permissible limit of pH for drinking water is 6.5–8.5 [14]. All pH values of groundwater samples were within the WHO permissible limit for drinking water. The electrical conductivity (EC) provides information on the overall amount of dissolved salts by measuring the salt concentrations of water to provide ionic concentrations [28]; It depends upon temperature, concentration and types of ions presents [27]. EC in water samples could be due to leaching or dissolution of the aquifer material or mixing of saline sources or a combination of these processes [12,29]. Groundwater EC ranged from 167 to 8880 μS/cm with an average value of 1518 μS/cm. The electrical conductivity can be classified as type I if EC < 1500 μS/cm; type II if EC lies between 1500 and 3000 μS/cm and type III if EC >3000 μS/cm [30]. According to the above classification, about 69% of groundwater samples fall under type I (low enrichment of salts), 26% under type II (medium enrichments of salts) and 5% under type III (high enrichments of salts).

3.2. Groundwater Suitability for Drinking

Quality of groundwater determines its suitability for different purposes depending upon the specific standards. To assess the suitability for drinking, the physicochemical and chemical parameters of groundwater quality of the study area are compared with the standards guidelines values as recommended by the WHO [13,14] for drinking purpose. Furthermore, the WQI, TH and TDS were also determined. The physical and chemical water quality parameters of the study area resulting from the chemical water analysis as well as the standard guideline values proposed by the WHO are reported in Table 2. According to the median values of chemical data of groundwater samples, HCO_3^- and Na^+ are respectively the most dominant anion and cation in groundwater samples. The relative abundance of cation and anion of the study area were ranked in the order of $Na^+ > Ca^{2+} > Mg^{2+} > K^+$ and $HCO_3^- > Cl^- > SO_4^{2-} > NO_3^- > F^-$ respectively. Calcium and magnesium are common elements which are generally found in water. The concentration of calcium of groundwater samples varies from 18 to 562 mg/L with an average value of 103 mg/L. About 48% of groundwater samples exceed the allowable limit for dinking purpose. Magnesium is the third most abundant cation in groundwater samples. Its concentration varies from 2.7 to 168 mg/L with an average value of 46 mg/L. The majority of the groundwater samples have magnesium content below the standard limit established by the WHO for human consumption. Sodium is one of the most important constituents of groundwater because at high concentration (>200 mg/L), the water is not suitable for domestic use by causing severe health problems like hypertension, congenial diseases, kidney disorders and nervous disorders in human body [31]. Sodium is the dominant cation in our groundwater samples. Its concentration varied from 8.1 to 1106 mg/L with an average value of 142 mg/L. Sodium content was highly variable in the study area inducing a standard deviation value higher than the mean value of sodium concentration (Table 2). Most of groundwater samples were suitable for drinking purpose. However, six samples (14%) were above the permissible limit for drinking purpose. Potassium is a naturally occurring element; However, its concentration remains quite lower compared with calcium, magnesium and sodium. Its concentration in drinking waters seldom reaches 20 mg/L [30]. The potassium is relatively low and ranged from 0.3 to 11 mg/L with an average value of 3.2 mg/L. It is observed that all groundwater samples fall below the allowable limit of WHO for drinking water.

Among the anions, bicarbonate is the dominant anion found in groundwater samples. In this study, the concentration of bicarbonate ranged from 9.4 to 541 mg/L with an average value of 297 mg/L. About 10% of groundwater samples have bicarbonate concentration higher than the permissible limit for drinking water. Sulfate concentration in natural water is usually found between 2 and 80 mg/L and abnormally high concentration of sulfate may be attributed to rock weathering or anthropogenic sources like industrial and agricultural effluents [28]. Sulfate concentrations above 250 mg/L in drinking water may cause unpleasant taste and corrosion of distribution pipes; while concentrations higher than 500 mg/L may cause risk to human health such as gastrointestinal disorders [13]. The concentration of sulfate in groundwater samples ranged from 1.2 to 528 mg/L with an average value of 71 mg/L. It was found from sulfate concentration that only three samples (7%) exceeds the allowable limit of WHO for drinking water. Nitrate is the most common pollutant found in water and can sometimes be used as a tracer of water movement in the soil. Nitrate pollution of groundwater has become a worldwide problem because of its harmful effects on the environment (eutrophication of lakes and rivers) and particularly on human health (occurrence of methemoglobinemia in infants).In this study, nitrate concentration is relatively low, varying from 0.1 to 432 mg/L with an average of 45 mg/L. Then 5 upon 42 groundwater samples (13%) show high values of nitrate exceeding the allowable limit for drinking purpose (50 mg/L). High chloride concentration in drinking water causes health human issues (gastrointestinal irritation, hypertension, ventricular hypertrophy, osteoporosis, renal stones and asthma) [6]. In this study, chloride concentration of groundwater samples ranged from 12 to 2627 mg/L with an average value of 280 mg/L. From the concentration of chloride 36% of the total sample exceed the allowable limit of WHO. Fluoride is an important element required for humans' health, however, high fluoride concentrations make the water unsuitable for human consumption. Fluoride in water is mainly derived from the weathering of fluoride bearing rock forming minerals like muscovite, biotite, fluorite, fluoro-apatite [28]. Fluoride concentration varied between 0.1 and 9.4 mg/L with an average value of 3.2 mg/L. From the fluoride contents, most of the samples (69%) exceed the allowable limit of WHO (1.5 mg/L) indicating unsuitability for drinking purpose (Table 2).

3.2.1. Total Hardness

Water TH is calculated from the concentrations of cations (calcium and magnesium) and anion (bicarbonate, chloride and sulfate) [32]. High TH causes scaling of pots and boilers, closure to irrigation pipes and may cause also health problems to humans [25]. Consumption of water with high TH may raise the risk of calcification of arteries, urinary concretions, diseases of kidney or bladder or stomach disorder [6]. The total hardness values of groundwater samples in the study area were calculated using Equation (12) [33] where Ca^{2+}, Mg^{2+} and TH are expressed in mg/L (Table 3).

$$\text{TH } (as \text{ CaCO}_3) = 2.497 * \text{Ca}^{2+} + 4.115 * \text{Mg}^{2+} \quad (12)$$

Table 3. Groundwater quality classification based on TH and TDS [33,34].

Parameters	Range	Water Type	Number of Samples	% of Samples
TH (mg/L)	<75	Soft	1	2
	75–150	Moderately hard	0	0
	150–300	Hard	10	24
	>300	Very hard	31	74
TDS (mg/L)	0–250	Very fresh	1	2
	250–1000	Fresh	28	67
	1000–10,000	Brackish	13	31
	10,000–100,000	Saline	0	0
	>100,000	Brine	0	0

The computed values of TH ranged from 55 to 2096 mg/L with an average value of 448 mg/L. The maximum allowable limit of TH for drinking purpose is 500 mg/L and the most desirable limit is 100 mg/L [14]. High hardness is usually undesirable because it can cause lime buildup (scaling) in pipes and also in water heaters, which over the time will decrease water heater efficiency and decrease lathering of soap. The computed values of TH show that 29% of groundwater sample were above the maximum permissible limit of 500 mg/L. Furthermore, based on TH values of water, Sawyer and Mc Mcartly [34] classified groundwater into 4 categories such as soft (TH < 75), moderate hard (TH: 75–150), hard (TH: 150–300) and very hard (TH >300 mg/L). According to the above classification, the majority of groundwater samples (74%) indicates very hard water while 24% and 2% represents respectively hard and soft water. The hardness of the groundwater can be associated with calcium and magnesium derived from the dissolution of carbonate minerals in geological formations.

