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Assessment of Groundwater Quality for Drinking and Irrigation Uses in the Samba Dia Area, Central West Senegal

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Abstract

In the Sahelian zone in Africa, groundwater is the main source of drinking water for domestic, industrial, and agricultural uses. The groundwater of the Samba Dia sandy aquifer was assessed for understanding processes controlling the hydrogeochemistry and its drinking and irrigation suitability, on the basis of various water quality parameters. For the present study, thirty-three groundwater samples were collected in wells of the study area during the dry season in March 2021 and subjected to analysis for chemical characteristics (major ions), pH, electrical conductivity (EC), and total dissolved solids (TDS). Gibbs plot depicts that the process of ionic exchange is mainly due to the dissolution of water-rock interaction. The Piper diagram indicates a largely dominant sodium chloride facies with 70% of the groundwater samples followed by calcium chloride facies (18%) than calcium bicarbonate facies (12%). Analytical results of hydrogeochemical parameters of groundwater samples reveal that the majority of samples are within the World Health Organization safety range for drinking water. TDS and electrical conductivity (EC) values of groundwater indicate that 70% and 61% are safe for drinking water, respectively. Sodium percentage (% Na), Sodium Adsorption Ratio (SAR) values, and Ca/Mg ratio were calculated and compared with the standard guideline values recommended by the World Health Organization and agricultural water standards. This study shows that the groundwater in the area is mostly chemically suitable for drinking and irrigation, although some wells at the edge of the area exhibit signs of progressive salinization and traces of pollution.

Keywords

Samba Dia, Groundwater, Hydrogeochemistry, Suitability, Drinking, Irrigation

1. Introduction

Groundwater is essential for human life and socio-economic development. In the area of Samba Dia, located 100 km South of Dakar (Western Senegal), groundwater is the main source of drinking water and irrigation. Hence, determining its usefulness for domestic and agricultural purposes requires an in-depth understanding of its chemical quality. The Quaternary aquifer remains the primary source of exploited groundwater because the Paleocene and Maastrichtian aquifers are not of hydrogeological interest since they contain brackish to saline water [1].

However, natural (saltwater intrusion and drought) and anthropogenic sources threaten this Quaternary aquifer [1] [2] [3]. Anthropogenic sources include uncontrolled and abusive abstraction because of population growth [4] [5] [6] [7], which has resulted in the depletion of the water table. A direct consequence of this could be the observed salinization of the Quaternary surface aquifer due to its proximity to seawater to the west and the hypersaline waters of the Saloum estuary to the east and south. The upwelling of seawater in these river systems can reach tens of kilometers inland, contaminating the surface water. Moreover, the recurrent droughts observed in this region over the years have led to a general decrease in rainfall and a progressive disappearance of surface water [4] [5] [8] [9] [10]. In this peculiar situation, examination of the potential for groundwater use by carrying out a hydrogeochemical study becomes essential. The latter consisted of assessing of the chemical processes responsible for water mineralization and appreciating the physical and chemical quality of the groundwater. The main objectives of this study are 1) to determine the origin of the chemical composition of groundwater in the area and 2) evaluation of water suitability for drinking and irrigation purposes. Analysis of groundwater physicochemical parameters and chemical constituents sheds light on groundwater's geochemical evolution. We also evaluate the suitability of groundwater for drinking using salinity (expressed by EC), pH, TDS, and major ions (chloride, sodium, sulfate, and nitrate). Furthermore, we evaluate water suitability for irrigation with the percentage of sodium, the sodium absorption ratio (SAR), and the calcium/magnesium ratio. Then, the presentation of geochemical data using graphical charts such as the U.S. salinity diagram and Wilcox salinity diagram helps to recognize various hydrogeochemical types in groundwater. Finally, the results were compared with WHO standards [11] [12] for groundwater use.

2. Materials and Methods

2.1. Presentation of the Study Area

2.1.1. Geographical and Climatic Context

The Samba Dia area is located in the municipality of Fimela in the department of Fatick, Senegal (**Figure 1**). It overlaps between the small coast (Mbour) and the Saloum Delta (Fatick). It is located between latitudes 14˚05' and 14˚50' North and longitudes 16˚25' and 17˚00' West. A flat relief characterized the topography

