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Posted Date: 1 February 2023

doi: 10.20944/preprints202302.0013.v1

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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: Senegal central regions face rainfall deficit combined with scarcity of surface water and poor quality. Populations use groundwater for drinking and irrigation. A Groundwater assessment studiebased on 42 samples aims to determine their quality. Several parameters (TDS, TH, WQI, SAR, RSC, %N, PI, KR and MR) and ion chemistry determined. Samples exhibit an alcaline pH (7.6) and hydrochemical facies mainly Ca-Na-Mg-HCO3. The ionic dominance is $Na^+ > Ca_2^+ > Mg_2^+ > K^+$ and $HCO_3^- > Cl^- > SO_4^{2-} > NO^{3-} > F^-$. From TDS and WQI index most of the groundwaters are suitable for drinking. Irrigation quality (based on SAR, %N, RSC, KR, MR) varie from excellent to good water type. Plotting chemical data (USSL salinity & Wilcox diagrams) reveals that the majority of the groundwater samples belong to the fields excellent to good and from good to permissible. Natural processes (rock weathering, mineral dissolution, evaporation and ion exchange) control groundwater quality. As the region faced a persistent rainfall deficit combine with fragile groundwater quality should alert the stakeholders. A sustainable development of the region can be faced if strong measures are planned to follow water quality evolution and quantity available for human purposes

Keywords: groundwater quality; irrigation and drinking water; hydrochemistry; WQI; geochemistry process; Senegal

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 fact, water is the main natural resource essential for production and for any other human activity. In many countries, groundwater is the main resource available to meet domestic, agricultural and industrial water needs. About one-third of the world's population use groundwater for drinking purpose with or without treatment [2]. Systematic reliance on groundwater to meet the multiple water needs of populations is particularly notable in arid and semi-arid areas where water demand remains very high. In these areas, the scarcity of rainfall combined with high population growth, various human activities (industrial and agricultural) lead to overexploitation of groundwater resulting in a considerable decline in groundwater levels and a degradation of their chemical quality [3]. The chemical composition of groundwater depends on several factors including nature of recharge, hydrologic gradient, residence time of groundwater in the aquifer, pollution by anthropogenic activities and rock–water interactions beneath the surface [4]. Therefore, an assessment of both the quantity and quality of groundwater is an essential step to ensure effective management and sustainable economic development. For the past few decades, several research works have been carried out to determine the quality of water and especially to determine its suitability for domestic or agricultural use [3,5–7]. In fact, in areas of high agricultural activity, groundwater quality is often threatened by the use of fertilizers and pesticides to increase agricultural yields. In the groundnut basin, which includes a large part of our study area, groundwater is used extensively for crop irrigation and human consumption. However, the consumption and use of poor quality water for drinking and for agriculture are recognized as a danger to the health of the population with the appearance of waterborne diseases but also a decrease in agricultural production. Thus, the main objective of this study is to evaluate the quality of groundwater and to determine its suitability for human consumption and use for irrigation.

2. Study Area Description

2.1. 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. The rainfall data of the stations of Mbour and Fatick, 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 561mm and 595mm. 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 Harmatan) leads to high evaporation in the area. Thus, the average potential evaporation increases from 1600mm/year in Mbour to 2200 mm/year in Fatick. 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 in December and January.

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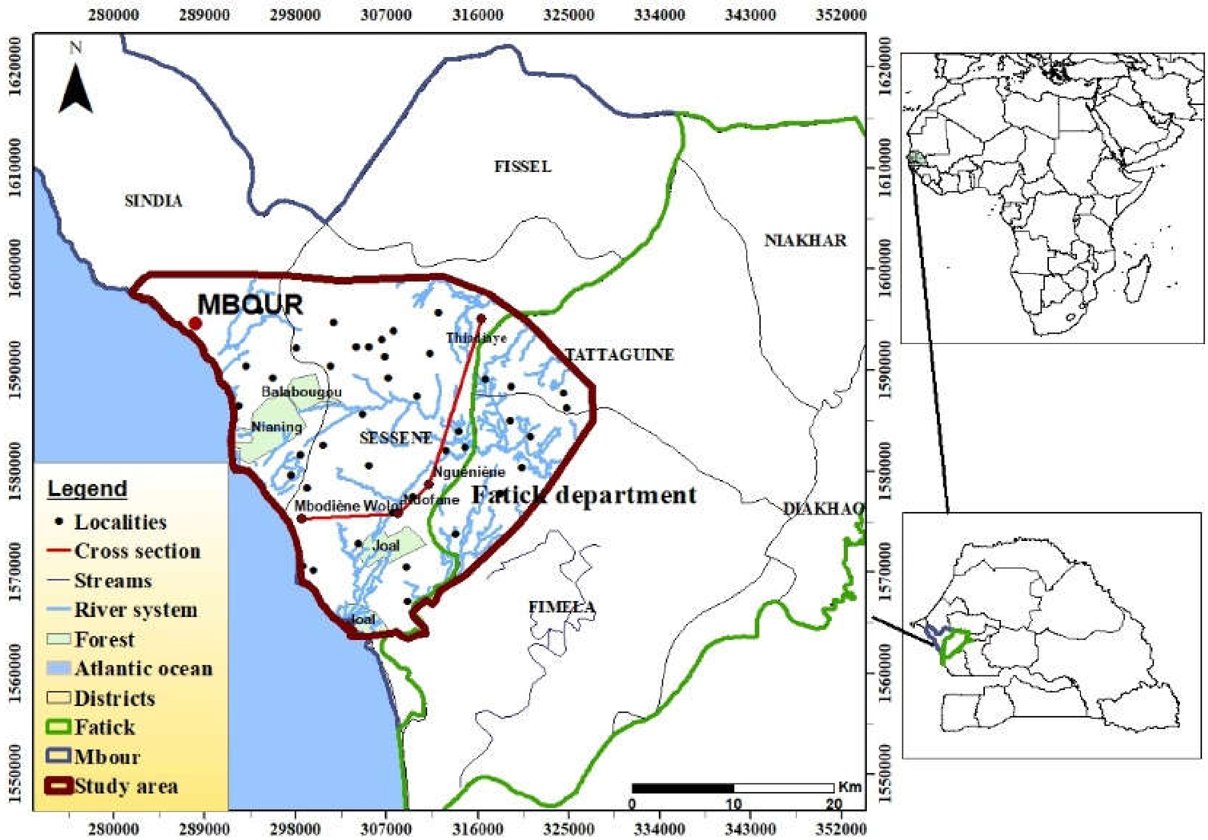

Figure 1. Location map showing the localisation of the study area.