3.2.2. Total Dissolved Solids

TDS is an important water quality parameter which is widely used to assess the suitability of water for drinking and irrigation purposes. High values of TDS in groundwater may affect persons who are suffering from kidney and heart diseases [22]. The high content of TDS in water can be due to anthropogenic sources such as domestic sewage, septic tanks and agricultural activities. Higher concentration of TDS causes gastrointestinal irritation in human and may also lead to laxative effects [6]. The total dissolved solids of groundwater samples varied from 112 to 5950 mg/L with an average value of 1017 mg/L. The highest desirable and maximum permissible limit of TDS in drinking water are respectively up to 500 and up to 1500 mg/L [14]. TDS values of groundwater samples of the study area shows that 17% of water are under the highest desirable limit indicating that they can be used for drinking purpose without any risk. Furthermore, Todd [33] classified water, using TDS values, into five categories which are represented as very fresh (0–250 mg/L); fresh (250–1000 mg/L); brackish (1000–10,000 mg/L); saline category (10,000–100,000 mg/L) and brine category (TDS > 100,000 mg/L) (Table 3). According to the above classification, most of the groundwater samples (67%) fall under the fresh water category while 31% and 2% fall respectively under the brackish and very fresh water categories.

3.2.3. Water Quality Index

WQI for drinking purpose of the study area were determined. The computed values of WQI were generally used to classify the quality of water into five categories such as excellent, good, poor, very poor, and unsuitable for human consumption [13,14,17,22,35,36]. Table 4 shows the classification of groundwater quality based on the water quality index. In the study area, the calculated values of WQI ranged from 17.6 to 469 with an average value of 99. In this study, the computed values of WQI indicates that the majority of groundwater samples fell under excellent water and good water categories with respectively 12% and 52% of groundwater samples. However, 33% shows poor water and only one sample (Well 18, located in Nianing, close to the coast on Figure 2) has water quality unsuitable water for drinking purpose. The unsuitability of groundwater, observed in well 18, is due to a contamination by high nitrate content (432 mg/L), very high electrical conductivity (8880 μS/cm). and the high ion concentration (Na^+, Ca^{2+}, Cl^-, $SO_4{}^{2-}$ and F^-, respectively 1106 mg/L, 562 mg/L, 2626 mg/L, 433 mg/L and 2 mg/L).

Table 4. Water quality classification based on WQI.

WQI Values	Water Quality Status	Number of Samples	% of Samples
<50	Excellent water	5	11.9
50–100	Good water	22	52.4
100–200	Poor water	14	33.3
200–300	Very poor water	Nil	Nil
>300	Unsuitable water for drinking	1	2.4

3.3. Groundwater Suitability for Irrigation

3.3.1. Sodium Adsorption Ratio

SAR is an important water quality parameter to measure the suitability of water for irrigation use. Effectively excessive sodium content, relative to the calcium and magnesium, can deteriorate the soil characteristics; Thereby reducing the soil permeability and structure [3,33,36]. The use of water with high content of SAR requires soil amendments to prevent long-term damage of soil. Sodium in water can displace the calcium and magnesium in soil, leading to a decrease in infiltration and permeability of the soil [30]. As proposed by Richards [37], groundwater samples having SAR values less than 10 are considered excellent quality for irrigation, 10 to 18 as good, 18 to 26 as fair, and above 26 are unsuitable for irrigation use. The computed values of SAR in the study area ranged from 0.5 to 14.6 with an average value of 2.6. Based on the above classification, majority of groundwater samples (95%) fall in the excellent water category. The remaining 5% belong to good category of water, suitable for irrigation purpose. The US Salinity Laboratory diagram (USSL) was used to confirm water quality assess for irrigation purpose. The USSL salinity diagram (Figure 6) reveals that the majority of the groundwater samples (64%) fall in the field C3S1. It indicates high salinity and low sodium water category acceptable for irrigation, for almost all type soils type with little risk due to exchangeable sodium [38,39]. Such use is conditioned by good drainage of the soils because the high salinity may affect crop growth causing osmotic effects and nutritional disorders [21]. In addition, 16% of groundwater samples belong to C2S1 category, indicating medium salinity and low alkalinity water. They can be used for irrigation with moderate leaching and moderate permeability leaching soil characteristics [22]. One sample fall in the field C1S1 category indicating low salinity and alkalinity allowing it use to irrigate most of soil and crops with less negative impact [37]. Groundwater falling in the category C3S2 represents around 2% of groundwater samples which can be used to irrigate salt tolerant and semi tolerant crops under adapted drainage conditions [30]. The remaining groundwater samples fall in the field C4S1 (2%), C4S2 (7%) and C4S4 (5%) indicating very high salinity and low to very high alkalinity. The C4S4 water category (very high salinity and very high alkalinity) is observed in borehole (B15) and Dug Well (DW18). They reveal high salinity water (EC= 4500 μS/cm), high chloride and sodium contents (Cl = 1107 and Na = 787 mg/L respectively) and anthropogenic pollution with high nitrate and sulfate contents (NO_3 = 432 mg/L, SO_4 = 432 mg/L). Such water is generally unfit for irrigation use in the farmland where restricted drainage occurred. Hence, irrigation use of such water may affect the yield of crops.

3.3.2. Sodium Percent

Sodium in soil is considered vital for determining groundwater suitability for irrigation purpose because Na^+ reacts with soil reducing its permeability and little or no plant growth [16]. In addition, high concentrations of sodium in irrigation water tend to be absorbed by clays and to displace Ca^{2+} and Mg^{2+} by ion exchange, reducing the permeability and resulting in soil with poor drainage and thus limits air and water circulation during wet conditions [40–42]. The computed values of %Na in the studied area range from 17 to 76% with an average value of 35%. Generally, this indicator allows classification: if the %Na is less than 20% water is excellent, good one, for %Na values ranging from 20 to 40%, permissible water for %Na values varying between 40 and 60%, doubtful water for %Na values ranging from 60 to 80% and unsuitable water for %Na values over 80%. According to this classification, most of the groundwater samples fall in excellent (12%) and good (62%) water type for irrigation. Around 21% and 5% fall respectively into permissible and doubtful water category. In addition, the diagram of Wilcox [26] was used to study the integrated effect of electrical conductivity and sodium percent. Wilcox diagram indicates that 21% and 57% belong respectively to excellent to good and good to permissible for irrigation purpose. The remaining groundwater samples fall in the permissible to doubtful (5%), doubtful to unsuitable (12%) and unsuitable water category (5%) (Figure 7). The unsuitable water category is observed in borehole (B15) and Dug Well (DW18). These two points are characterized respectively by high salinity of water with high chloride and sodium contents (Cl = 1107 and Na = 787 mg/L) high nitrate and sulfate contents (NO_3 = 432 mg/L, SO_4 = 432 mg/L).