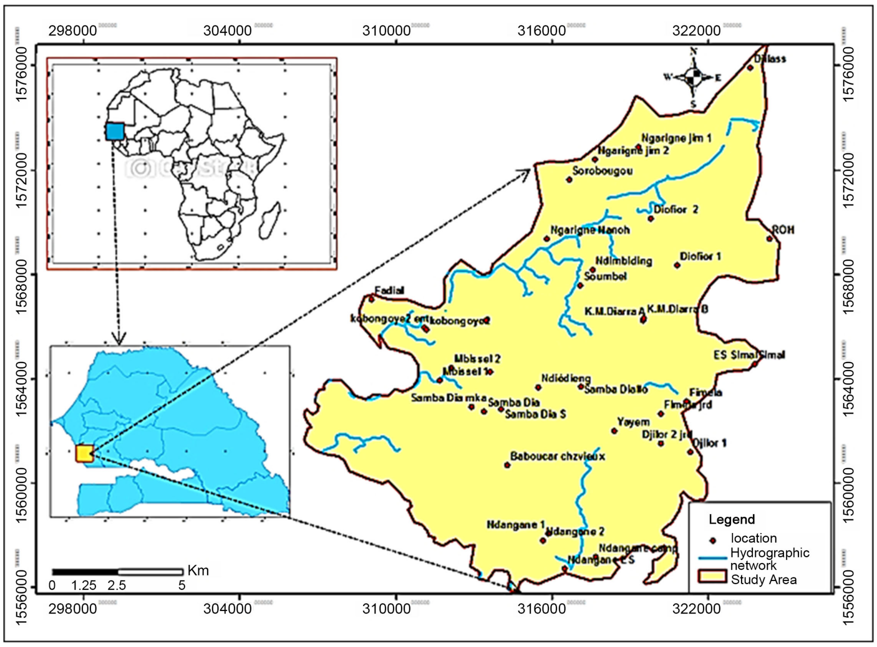

Figure 1. Location and sampling network of the study area.

with a slight slope towards the lower areas of the Saloum [13]. Shallow NE-SW trending talwegs cut into the southwest and northern edges. The boundary between the area and the "tannes" (corresponding locally to vast areas of denuded saline soils) is often a more or less steep slope, giving the area a plateau-like appearance with an altitude of the "tannes" not exceeding 2 to 3 m [5]. A persistent drought that began in 1969 [9], leading to a general decline in rainfall characterized the region. The region is in a transition zone subject to the influence of the maritime trade winds, the harmattan, and the monsoon. The climate is of the tropical Sudano-Sahelian type, characterized by two main seasons:

- a dry season (from October to June) during which the country is subject to the influence of two main atmospheric currents (Trade Winds and Harmattan);
- a rainy season of three to four months (from June/July to September) influenced by the monsoons, during which rainfall is recorded over the entire area.

The average annual rainfall in the area was around 600 mm from 1988 to 2018 according to climatic information collected by the National Agency for Meteorology and Civil Aviation (ANACIM) at its station in Fatick. It is important to note that the peak rainfall is regularly recorded between August and September, which are the rainiest months. In Fatick, potential evaporation is estimated at an average of 2200 mm/year and the average minimum and maximum temperatures vary from 20˚C to 40˚C. Relative humidity varies from 60% to 95% and is high from July to October.

2.1.2. Geological and Hydrogeological Setting

In the study area, the post-Paleozoic sedimentary series of the Senegal-Mauritania basin is well represented. It is known without interruption from the Triassic to the Quaternary thanks to oil and hydraulic drilling [14]. The detrital formations of the Campanian-Maastrichtian age are composed of lignite-bearing sands, clay, and sandstone [15]. The carbonate formations correspond to limestones of the Paleocene and Eocene ages containing marl and clay [16]. These formations of variable thicknesses sink from west to east and are surmounted by sands containing a water table and a recent lateritic cuirass of mio-plio-quaternary age [5] [15]. The Samba Dia aquifer is essentially made up of fine to medium-grained quartz sand from the Quaternary, to which are added, in a lesser proportion, clays, and various coarse elements: ferruginous gravel, shells, and pebbles. The lower limit is made up of compact marl and marl-limestone [5] [8] [17] which can be clayey in certain sectors. The strength of the Miocene and Plio-Quaternary formations is on average between 20 and 30 m and is maximal in the Ndagane area culminating at 40 m [5] [16]. All of the wells at the sampling site tap into the Quaternary surficial aquifer at a shallow depth, often between 5 and 10 meters. There are no functional water wells in this site today because the other Eocene, Paleocene, and Maastrichtian aquifers present in the area are not of great hydrogeological interest with brackish to salty waters [16] [18]. The study of hydrodynamic parameters gives respectively the transmissivity and the coefficient of permeability average values of about 3.5×10^{-3} $m^2 \cdot s^{-1}$ and 1.80×10^{-4} ms^{-1} while the effective porosity is around 22% on average. These hydrodynamic parameters show that the aquifer of the Samba Dia area is very permeable, especially in its upper part [5].