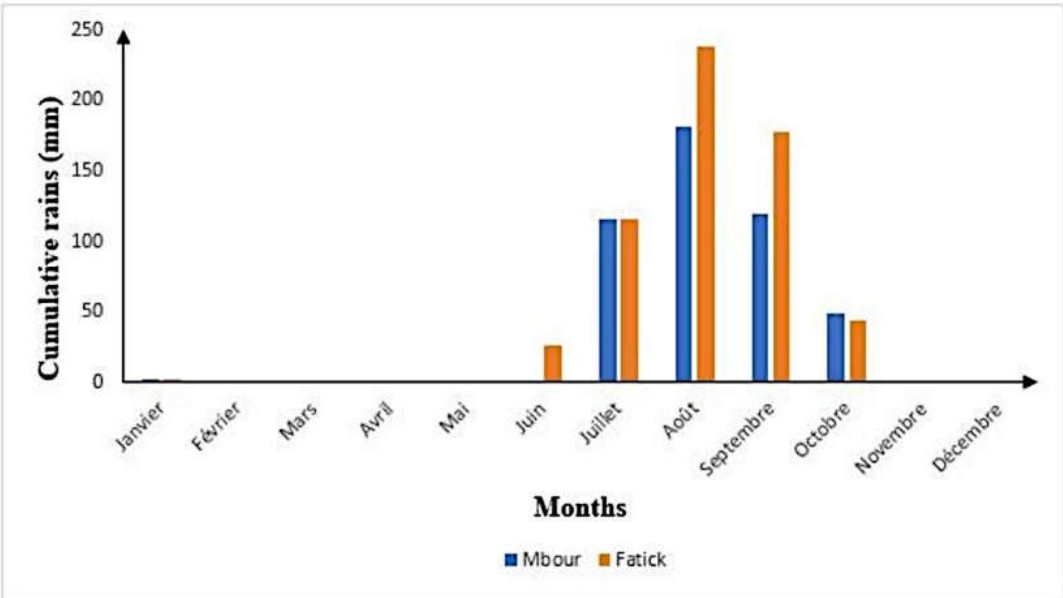

Figure 2. Average monthly rainfall from 1991 to 2020 at the Mbour and Fatick station.

2.2. 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. Thus, 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).

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The Eocene 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 [8]; 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 [9].

The lower Eocene base consists of gray marl and clay with intercalation of flint [10]. 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 [9]. In the study area, the Paleocene formations, with an average thickness of 100m, 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 [10].

The shell limestones, with little marl, are karstified or fissured and often sandstone. They occupy the middle and upper horizons of the Paleocene [10]. At its bottom, the Paleocene is made up of frank limestone and grey marly limestone which can be sandstone.

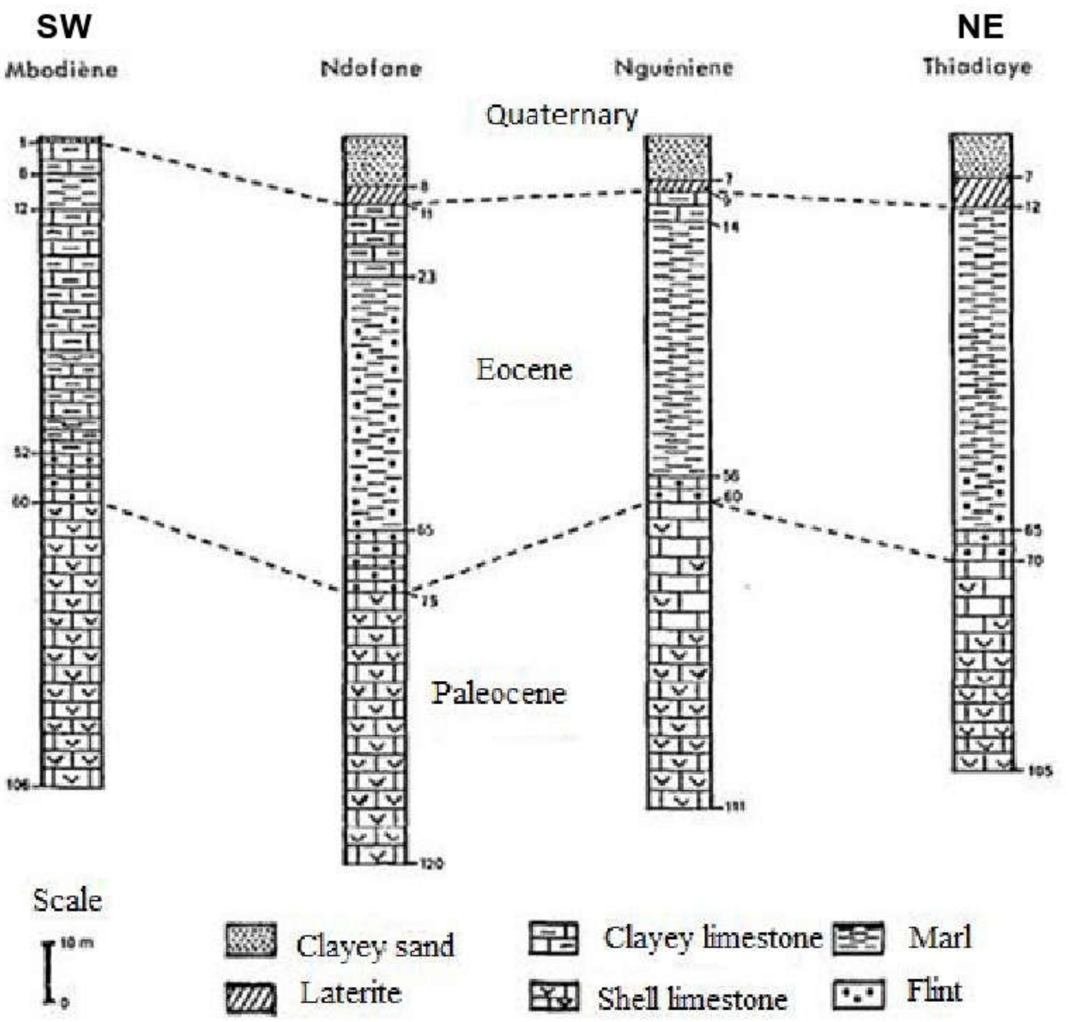

Figure 3. Lithology and stratigraphic correlation at the Mbodiène, Ndofane, Nguéniene and Thiadiaye boreholes [10].