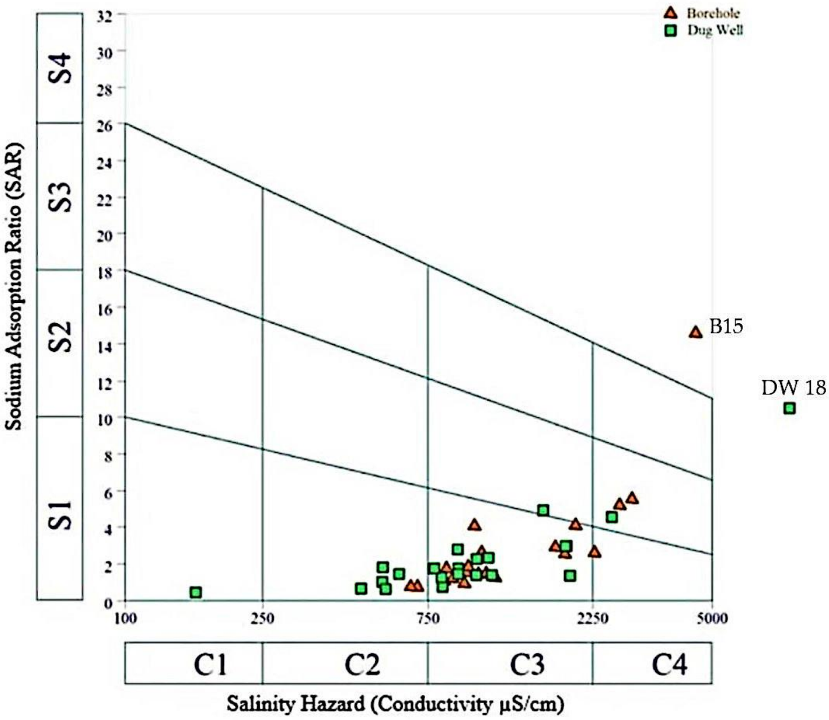

Figure 6. US salinity diagram of groundwater of the study area.

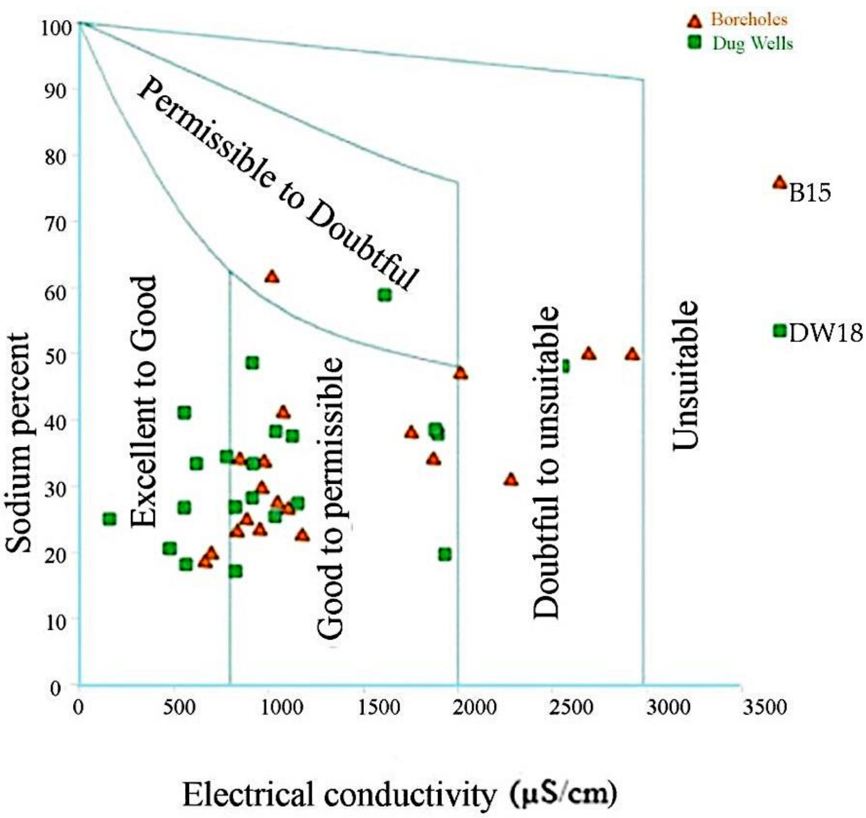

Figure 7. Plot of sodium (%) versus Electrical conductivity (µS/cm).

3.3.3. Residual Sodium Carbonate

The RSC is known as the excess quantity of sodium, bicarbonate and carbonate in water which is considered to be detrimental to the physical properties of soils as it causes dissolution of organic matter in the soil [3,38]. The sum of carbonate and bicarbonate in water over the sum of calcium and magnesium define potential use of water for irrigation. Lloyd and Heathcote [41] classified water for irrigation as good for RSC values lower than 1.25, doubtful for RCS between 1.25 to 2.50 and unsuitable, for RSC values greater than 2.50. In this study, the RSC values varied from −41.7 to 1.7 with an average value of −4.1. Based on the computed values of RSC, most of groundwater samples (95%) fall in good category of water indicating their suitability for irrigation use; While 4.8% fall in doubtful water category.

3.3.4. Permeability Index

The Permeability Index is an important water quality parameter used to determine the quality of irrigation water in agricultural areas. Long-term use of groundwater for irrigation affects the permeability index of groundwater, which in turn is influenced by Na^+, Ca^{2+}, Mg^{2+} and HCO_3^- concentrations [6]. According to Doneen [42] PI value greater than 75% is categorized in Class I (excellent water quality for irrigation). Class II, for PI between 25 and 75% indicating good water quality for irrigation. Class III, for PI values lower than 25% indicating unsuitable water for irrigation. The computed values of PI range from 30 to 84 with an average value of 54. All the groundwater samples fall in Class I (7%) and Class II (93%) indicating respectively excellent and good water categories for irrigation purposes.

3.3.5. Kelly Ratio

Kelly Ratio is another parameter used to evaluate the quality of water for irrigation purpose. It is based on the sodium content against calcium and magnesium concentration [43]. Water with KR < 1 is considered suitable for irrigation use, whereas water with KR > 1 is unsuitable for agricultural purpose due to alkali hazards. The computed values of KR ranged from 0.2 to 3.1 with an average value of 0.6. According to this indicator 90.5% of groundwater samples have KR < 1 indicating that most of groundwater is suitable for irrigation purpose.

3.3.6. Magnesium Ratio

MR is an expression of Magnesium Hazard (MH), which was developed by Palliwal [44] to assess the suitability of water for irrigation. High index of magnesium hazard value (>50%) in irrigation water induces adverse effect on the crop yield by alkalinisation. The computed values of MR varied from 9.6 to 74.6% with an average value of 42%. Around 40% of groundwater samples are unsuitable for irrigation purpose while 60% of the samples (with an MR lower to 50) suggest that they can be used for irrigation.