The piezometric map (**Figure 2**) of the area shows that groundwater flows are divergent on either side of a divide passing through the center of the map. The piezometric pattern highlights three depression zones located in Kobongoye, Ndangane and Djilor and a dome zone at Diofior. The calculation of the hydraulic gradient gives a low value on the Samba Dia-Kobongoye (West) and Yayeme-Djilor (South) axes. On the Diofior-Ngarigne axis located at the eastern end, the value of the gradient increases and the izopiezes are separated. This reflects a high flow velocity and low transmissivity of the aquifer.

2.2. Sampling and Chemical Analysis

Groundwater samples were collected from 33 wells during March 2021 in 250 mL polypropylene bottles and stored under optimal conditions. Electrical conductivity (EC), temperature (T˚C), Total dissolved Solid, and pH were measured *in situ* with a portable multi-parameter WTW 350i. An acoustic and light signal probes the measurement of the depth of water in the wells. Major anions and cations were determined at the hydrochemistry laboratory of the geology department of Cheikh Anta Diop University. We executed the analyses using the ion chromatography method with AQUION-DIONEX. The exchange processes were carried out via AS14 A-AERS 500 columns for anions (F^-, Cl^-, NO_3^-, SO_4^{2-}) and CS12 A-CERS 500 for cations (Na^+, K^+, Mg^{2+}, Ca^{2+}).

A THERMO Ice 3000 AAS was used to determine iron and a 0.05 N solution of sulphuric acid was employed to analyze carbonate using the titrimetric method. Several hydrogeochemical methods are used to process the chemical analysis.

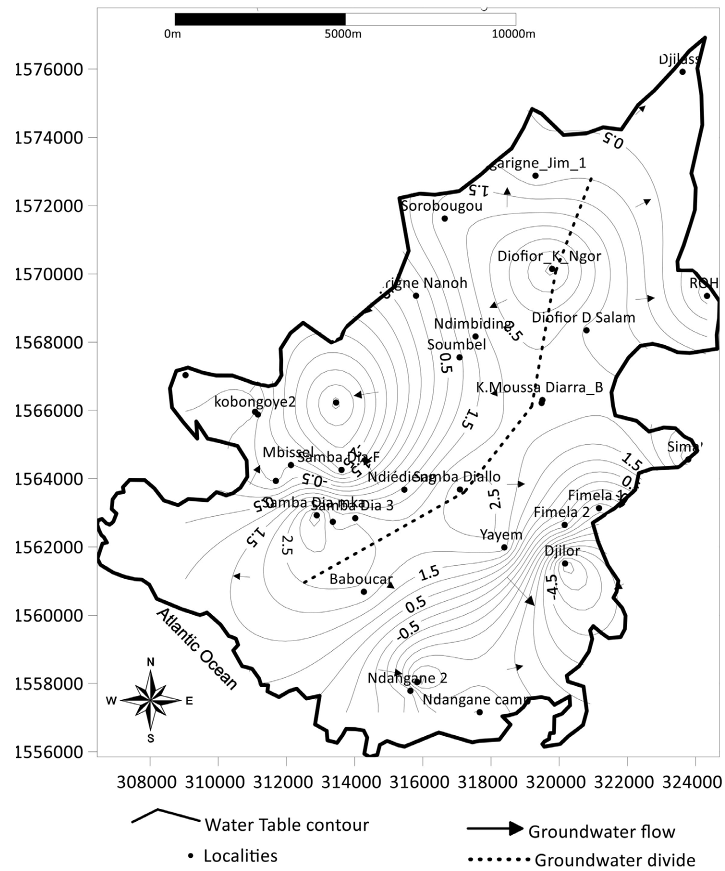

Figure 2. Piezometric map of the Samba Dia aquifer in March 2021.

These include the Piper diagram [19] for determining chemical facies and the Gibbs diagram, which is used to qualify the different mineralization processes, the percentage of sodium, and the Wilcox diagram and the Sodium Absorption Ratio (SAR) to measure the suitability of groundwater for irrigation. Besides, we studied major ions and physicochemical parameters in detail to assess the suitability of groundwater for drinking based on the standards indicated by the WHO.