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

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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 [10]. Its bottom is mainly made of marlstone, which as a result of a change of facies, are replaced by shell limestone in the west, and by marlstone in the North-West, East and South [11]. The Paleocene aquifer is currently the most exploited due to the depletion or salinization in some areas of the superficial aquifers.

2.3. 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 Nguéniène 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.

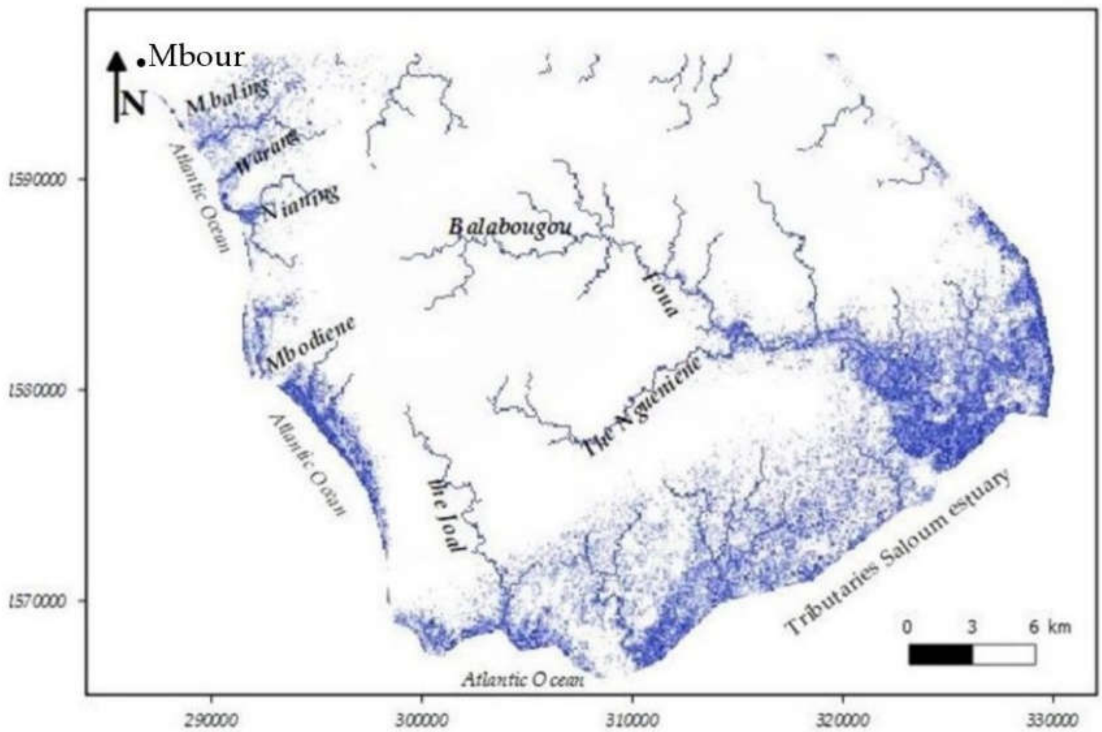

Figure 4. Hydrographic surface network of the study area.

3. Materials and Methods

3.1. 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 GARMIN (GPSMAP-64s) global positioning system (GPS). Physical parameters such as Temperature, Electrical conductivity (EC) and pH were measured in the field using a portable multi-parameter (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, Besancon, 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 (50ml) was treated with HNO_3 for cations and metal analysis. However, before filtration, the bicarbonate were 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) given bellow. The computed values show that the majority of groundwater samples have an ion balance error within the allowed limit of ±5 % [12].

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

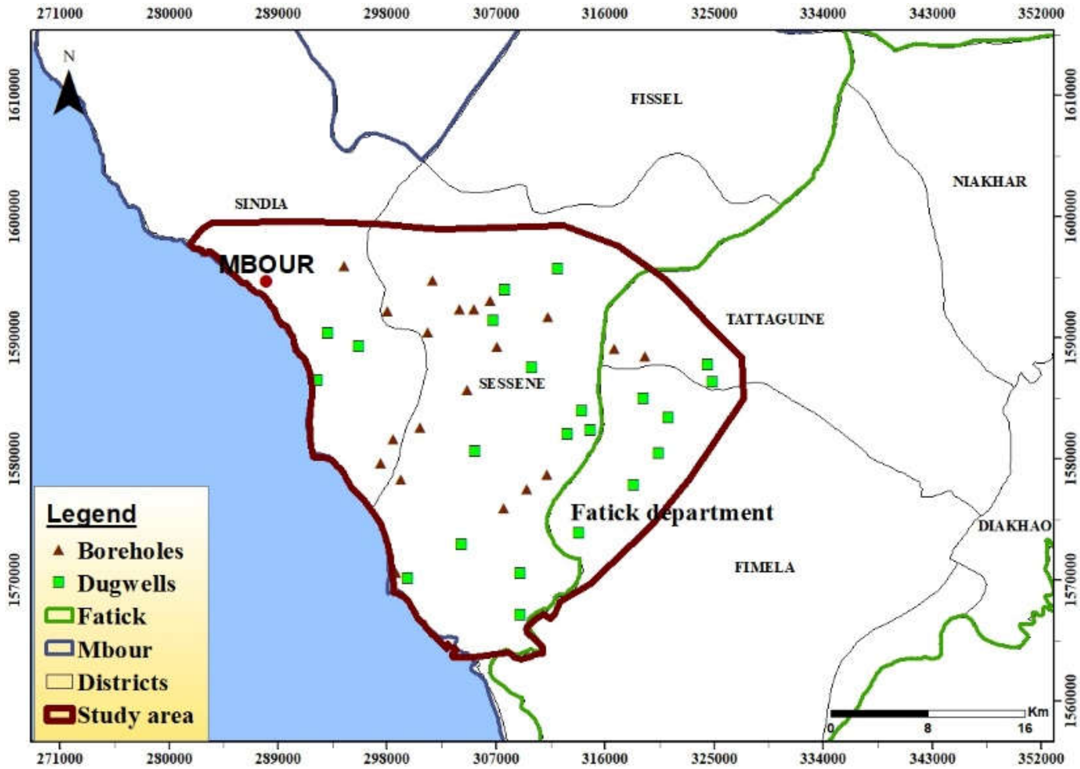

Figure 5. Location of sampling points in the study area.