3.4. Mechanisms Controlling Groundwater Chemistry

The chemical variation of groundwater composition is mainly controlled by several natural processes such as rock weathering, mineral dissolution, ion exchange as well as atmospheric input and anthropogenic activity. In this study, Gibbs [45] diagram is used to identify the source of dissolved chemical constituents of groundwater. It is widely used in many countries to identify the major factors controlling the chemical composition of water in different geological environment [3,21,46]. In this study, the carbonate weathering can be an important process since the geological formations are mainly composed of limestone and marl. The plot of groundwater chemical data on the Gibbs diagram shows that most of groundwater samples fall in the rock dominance area indicating that water-rock interaction is one of the main geochemical process controlling the chemical composition of groundwater. However, some groundwater samples are located in the evaporation dominance zone where evaporation plays an important role in the variation of groundwater chemistry (Figure 8). To precise the contribution of water-rock interaction in the variation of the chemical composition of waters, other bivariate plots and ionic ratios are used. Weathering of carbonate, silicate and sulphide minerals and dissolution of evaporites are considered as the major lithogenic source of the dissolved ions in water [28].

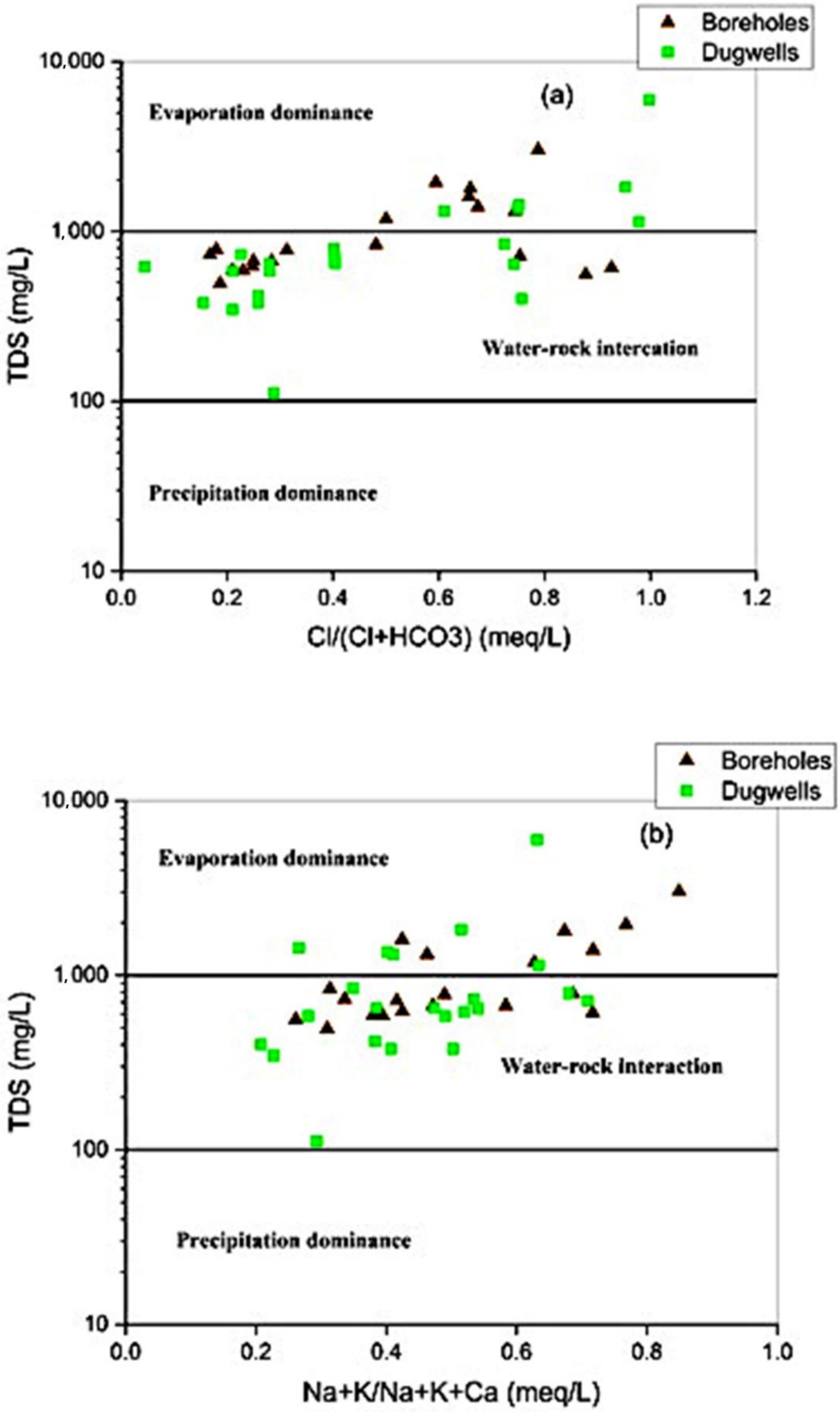

Figure 8. Gibbs plot (**a**) TDS versus $Cl^-/(Cl^- + HCO_3^-)$ and (**b**) TDS versus $(Na^+ + k^+)/(Na^+ + K^+ + Ca^{2+})$.

In addition, ionic ratio was generally used to determine the source of dissolved solutes ions in groundwater. Hence, the (Ca^{2+} + Mg^{2+})/HCO_3^- and Ca^{2+}/Mg^{2+} ratios were often used to identify the source of calcium and magnesium in groundwater. Calcium and magnesium can be derived from weathering of Ca-bearing minerals such as calcite, dolomite and aragonite. If the ratio Ca^{2+}/Mg^{2+} = 1, dissolution of dolomite should occur, whereas a ratio ranging from 1 to 2 is indicative of calcite contribution. However, higher Ca^{2+}/Mg^{2+} molar ratio (>2) indicates the dissolution of silicate minerals, which contribute calcium and magnesium to groundwater [18,47,48]. Furthermore, if Ca^{2+} and Mg^{2+} were only derived from the dissolution of carbonates in the aquifer minerals and from the weathering of accessory pyroxene or amphibole minerals, the ratio of (Ca^{2+} +Mg^{2+})/HCO_3^- would be about 0.5 [49]. The computed values Ca^{2+}/Mg^{2+} ratio of the study ranged from 0.34 to 9.41. About 38% of groundwater samples shows Ca^{2+}/Mg^{2+} ratio higher than 2 which is indicative of contribution of silicate minerals dissolution, whereas 21% of groundwater samples have a Ca^{2+}/Mg^{2+} ionic ratio between 1 and 2 indicating the dissolution of calcite. The remaining groundwater samples (17) have a Ca^{2+}/Mg^{2+} ratio less than 1 with 7 of them having a ratio close to 1 indicating the contribution of dolomite dissolution. Furthermore, the computed values of ($Ca^{2+}Mg^{2+}$)/HCO_3^- ratio show that all groundwater samples have values greater than 0.5. It suggests that dissolution of carbonate minerals and weathering of silicates are not the only sources of calcium and magnesium of waters. The plot of Na^+ vs. Cl^- (Figure 9) shows that some samples plot along the 1:1 line suggesting the halite dissolution another source of ions Na^+ and Cl^- in groundwater. However, most of groundwater samples fall below the 1:1 line revealing the dominance of Cl^- over Na^+ (Figure 9). The decrease of Na^+ in groundwater samples may be due to other processes such as ion exchange. The ion exchange between groundwater and its host environment during residence or in movement processes are the important controlling factors for water chemistry variation in many areas. This ion exchange process is considered, in a previous study [50] to be the or one of the main factors controlling the chemical composition of groundwater. In this study, the ion exchange process is investigated by reporting the chemical analysis results of groundwater samples on the binary diagram (Ca^{2+} + Mg^{2+} − SO_4^{2-} − HCO_3^-) vs. [(Na^+ + K^+) − Cl^-] (Figure 10). If cation exchange controls the ionic composition of groundwater, the relation between these two parameters should be linear with a slope of −1 [51]. In this study, the plot of groundwater samples on the scatter diagram (Ca^{2+} + Mg^{2+} − SO_4^{2-} − HCO_3^-) vs. [(Na^+ + K^+) − Cl^-] indicates that most of groundwater samples falls on or close a straight line with a slope of −1.12 with an r^2 = 0.96 suggesting an occurrence of reverse ion exchange in groundwater.