3. Results and Discussions

3.1. Groundwater Hydrogeochemistry

The results of the hydrogeochemical analyses are reported in **Table 1**. The minimum, maximum and average values of hydrochemical parameters and major elements are indicated in **Table 1** to compare with the WHO standard and to check the suitability for different uses.

3.1.1. Gibbs Diagram

The origin of dissolved ions can be assessed with sample plotting [20], [21] recommended a simple plot of TDS versus $Na^+/(Na^+ + Ca^{2+})$ and $Cl^-/Cl^- + HCO_3^-$ weight ratio to differentiate the influences of rock-water interaction, evaporation, and precipitation on water chemistry. The Gibbs diagram (**Figure 3(a)** and **Fig-**

ure 3(b)) then highlights three (3) domains or media that characterize the mineralization process: evaporation (1), water-rock interaction (2), and precipitation (3).

In the study area, the data points suggest that the chemical weathering of rock-forming minerals is the dominant factor that essentially controls groundwater chemistry. Higher evaporation due to chemical weathering and or anthropogenic activities increases TDS and samples tend to move from the rock dominance to the evaporation zone [22].

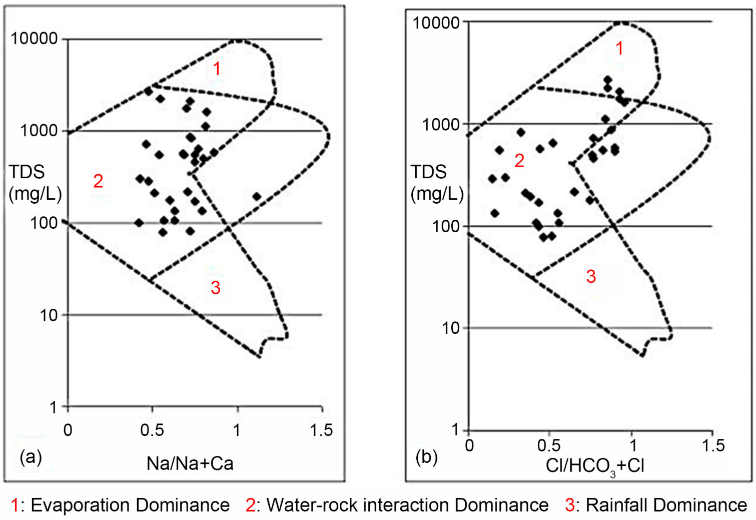

Figure 3. Mechanism controlling groundwater chemistry, (a): TDS vs. Na/Na + Ca and (b): TDS vs. $Cl/HCO_3 + Cl$.

Table 1. Descriptive statistics of hydrogeochemical data.

Variables	WHO standard	Mean	Minimum	Maximum	units
T˚C	-	28.97	24.50	35.30	˚C
pH	6.5 - 8.5	8.3	5.9	10.7	
TDS	500 - 1500	7406	78.00	14734	mg/L
c25˚C	1500	12653.5	107.00	25200.00	µS/cm_
Ca	75 - 200	236.735	5.76	467.71	mg/L
Mg	50 - 150	247.895	0.83	494.96	mg/L
Na	150	2240.92	9.85	4472	mg/L
K	12	105	0.30	209.7	mg/L
HCO_3^-	250	225.7	12.20	439.20	mg/L
Cl	250 - 600	4098.755	13.26	8184.25	mg/L
SO_4	250	278.975	0.95	557	mg/L
NO_3	45	443.33	2.86	883.8	mg/L
SAR	≥26	18.69	0.17	37.22	Meq/L
%Na	≥60	42.08	2.29	81.87	%
Ca/Mg	≥1	09.60	0.34	18.87	Meq/L

3.1.2. Piper Diagram

The Piper diagram (**Figure 4**) allows a representation of the cations and anions on two specific triangles whose sides show the relative contents of major ions in the water [23]. We can observe that Na^+ and Cl^- ions are dominant. The results of water analyses in the Samba Dia aquifer are plotted on the triangular diagram [23], which shows the impact of lithological facies on water quality and also allows us to estimate the percentages of chemical elements and their classification. Three main water types have been identified based on varying ionic major concentrations. Majority of groundwater samples (70%) represent NaCl type. Minor representations (12%) and (18%) are also noted corresponding respectively the Ca-HCO_3 and Ca-Cl types. Na-Cl water type has a wide range of electrical conductivities. Most of samples (64%) with a Na-Cl water type have a low to medium mineralization, with an electrical conductivity of less than 1500 µS/cm. These wells are located in the central part of the study area where the water is soft. The geochemical signature of this type is characteristic of water in the recharge zone. Na-Cl water type for these water samples is related to other processes (water rock interaction) rather than mixing with saline water. The remaining 36% of the samples have EC values above 1500 µS/cm, half of them between 1500 and 3000 µS/cm. The EC values for Na-Cl type waters can exceed 3000 µS/cm and reach 22500 µS/cm at water points located in the peripheral zones near salty surface waters on a South-East to North-East axis such as at Ndangane (P8), Fimela (P12), Yayem (P13), Diofior Darou Salam (P24A) with high chloride concentrations respectively of 8184 mg/L, 666 mg/L, 433 mg/L and 1017 mg/L. These water samples are under the influence of salty surface waters