3.2. Drinking Water Quality Evaluation

Water quality is an important factor in assessing its 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 [24,25] 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 [3,7,13–18]. 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]. The water quality index (WQI) was computed by assigning weight (wi) 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^{-}), Total Dissolved Solid (TDS) due to their major significance in water quality assessment [16,19]. A minimum weight of 1 have been assigned to bicarbonate since it play an insignificant role in the water quality assessment [14,20–22] and does not contribute to groundwater contamination [23]. 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).

$$Wi = \frac{\mathrm{wi}}{\sum_{i=1}^{n} wi} \quad (2)$$

where Wi is the relative weight, wi is the weight of each parameter, n is the number of parameters. The weight (wi), the calculated relative weight (Wi) values and the WHO standards [24,25] for each parameter are given in Table 1.

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

$$qi = \frac{\mathrm{Ci}}{Si} * 100 \quad (3)$$

Where qi is the quality rating, Ci is the concentration, in milligrams per liter, of each chemical parameter and Si is the WHO standard of each chemical parameter in milligrams per liter according to the guidelines of the [25]. Before computing WQI, the SIi, of each chemical parameter is first calculated using Equation (4). Finally the Water Quality Index (WQI) is calculated by summing the SIi Equation (5).

$$SIi = \mathrm{Wi} * \mathrm{qi} \quad (4)$$

$$WQI = \sum_{i=1}^{n} \mathrm{SIi} \quad (5)$$

where SIi is the Sub-index of each parameter
qi is the rating based on concentration of each parameter
n is the number of parameters.

Table 1. Relative weight of chemical parameters.

Chemical Parameters	**WHO Standard [24,25]**	**Weight (wi)**	**Relative Weight (Wi)** $Wi = \frac{\mathrm{wi}}{\sum_{i=1}^{n} \mathrm{wi}}$
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
		$\sum wi = 41$	$\sum Wi = 1$

3.3. 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. Our study area is characterized by a strong agricultural activity during the rainy and the dry season. Hence water quality assessment for irrigation is vital is this area. The irrigation suitability of groundwater, in this area, is assessing using several parameters such as Sodium Adsorption Ratio (SAR), Sodium percent (%N), Residual Sodium Carbonate (RSC), Permeability Index (PI), Kelley Ratio (KR) and Magnesium Ratio (MR). These water quality parameters were computed using, respectively, the equations (6 to 11) where all ion concentrations are expressed in milliequivalents per liter (meq/l).

$$SAR = \frac{\mathrm{Na}}{\sqrt{(\mathrm{Ca} + \mathrm{Mg})/2}} \quad (6)$$

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

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

$$PI = \frac{\mathrm{Na}+\sqrt{HCO3}}{\mathrm{Ca+Mg+Na}} * 100 \quad (9)$$

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

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

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

4. Results and Discussions

4.1. 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. The physicochemical characteristic of groundwater samples was statically analyzed and the results are presented in table. Descriptive statistics analysis such as maximum, minimum, mean, median and standard deviation of the physicochemical characteristics of groundwater samples is presented in Table 2.

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 combinaison 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 in alkaline nature. The permissible limit of pH for drinking water is 6.5 – 8.5 [25]. All pH values of groundwater samples were within the WHO permissible limit for drinking water. The electrical conductivity provides information on the overall amount of dissolved salts and reflects the efficiency with which the water conducts an electrical current. It measures the salt concentrations of water and provides indication of ionic concentrations [28] and depends upon temperature, concentration and types of ions presents [27]. Electrical conductivity 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]. The electrical conductivity of groundwater in the study area 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).

4.2. 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 World Health Organization [24,25] for drinking purpose. Furthermore, the water quality index (WQI), total hardness (TH) and total dissolved solids (TDS) which are others important water quality parameter were also used in this study. 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 its higher concentration, more than 200 mg/L, makes the water unsuitable for domestic use and causes severe health problems like hypertension, congenial diseases, kidney disorders and nervous disorders in human body [31]. In the study area, sodium is the dominant cation in 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 because the standard deviations were largely higher than the mean value (Table 2). Most of groundwater samples were suitable for drinking purpose. However, six samples (14%) had high content of sodium which 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 concentration in groundwater of the study area was 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 of the study area. The concentration of bicarbonate in groundwater samples 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. Sulphate concentration in natural water is usually found between 2 and 80 mg/L and abnormal higher concentration of sulphate 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 [24]. 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 in groundwater samples that only three (7.1%) 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 the study area, the nitrate concentration is relatively low. Nitrate contents vary from 0.1 to 432 mg/L with an average of 45 mg/L. About 13% of groundwater samples shows high values of nitrate exceeding the allowable limit for drinking purpose (50 mg/l). High concentration of nitrate were observed in Dug wells 13,

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18, 20 and boreholes F3 and F11. Chloride in drinking water is not generally harmful to human unless present in higher concentration. High concentration of Cl^- renders salty taste to water and beverages. Consumption of high-chloride water leads to health issues related to hypertension, ventricular hypertrophy, osteoporosis, renal stones and asthma [6]. The chloride concentration of groundwater samples in the study area ranged from 12 to 2627 mg/L with an average value of 280 mg/L. From the concentration of chloride in groundwater samples, it was found that 36% of the total sample have chloride content above the allowable limit of WHO. Fluoride is one of the trace element found in water and which 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 in groundwater samples of the study area varied between 0.1 and 9.4 mg/L with an average value of 3.2 mg/L. From the fluoride contents of groundwater samples, it is found that most of the samples (69 %) have fluoride content above the allowable limit of WHO (1.5mg/L) indicating the unsuitability for drinking purpose (Table 2).

Table 2. Descriptive statistics and comparison with WHO values.

Water Quality Parameters	Min.	Max.	Mean	Median	Standard Deviation	WHO Standard Limit [25]	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

Total Hardness (TH)

The Total Hardness of water is mainly caused by the presence of cations such as calcium and magnesium and of anion such as bicarbonate, chloride and sulfate in the water [32]. TH of water can cause scaling of pots and boilers, closure to irrigation pipes and may cause also health problems to humans such as kidney failure [23]. It is an important water quality parameter which is often used to ascertain the suitability of water for drinking purpose. 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).

$$TH\ (as\ CaCO3) = 2{,}497 * Ca^{2+} + 4{,}115 * Mg^{2+} \quad (12)$$

The computed values of TH ranged from 55.4 to 2096.5 mg/L with an average value of 448.2 mg/L. The maximum allowable limit of TH for drinking purpose is 500 mg/L and the most desirable limit is 100 mg/L [25]. 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 shows that 28.6 % of groundwater sample were above the maximum permissible limit of 500 mg/L. Furthermore, based on TH values of water, [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 classification proposed by [34], the majority of groundwater samples (73.8 %) indicates very hard water while 23.8 % and 2.4 % represents respectively hard and soft water.