Hydrochemical Facies

Hydrochemical facies (water masses with different geochemical attributes) are helpful for comparing origins and distribution of groundwater. Results of chemical analysis of groundwater samples have been plotted on the diagram proposed by Piper [52] to identify the main groundwater types. The Piper's diagram consists of three distinct fields: two triangular fields (cation and anion) and one diamond-shaped field. The overall characteristics of water are represented in the diamond-shaped field by projecting the position of plots in the triangular fields. The plot of chemical data on the Piper diagram reveals the presence of several groundwater type such as Na-K-Cl, Ca-Cl, Ca-Mg-HCO_3, mixte Ca-Na-Mg-HCO_3 and mixte Ca-Na-Cl (Figure 11).

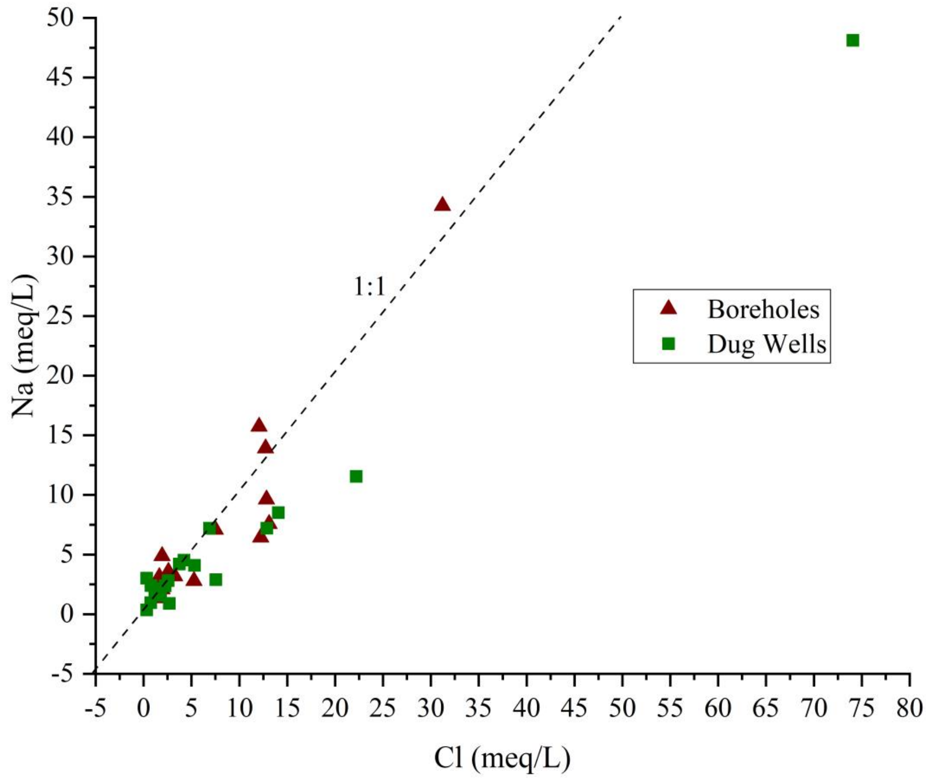

Figure 9. Scatter plot of Na vs. Cl.

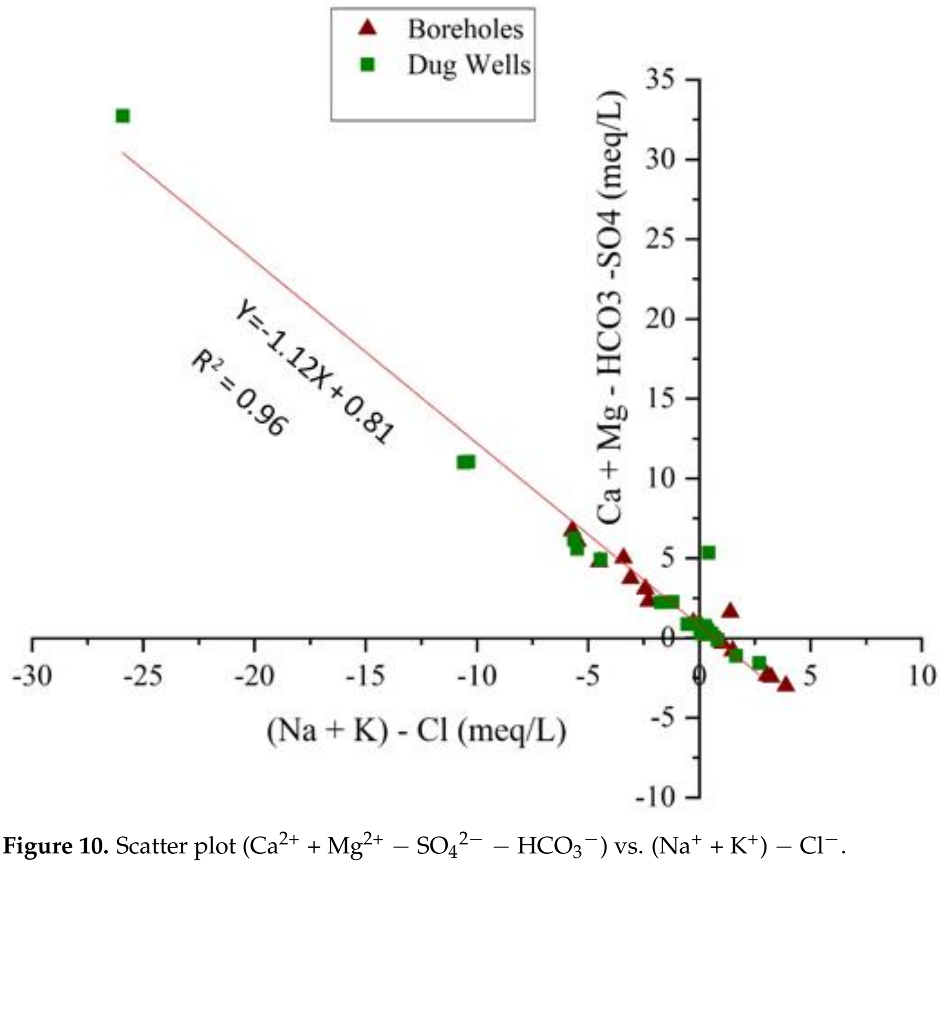

Figure 10. Scatter plot ($Ca^{2+} + Mg^{2+} - SO_4{}^{2-} - HCO_3{}^{-}$) vs. ($Na^{+} + K^{+}$) $- Cl^{-}$.

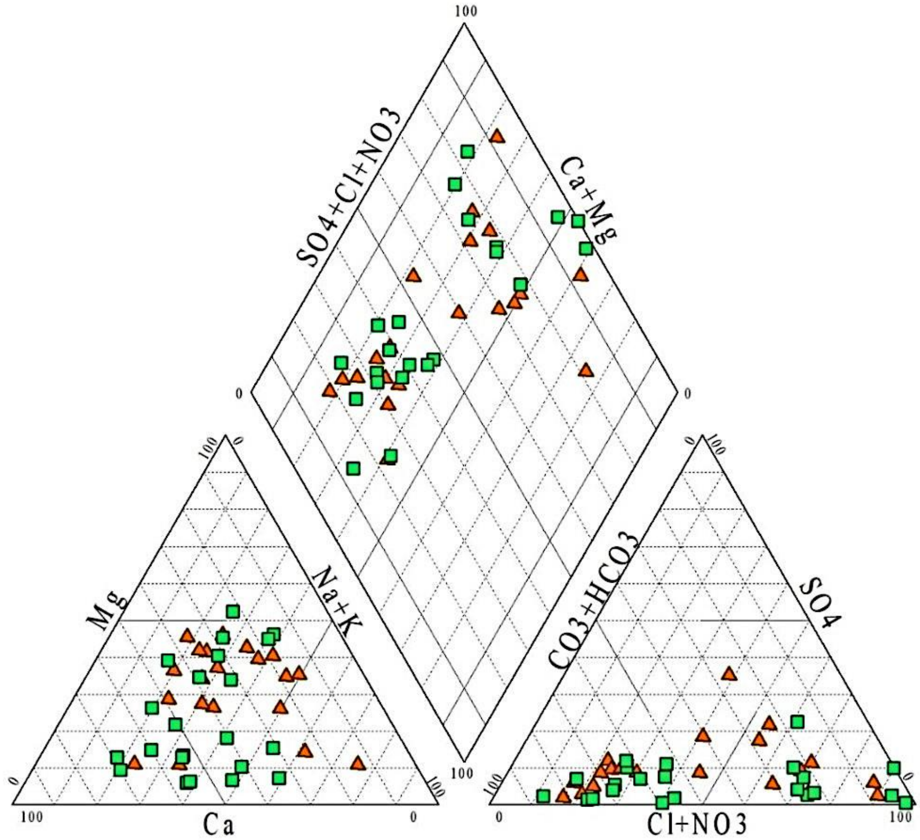

Figure 11. Piper plot s illustrated with groundwater types of the study area.

4. Conclusions

This study was carried out in the area of West central Senegal in order to assess the quality of groundwater and determine its suitability for irrigation and human consumption. For this purpose, several parameters of groundwater quality evaluation were determined in association with the use of several geochemical plots. The parameters followed and/or calculated are Kelly ratio (KR), magnesium hazard (MH), magnesium ratio (MR), permeability index (PI), residual sodium carbonate (RSC), total dissolved solids (TDS), total hardness (TH), sodium adsorption ratio (SAR), sodium percent (%Na), US salinity laboratory (USSL), water quality index (WQI) under the World Health Organization recommendations. So many parameters for groundwater quality evaluation regarding theirs uses (irrigation or drinking water) clearly reflect the complexity of such approach and some parameters' limitations. Basically, if a groundwater can be exploited for irrigation, it can be not possible for drinking purpose. It becomes complex with irrigation purpose because norms or policy are not compulsory, or not considered. Reasons why sub-categories (i.e.,: USSL or RSC) are considered to allow a better discrimination of water quality in function of their uses and the preservation of the resources (water and soil in this study). In this research, we fully assumed the decision to consider an extensive selection of parameters to alert stakeholders to the complexity of regional resources, case studies, trend and limitations to consider. Then, parameters do not consider the same object which can be global (EC, TDS, TH for example) others are focused on one indicator (%Na, KR, MR). By using a few indicators, the main risk is providing blurry classification or wrong one which can cause irremediable resource degradation.

The in-situ measurements of pH indicate that groundwater is neutral to slightly alkaline while the electrical conductivity shows weak to strongly mineralized waters with a maximum value of 8880 µS/cm. The plot of the chemical data on the Piper diagram reveals several types of water in which mixte-Na-Ca-Mg-HCO_3 is the dominant one. The classification of water, according to TDS for human consumption, confirms that the majority (69%) of groundwater samples belongs to soft water category. Furthermore, the WQI (used to quantify the overall quality of groundwater for drinking) indicates that the majority of groundwater samples is suitable for drinking. However, some limitations have to be considered. For example, the comparison of fluoride contents in groundwater with the WHO standard limits reveals that the majority of groundwater sample (69%) is above the WHO allowable limit (1.5 mg/L)! In that case, it indicates that groundwater resource of the region is mostly unfit for drinking purpose without treatment.

Water quality evaluation for irrigation is paramount since agriculture is the region's main economic activity. Hence, the suitability of groundwater was determined using several water quality parameters (SAR, %Na, RSC, KR and MR). Results reveal that most of groundwater samples are suitable for irrigation purpose. However as observed for drinking water category, some restrictions must also be considered. The USSL diagram indicates that the majority of groundwater samples (64%) fall in the field C3S1 (irrigation on all type of soil with little exchangeable sodium). From Wilcox diagram 21% and 57% of groundwater samples fall respectively in the field of excellent to good and in the field of good to permissible water categories.

Results of this study show that groundwater resources must be considered highly sensitive depending on physical and chemical processes developed. The equilibrium point depends partially, on the interaction between water and rocks. Gibbs plots indicate that water- rocks interaction, with some extent evaporation, is the main processes controlling groundwater composition while ionic ratios and geochemical bivariate plots reveal ion exchange and mineral dissolution play also important role in the groundwater chemistry.

This study shows that, for human consumption, preliminary treatment of water with respect to fluoride limit, is necessary to avoid harmful effects on the population's health.

On the other hand, the evaluation of groundwater for irrigation purposes highlights that the majority of groundwater samples could be suitable for agricultural under some restrictions or recommendations. The main of them are relative to the soil nature and chemical composition of the water to prevent soils degradation combined with excessive water consumption due to agriculture practices.

Regular monitoring of the evolution of water quality is required to limit salinization process associated with irrigation water return for long-term use. Furthermore, regulation about fertilizers in the agricultural area should be consider to avoid an increase in nitrate concentration. One of the conclusions of this work is that the quality of water, depending on its use and the target, calls upon numerous indexes, references and standards, each with its independent meaning. It is then possible to qualify water as potable according to one index and no-drinkable according to another. For example, the acceptable nitrate level for drinking water varies from 50 mg/L in the EU for an adult, but only 10 mg/L for an infant. Therefore, by integrating all the physico-chemical parameters, we can qualify water according to the intended use and the type of consumer.