Total Dissolved Solids (TDS)

Total dissolved solids It 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 are generally not harmful to human beings but high concentration of these may affect persons who are suffering from kidney and heart diseases [20]. 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 [25]. 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 [33] classified water, using TDS values, into five categories which are represented as very fresh (0-250 mg/L); fresh (250-1000mg/L); brackish (1000-10000 mg/L); saline category (10000-100000 mg/L) and brine category (TDS > 100000 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.

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

Parameters	Range	Water Type	Number of Samples	% of Samples
TH (mg/L)	< 75	Soft	1	2.4
	75 - 150	Moderately hard	0	0
	150 - 300	Hard	10	23.8
	> 300	Very hard	31	73.8
TDS (mg/L)	0-250	Very fresh	1	2
	250 - 1000	Fresh	28	67
	1000 – 10000	Brackish	13	31
	10000-100000	Saline	0	0
	> 100000	Brine	0	0

Water Quality Index (WQI)

Water quality type for drinking purpose of the study area were also determined using the Water quality index. 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]. 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 469.2 with an average value of 99.3. 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 11.9% and 52.4% of groundwater samples. However, 33.3% shows poor water and only one sample (2.4%) Well 18 located in Nianing show groundwater which is unsuitable water for drinking purpose. The unsuitability of groundwater observed in well 18 is due to the pollution in this well with high nitrate content (432.2 mg/L), very high electrical conductivity (8880µS/cm) and the high content of ions such as Na^+, Ca^{2+}, Cl^-, SO_4^{2-} and F^- which recpectively 1106 mg/L, 562 mg/L, 2626 mg/L, 433 mg/L and 2 mg/L.

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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

4.3. Groundwater Suitability for Irrigation

Sodium Adsorption Ratio (SAR)

Sodium adsorption ratio (SAR) is an important water quality parameter to measure the suitability of water for irrigation use, because high sodium concentration can reduce the soil permeability and soil structure [33]. Excessive sodium content relative to the calcium and magnesium may deteriorate the soil characteristics, thereby reducing the soil permeability and inhibiting the supply of water needed for the crops [3]. The use of water with high content of SAR may require soil amendments to prevent long-term damage of soil because sodium in water can displace the calcium and magnesium in soil leading to a decrease in infiltration and permeability of the soil to water [30]. As proposed by [36], 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 (95.2%) in the study area fall in the excellent water category and the remaining 4.8% fall in good category of water indicating that groundwater of the study area is suitable for irrigation purpose. The United States Salinity Laboratory diagram was also used to assess the suitability of groundwater samples for irrigation purpose. The plot of chemical data on the USSL salinity diagram (Figure 6) reveals that the majority of the groundwater samples (64.3%) fall in the field C3S1, indicating high salinity and low sodium water which can be used for irrigation for almost all type soil with little danger of exchangeable sodium [37,38]. However this kind of water requires good drainage because the high salinity may affect crop growth and can cause osmotic effects and nutritional disorders. In addition, 16.7% of groundwater samples fall in C2S1 category indicating medium salinity and low alkalinity water which can be used for irrigation, where moderate amount of leaching occurs and moderate permeability with leaching soil [20]. One sample (2.4%) fall in the field C1S1 category indicating low salinity and low alkalinity which can be used to irrigate most of soil and crops with less negative impact [36]. About 2.4% of groundwater samples fall in the category C3S2 which can used to irrigate salt tolerant and semi tolerant crops under favorable drainage condition [30]. The remaining groundwater samples fall in the field C4S1 (2.4%), C4S2 (7.1%), C4S4 (4.8%) indicating very high salinity and low to very high alkalinity. The C4S4 water category representing very high salinity and very high alkalinity is observed in borehole (B15) and Dug Well (DW18) which respectively present a high salinity of the water (EC= 4500 µS/cm) with high chloride and sodium contents (Cl=1107 and Na= 787mg/L) and anthropogenic pollution with high nitrate and sulfate contents (NO3=432 mg/L, SO4 = 432 mg/L). Water with high salinity is generally unfit for irrigation use in the farmland where restricted drainage occurred. Hence, usage of such water having high salinity for irrigation may affect the yield of crops.

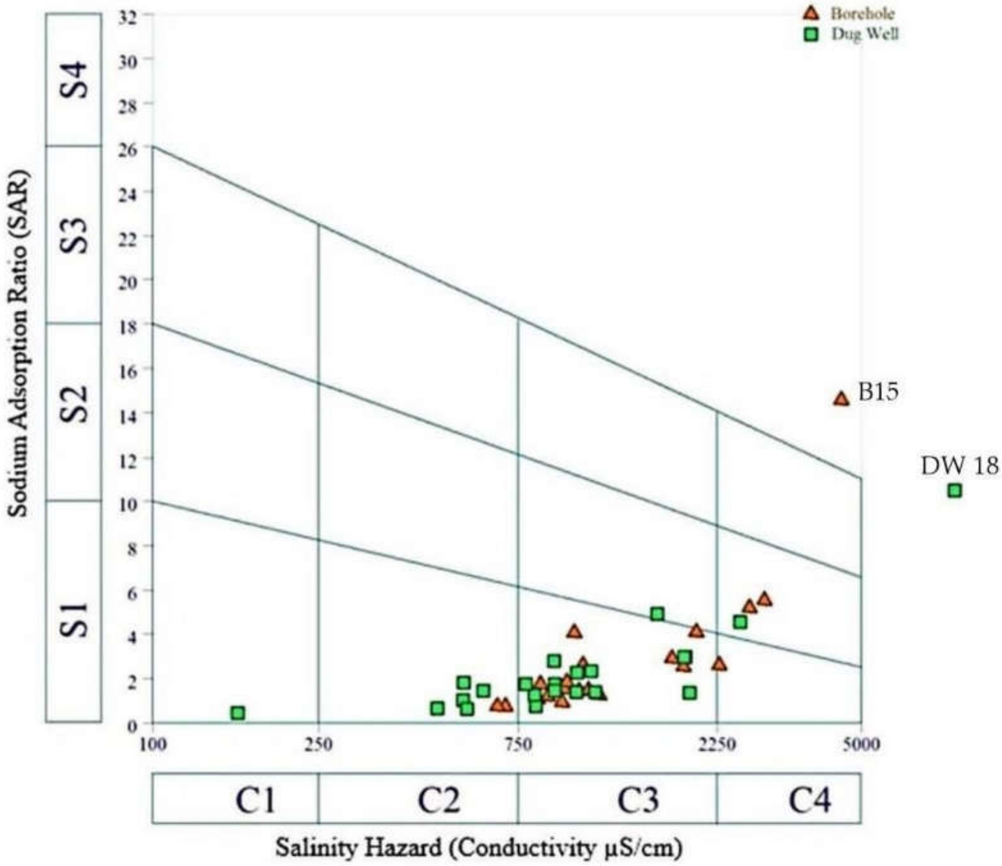

Figure 6. US salinity diagram of groundwater of the study area.