Human activities continuously impact the groundwater quality, which can quickly become unsuitable for drinking and agriculture uses. This study doesn't consider emergent contaminants (organic and inorganic), agriculture practices, or socio-economic considerations in the short term (decade). However, our main conclusion is that from the 90′s years and Travis's works [8], the evolution of the groundwater quality of the west central Senegal has gone fast with a constant progression of unsuitable water, whatever the use, due to the progressive chemical adaptation to their environment and the environment.

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Abbreviations

CBE	Charge Balance Error
GPS	Global Positioning System
KR	Kelly Ratio
MR	Magnesium Ratio
PI	Permeability Index
TDS	Total Dissolved Solids
SAR	Sodium Adsorption Ratio
WHO	World Health Organization
EC	Electrical Conductivity
ICP-MS	Inductively Coupled Plasma-Mass Spectrometry
MH	Magnesium Hazard
pH	Hydrogen potential
RSC	Residual Sodium Carbonate
TH	Total Hardness
%Na	Sodium percent
WQI	Water Quality Index

References

1. Pointet, T. The United Nations World Water Development Report 2022 on Groundwater, a Synthesis. *LHB* **2022**, *108*, 2090867. [CrossRef]
2. Nickson, R.T.; McArthur, J.M.; Shrestha, B.; Kyaw-Nyint, T.O.; Lowry, D. Arsenic and other drinking water quality issues, Muzaffargarh District, Pakistan. *Appl. Geochem.* **2005**, 55–68. [CrossRef]
3. Amiri, V.; Sohrabi, N.; Dadgar, M.A. Evaluation of groundwater chemistry and its suitability for drinking and agricultural uses in the Lenjanat plain, central Iran. *Environ. Earth Sci.* **2015**, *74*, 6163–6176. [CrossRef]
4. Krishna Kumar, S.; Chandrasekar, N.; Seralathan, P.; Godson, P.S.; Magesh, N.S. Hydrogeochemical study of shallLow carbonate aquifers, Rameswaram Island, India. *Environ. Monit. Assess.* **2011**. [CrossRef]
5. Subramani, T.; Elango, L.; Damodarasamy, S.R. Groundwater quality and its suitability for drinking and agricultural use in Chithar River basin, Tamil Nadu, India. *Environ. Geol.* **2005**, *47*, 1099–1110. [CrossRef]
6. Sharma, D.A.; Rishi, M.S.; Keesari, T. Evaluation of groundwater quality and suitability for irrigation and drinking purposes in southwest Punjab, India using hydrochemical approach. *Appl. Water Sci.* **2016**. [CrossRef]
7. Adimalla, N.; Dhakate, R.; Kasarla, A.; Taloor, A.K. Appraisal of groundwater quality for drinking and irrigation purposes in central Telangana, India. *Groundw. Sustain. Dev.* **2020**, *10*, 100334. [CrossRef]
8. Travi, Y. Hydrogéologie et hydrochimie des aquifères du Sénégal. Hydrogéochimie du fluor dans les eaux souterraines. Strasbourg, Institut de Géologie – Université Louis-Pasteur. *Sci. Géologiques Mémoire* **1993**, *95*, 3–158.
9. Tine, A.K.; Ba, M.I.; Gladima–Siby, A.S.; Essouli, O.F.; Faye, A.; Sarr, B. Réactualisation de la situation hydrogéologique des aquifères du Maastrichtien et du Paléocène de la région de Mbour, Sénégal. *J. Sci. Technol.* **2011**, *9*, 23–32.
10. Sarr, B. Etude hydrogéologique de la région de Joal-Fadiouth (Sénégal). *Thèse Cycle. Univ. C. A. Diop, Dakar*. 1982, p. 192. Available online: https://documentation-miniere.sec.gouv.sn/biblio/opac_css/doc_num.php?explnum_id=225 (accessed on 15 April 2023).
11. Saint Marc, P.; Sarr, R. Precisions biostratigraphiques et paleoenvironnementales sur Ie sommet du Paleocene et la base de l'Eocene de la region de Mbour-Joal (Senegal). *J. Afr. Earth Sci.* **1984**, *2*, 203–207.
12. Hounslow, A.W. *Water Quality Data Analysis and Interpretation*; CRC Press: Boca Raton, FL, USA, 1995.
13. WHO. *Guidelines for Drinking Water Quality*, 3rd ed.; WHO: Geneva, Switzerland, 2004.
14. WHO. *Guidelines for Drinking Water Quality*, 4th ed.; WHO: Geneva, Switzerland, 2011.