Sodium Percentage (%N)

Sodium in soil is considered vital for determining groundwater suitability for irrigation purpose because Na^+ reacts with soil to reduce its permeability and support little or no plant growth [14]. 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 eventually resulting in soil with poor drainage and thus limits air and water circulation during wet conditions [41,42]. The sodium in irrigation waters is generally denoted as percent of sodium. The computed values of %N in the study area range from 17.1 to 75.7% with an average value of 34.5 %. Generally, water is classified as excellent water, if the %N values are less than 20%, good water, if the %N values ranged from 20 to 40%, permissible water, if the %N values ranged between 40 and 60%, Doubtful water, if the %N values varied from 60 to 80%, and unsuitable water, if the %N values are more than 80%. According to this classification, most of the groundwater samples fall in good (61,9%) to excellent (11,9%) water type for irrigation while 21.4% and 4.8% fall respectively into permissible and doubtful water category. In addition, the diagram of [26] was used to study the integrated effect of electrical conductivity and sodium percentage. The plot of groundwater samples on the Wilcox diagram indicate that 21% and 57% fall respectively in the field of excellent to good and in the field of good to permissible water categories indicating that the majority of groundwater is suitable 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 sampling points are characterized respectively by high salinity of water with high chloride and sodium contents (Cl=1107 and Na= 787

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mg/L) and an anthropogenic pollution with high nitrate and sulfate contents (NO3=432 mg/L, SO4 = 432 mg/L).

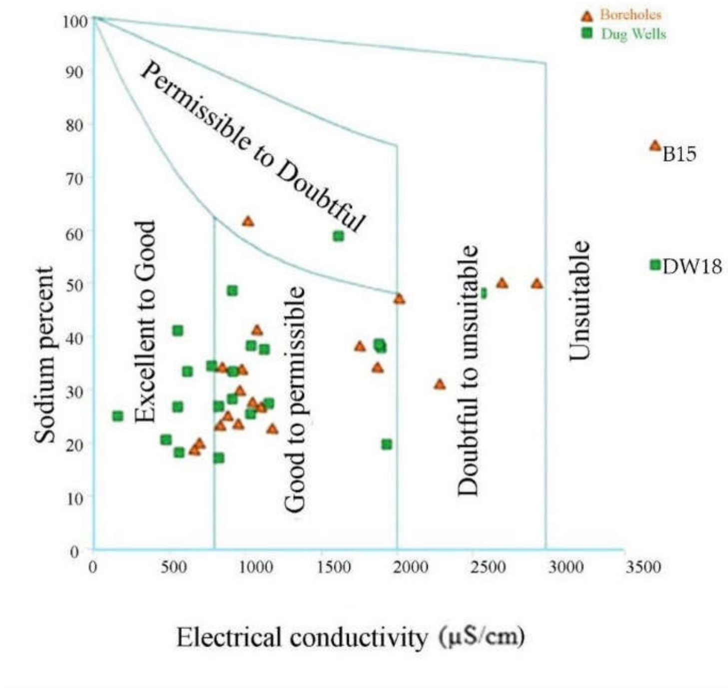

Figure 7. Plot of sodium percent versus Electrical conductivity.

Residual Sodium Carbonate (RSC).

The residual sodium carbonate (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, which in turn leaves a black stain on the soil surface on drying [3,37]. The excess sum of carbonate and bicarbonate in water over the sum of calcium and magnesium influences the suitability of water for irrigation. Therefore, the RSC is an important water quality parameter widely used to assess the suitability of water for irrigation. [41] classified water for irrigation as good if the RSC values are less than 1.25, doubtful, if the RSC values range from 1.25 to 2.50 and unsuitable, if the RSC values are greater than 2.50. In the study area, 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 (95.2%) of the study area fall in good category of water indicating their suitability for irrigation use, while 4.8% fall in doubtful water category.

Permeability Index (PI)

The Permeability Index (PI) is an important water quality parameter which determines the quality of irrigation water in agricultural area. Long-term use of groundwater for irrigation purposes affect the permeability index (PI) of groundwater, which in turn is influenced by Na^{+}, Ca^{2+}, Mg^{2+} and HCO_3^{-} concentrations [6]. The Permeability Index is developed by [42]. According to [42] with PI value greater than 75% is categorized in Class I which indicates excellent water quality for irrigation, Class II, if the PI varied from 25 to 75% indicating good water quality for irrigation and Class III, if the PI values of water are less than 25% indicating unsuitability of water for irrigation. In the study area, the computed values of PI ranged from 30 to 84 with an average value of 54. Based on the Permeability index values, all the groundwater samples of the study area fall in Class I (7.1%) and

Class II (92.9%) indicating respectively excellent and good water categories which are suitable for irrigation purposes.

Kelly Ratio (KR)

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

Magnesium Ratio (MR)

Magnesium ratio is an expression of Magnesium Hazard which was developed by [44] to assess the suitability of water for irrigation use. High index of magnesium hazard value (> 50%) in irrigation water has an adverse effect on the crop yield as the soil becomes more alkaline. The computed values of magnesium ratio of the study area is varied from 9.6 to 74.6% with an average value of 41.7%. The values of Magnesium ratio exceeds the value of 50 in about 40.5% of groundwater samples indicating unsuitable water for irrigation purpose while 59.5% of groundwater samples have a Magnesium ratio less than 50 suggesting that they are suitable for irrigation use.

4.4. 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, [45] diagram is used to identify the source of dissolved chemical constituents of water. This diagram is an effective tool to determine the main natural process and dominant factors controlling groundwater chemistry, which are precipitation dominants, rock dominants or rock-water interaction and evaporation dominants. It is widely used in many countries to identify the major factors controlling the chemical composition of water in different geological environment [3,19,46]. 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 in the study area. However, some groundwater samples are located in the evaporation dominance zone indicating that evaporation plays an important role in the variation of groundwater chemistry in the study area (Figure 8). To better understand the contribution of water-rock interaction in the variation of the chemical composition of waters, other diagrams 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].