15. Ramakrishnaiah, C.R.; Sadashivaiah, C.; Ranganna, G. Assessment of Water Quality Index for the Groundwater in Tumkur Taluk, Karnataka State, India. *E-J. Chem.* **2009**, *6*, 523–530. [CrossRef]
16. Vasanthavigar, M.; Srinivasamoorthy, K.; Vijayaragavan, K.; Rajiv Ganthi, R.; Chidambaram, S.; Anandhan, P.; Manivannan, R.; Vasudevan, S. Application of water quality index for groundwater quality assessment: Thirumanimuttar sub-basin, Tamilnadu, India. *Environ. Monit. Assess.* **2010**, *171*, 595–609. [CrossRef]
17. Sajil Kumar, P.J.; Elango, L.; James, E.J. Assessment of hydrochemistry and groundwater quality in the coastal area of South Chennai, India. *Arab. J. Geosci.* **2013**. [CrossRef]
18. Patel, P.; Raju, N.J.; Reddy, B.C.S.; Raja, S.U.; Gossel, W.; Wycisk, P. Geochemical processes and multivariate statistical analysis for the assessment of groundwater quality in the Swarnamukhi River basin, Andhra Pradesh, India. *Environ. Earth Sci.* **2016**, *75*, 611. [CrossRef]
19. Deepa, S.; Venkateswaran, S. Appraisal of groundwater quality in upper Manimuktha sub basin, Vellar river, Tamil Nadu, India by using Water Quality Index (WQI) and multivariate statistical techniques. *Model Earth Syst. Environ.* **2018**, *4*, 1165–1180. [CrossRef]
20. Talib, M.A.; Tang, Z.; Shahab, A.; Siddique, J.; Faheem, M.; Fatima, M. Hydrogeochemical Characterization and Suitability Assessment of Groundwater: A Case Study in central Sindh Pakistan. *Int. J. Environ. Res. Public Health* **2019**, *16*, 886. [CrossRef]
21. Adimalla, N.; Li, P.; Venkatayogi, S. Hydrogeochemical Evaluation of Groundwater Quality for Drinking and Irrigation Purposes and Integrated Interpretation with Water Quality Index Studies Environ. *Environ. Process* **2018**, *5*, 363–383. [CrossRef]
22. Varol, S.; Davraz, A. Evaluation of the groundwater quality with WQI (Water Quality Index) and multivariate analysis: A case study of the Tefenni plain (Burdur/Turkey). *Environ. Earth Sci.* **2014**. [CrossRef]
23. Arulbalaji, P.; Gurugnanam, B. Groundwater quality assessment using geospatial and statistical tools in Salem District, Tamil Nadu, India. *Appl Water Sci.* **2016**. [CrossRef]
24. Boateng, T.K.; Opoku, F.; Acquaah, S.O.; Akoto, O. Groundwater quality assessment using statistical approach and water quality index in Ejisu-Juaben Municipality, Ghana. *Environ. Earth Sci.* **2016**, *75*, 489. [CrossRef]
25. Chung, S.Y.; Venkatramanan, S.; Kim, T.H.; Kim, D.S.; Ramkumar, T. Influence of hydrogeochemical processes and assessment of suitability for groundwater uses in Busam City, Korea. *Environ. Dev. Sustain.* **2015**, *17*, 423–441. [CrossRef]
26. Wilcox, L.V. *Classification and Use of Irrigation Waters*; Circular N°969; U.S. Department of Agriculture: Washington, DC, USA, 1955; p. 19.
27. Hem, J.D. Study and interpretation of the chemical characteristics of natural waters. *USGS Water Supply Pap.* **1985**, *2254*, 117–120.
28. Kumar Singh, A.; Raj, B.; Tiwari, A.K.; Mahato, M.K. Evaluation of hydrogeochemical processes and groundwater quality in the Jhansi district of Bundelkhand region, India. *Environ. Earth Sci.* **2013**. [CrossRef]
29. Hem, J.D. *Study and Interpretation of the Chemical Characteristics of Natural Waters*, 3rd ed.; Book 2254; Scientific Publishers: Jodhpur, India, 1991; p. 263.
30. Sarath Prasanth, S.V.; Magesh, N.S.; Jitheshlal, K.V.; Chandrasekar, N.; Gangadhar, K. Evaluation of groundwater quality and its suitability for drinking and agricultural use in the coastal stretch of Alappuzha District, Kerala, India. *Appl. Water Sci.* **2012**, *2*, 165–175. [CrossRef]
31. Adimalla, N.; Venkatayogi, S. Geochemical characterization and evaluation of groundwater suitability for domestic and agricultural utility in semi-arid region of Basara, Telangana State, South India. *Appl. Water Sci.* **2018**, *8*, 44. [CrossRef]
32. Ravikumar, P.; Somashekar, R.K.; Angami, M. Hydrochemistry and evaluation of groundwater suitability for irrigation and drinking purposes in the Markandeya River basin, Belgaum District, Karnataka State, India. *Environ. Monit. Assess.* **2011**, *173*, 459–487. [CrossRef]
33. Todd, D.K. *Ground Water Hydrology*; Wiley: New York, NY, USA, 1980.
34. Sawyer, G.N.; Mc Mcartly, D.L. *Chemistry of Sanitary Engineers*, 2nd ed.; McGraw Hill: New York, NY, USA, 1967; p. 518.
35. Krishna Kumar, S.; Logeshkumaran, A.; Magesh, N.S.; Godson, P.S.; Chandrasekar, N. Hydro-geochemistry and application of water quality index (WQI) for groundwater quality assessment, Anna Nagar, part of Chennai City, Tamil Nadu, India. *Appl. Water Sci.* **2015**, *5*, 335–343. [CrossRef]
36. Xiao, J.; Jin, Z.; Wang, J. Assessment of the Hydrogeochemistry and Groundwater Quality of the Tarim River Basin in an Extreme Arid Region, NW China. *Environ. Manag.* **2014**, *53*, 135–146. [CrossRef]
37. Richards, L.A. *Diagnosis and Improvement of Saline Alkali Soils. U.S. Salinity Laboratory Staff*; Richards, L.A., Ed.; US Department of Agriculture: Washington, DC, USA, 1954; Volume 60, p. 160.
38. Kumar, M.; Kumari, K.; Ramanathan, A.L.; Saxena, R. A comparative evaluation of groundwater suitability for irrigation and drinking purposes in two intensively cultivated districts of Punjab, India. *Environ. Geol.* **2007**, *53*, 553–574. [CrossRef]
39. Arumugam, K.; Elangovan, K. Hydrochemical characteristics and groundwater quality assessment in Tirupur Region, Coimbatore District, Tamil Nadu, India. *Environ. Geol.* **2009**, *58*, 1509–1520. [CrossRef]
40. Kaur, T.; Bhardwaj, R.; Arora, S. Assessment of groundwater quality for drinking and irrigation purposes using hydrochemical studies in Malwa region, southwestern part of Punjab, India. *Appl. Water Sci.* **2016**. [CrossRef]
41. Lloyd, J.W.; Heathcote, J.A. *Natural Inorganic Hydrochemistry in Relation to Groundwater*; Clarendon: Oxford, UK, 1985; p. 294.
42. Doneen, L.D. *Notes on Water Quality in Agriculture. Davis: Water Science and Engineering*; University of California: Los Angeles, LA, USA, 1964.
43. Kelley, W.P. Use of saline irrigation water. *Soil Sci.* **1963**, *95*, 385–391. [CrossRef]

44. Palliwal, K.V. *Irrigation with Saline Water*; ICARI Monograph No.2: New Delhi, India, 1972; p. 198.
45. Gibbs, R.J. Mechanism controlling world water chemistry. *Science* **1970**, *170*, 1088–1090. [CrossRef]
46. Li, P.; Wu, J.; Qian, H. Hydrochemical appraisal of groundwater quality for drinking and irrigation purposes and the major influencing factors: A case study in and around Hua County, China. *Arab. J. Geosci.* **2016**, *9*, 15. [CrossRef]
47. Krishna Kumar, S.; Rammohan, V.; Dajkumar Sahayam, J.; Jeevanandam, M. Assessment of groundwater quality and hydrogeochemistry of Manimuktha River basin, Tamil Nadu, India. *Environ. Monit. Assess.* **2009**, *159*, 341–351. [CrossRef]
48. Yang, Q.; Li, Z.; Ma, H.; Wang, L.; Martín, J.D. Identification of the hydrogeochemical processes and assessment of ground water quality using classic integrated geochemical methods in the Southeastern part of Ordos's basin, China. *Environ. Pollut.* **2016**. [CrossRef]
49. Sami, K. Recharge mechanisms and geochemical processes in a semi-arid sedimentary basin, Eastern Cape, South Africa. *J. Hydrol.* **1992**, *139*, 27–48. [CrossRef]
50. Singh, A.K.; Mondal, G.C.; Singh, T.B.; Singh, S.; Tewary, B.K.; Sinha, A. Hydrogeochemical processes and quality assessment of groundwater in Dumka and Jamtara districts, Jharkhand, India. *Environ. Earth Sci.* **2012**, *67*, 2175–2191. [CrossRef]
51. Fisher, R.S.; Mulican, W.F. Hydrochemical evolution of sodium–sulfate and sodium–chloride groundwater beneath the Northern Chihuahuan desert, Trans-Pecos, Texas, USA. *Hydrogeol. J.* **1997**, *10*, 455–474. [CrossRef]
52. Piper, A.M. A graphical procedure in the geochemical interpretation of water analysis. *Trans. Am. Geophys. Union* **1944**, *25*, 914–928. [CrossRef]