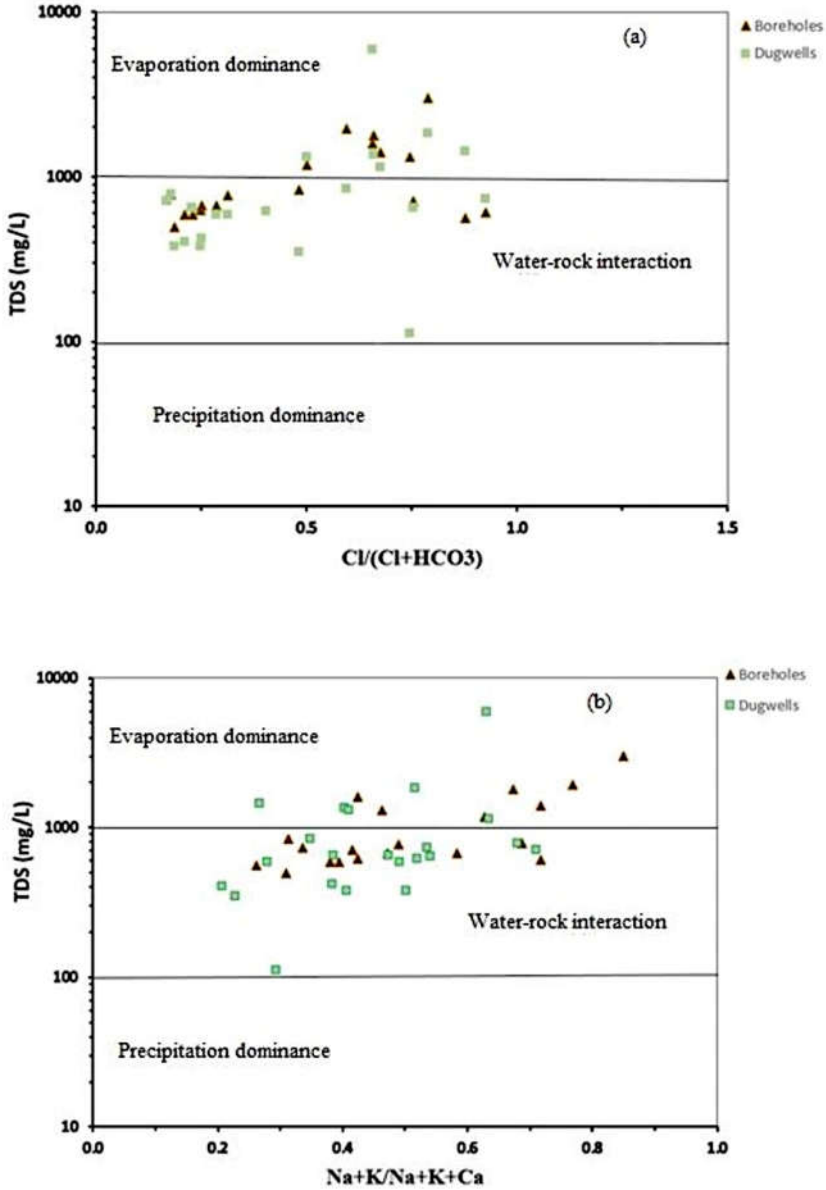

Figure 8. Gibbs plot (**a**) between TDS versus Cl^- / (Cl^-+HCO_3^-) and (**b**) between TDS versus (Na^++k^+) / (Na^++K^++ Ca^{2+}).

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 [16,47,48]. 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 area ranged from 0.34 to 9.41. About 38.10% of groundwater samples shows Ca^{2+}/Mg^{2+} ratio higher than 2 which is indicative of contribution of silicate minerals dissolution, whereas 21.43% 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

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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, indicating that dissolution of carbonate minerals and weathering of silicates are not the only sources of calcium and magnesium in the water. The plot of Na^+ vs Cl^- (Figure 9) show that some samples plot along the 1:1 line suggesting the dissolution halite which can be a source Na^+ and Cl^- in groundwater. However, most of groundwater samples fall below the 1:1 line indicating 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 several previous studies [50] to be the or one of the main factors that control 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^-) versus (Na^+ + K^+) - Cl^- (Figure 10). If cation exchange is an important process controlling 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^- indicate that most of groundwater samples falls on or close a straight line with a slope of -1.18 and R^2 = 0.96 indicating the occurrence of reverse ion exchange in groundwater.

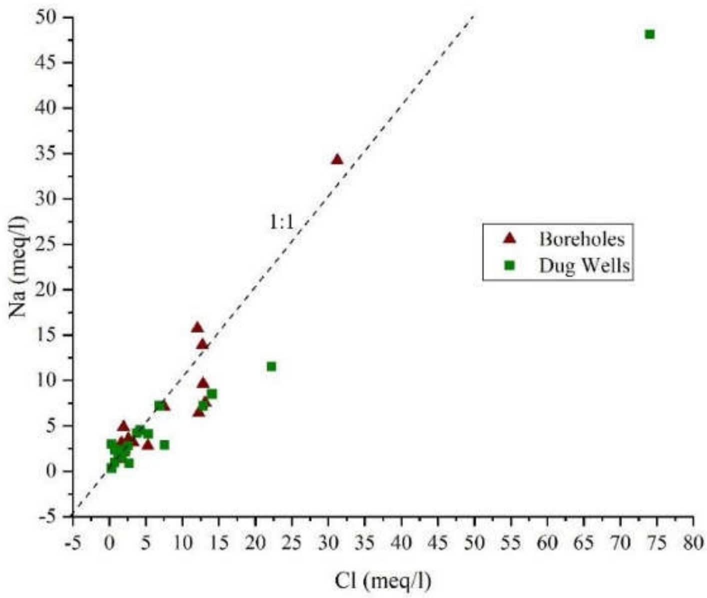

Figure 9. Scatter plot of Na versus Cl.

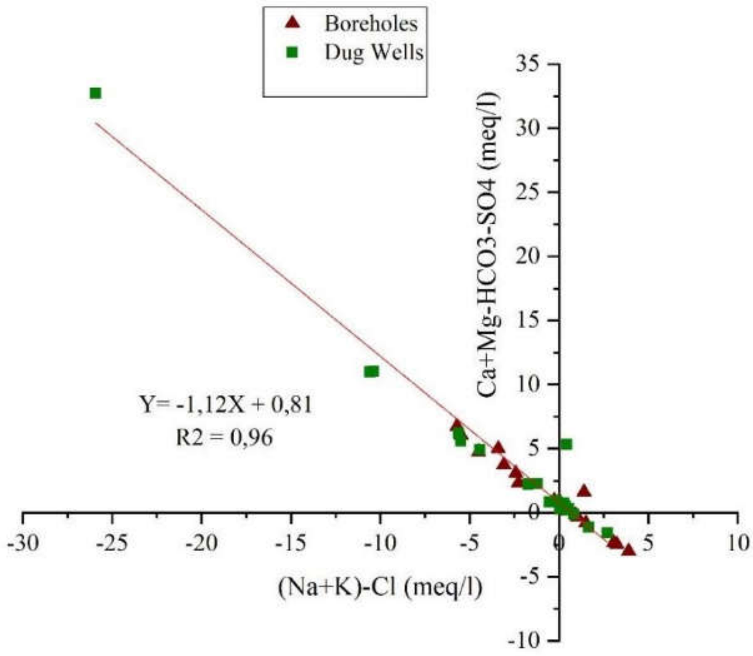

Figure 10. Scatter plot between (Ca^{2+} + Mg^{2+} - SO_4^{2-} - HCO_3^-) versus (Na^+ + K^+) - Cl^-

Hydrochemical Facies

Hydrochemical facies are water masses that have different geochemical attributes and are helpful for comparing the origins and distribution of groundwater. Results of chemical analysis of groundwater samples have been plotted on the diagram proposed by [52] to identify the main groundwater types in the study area. 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-HCO3, mixte Ca-Na-Mg-HCO3 and mixte Ca-Na-Cl (Figure 11).

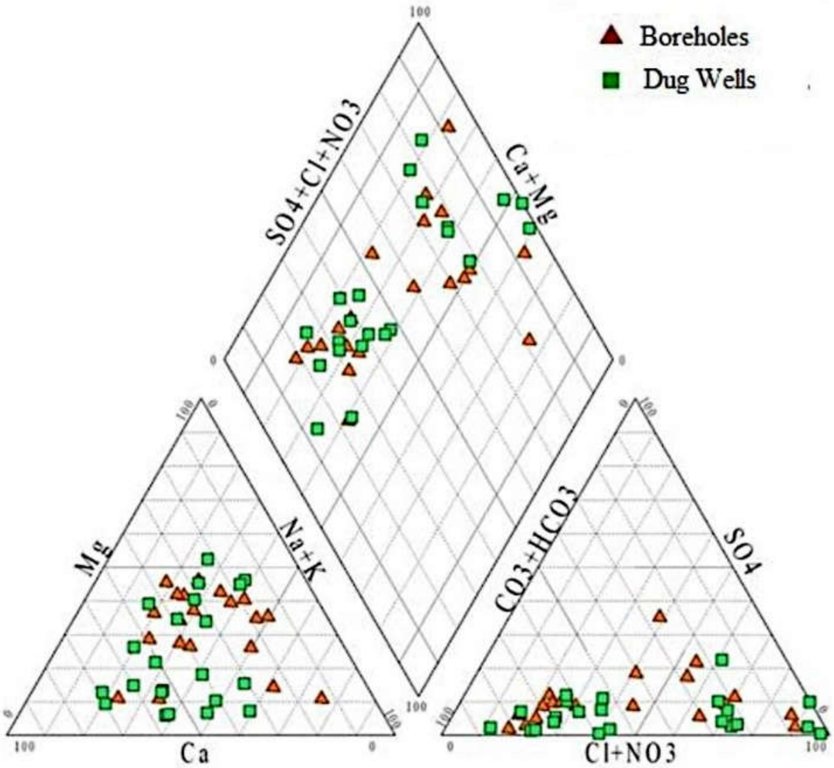

Figure 11. Piper plot s illustrated with groundwater types of the study area.

5. 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 in situ measurements of pH and electrical conductivity indicate respectively that the waters are neutral to slightly basic and the 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 that several types of facies of which mixte Na-Ca-Mg-HCO_3 constitutes the dominant facies. The classification of water according to TH and TDS for human consumption reveals respectively that the majority (73.8%) of waters are very hard, 23.8% are hard and 2.4% are soft while for TDS the majority (67%) of waters is in the soft water category. Water quality index (WQI) used to quantify the overall quality of groundwater for drinking water indicate that the majority of groundwater samples fell under excellent water and good water categories with respectively 12% and 52% of groundwater samples. In addition the comparison of ionic concentration with the standard limit of WHO, 2011 shows that most of groundwater samples are below the WHO permissible limits for drinking water indicating the suitability of groundwater for drinking purpose in the study area. Evaluation of water quality for irrigation is of utmost importance since agriculture is the main economic activity in the study area. Hence, the suitability of groundwater were determined using several water quality parameters. The computed values of Sodium adsorption ratio (SAR), sodium percentage (%N), Residual Sodium Carbonate (RSC), Kelly Ratio (KR) and Magnesium Ratio (MR) reveals that most of groundwater samples are suitable for irrigation purpose. Furthermore, the plot of groundwater samples on the US salinity diagram indicate that the majority of groundwater samples (64%) fall in the field C3S1, indicating high salinity and low sodium water which require proper drainage. Besides, Wilcox diagram reveals that 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 indicating that the majority of groundwater is suitable for irrigation purpose. The remaining groundwater samples fall in the permissible to doubtful (5%), doubtful to unsuitable (12%) water category and unsuitable water category (5%). The plot of chemical analysis results of groundwater samples on the Gibb diagram and the analysis and interpretation of ionic ratios and others binary diagrams indicate that rock weathering with some extent of groundwater evaporation, ion exchange, dissolution of mineral are the main processes controlling groundwater composition in the study area. This study shows that the waters of the study area are, for the majority of the sampled points, suitable for human consumption and for agricultural use. However, regular monitoring of the evolution of water quality is necessary to limit the salinization linked to the return of irrigation water for sustainable use of water resource in the study area. Furthermore, a regulation of the use of fertilizers in the agricultural area must be applied to avoid an increase in nitrate pollution that could result in a deficit in the supply of drinking water to the population.

Acknowledgments: The authors would like to thank the French Embassy for providing financial resources to go to the field for data collection. The authors are also very grateful to the laboratory of Chrono environment Laboratory at the University of Bourgogne French Comte, Besancon, France that performed the chemical analyses. The authors would also like to thank the anonymous reviewers for their valuable comments to improve the quality of the manuscript.

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