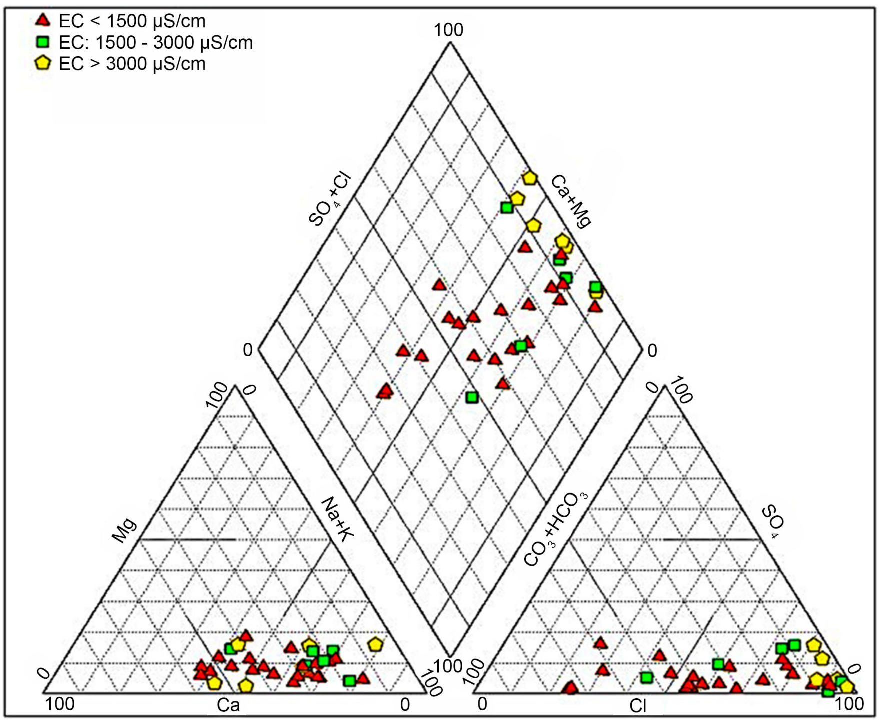

Figure 4. Piper diagram of the groundwater chemistry in March 2021.

or saline intrusion with this high chloride content. Some samples with a Ca-Cl water type have low mineralization with an EC of 140 µS/cm at Fadial (P22), 155 µS/cm at Kabongoye (P2) and 366 $\mu S \cdot cm^{-1}$ at Ndiedieng (P16). For these water types, two samples located in the Centre of the study area, have very high EC values at Djilass (P26) 4410 µS/cm and K Moussa Diarra (P18B) 5800 µS/cm with chloride concentrations of 1368 mg/Land 1620 mg/L. High Chloride values and Ca-Cl water type in wells P26 and P18B are associated with high nitrate contents, ranging between 71 and 668.6 mg/L and, therefore, are subject to local contamination (salty groundwater under freshwater and/or anthropogenic pollution) of the groundwater. Only one well (P31) has sodium bicarbonate facies with an EC of 1124 $\mu S \cdot cm^{-1}$ and a chloride concentration of 171 mg/L.

3.1.3. Base Exchange Index

The base exchange index (Bei) allows for highlighting the modifications of the water chemistry during its underground journey. The Bei is the ratio between the exchanged ions and the ions of the same nature originally existing in the water. It is obtained by the following Equation (2) [24] [25].

$$\text{Bei} = \left[r\text{Cl} - r\left(\text{Na} + \text{K}\right) \right] / r\text{Cl} \tag{2}$$

where Bei represents the base exchange index and is unitless; *r*Cl is the concentration in milliequivalents of chloride ions, $r\,(Na^+ + K^+)$ is the concentration in milliequivalents of the sum of sodium and potassium ions.

- If the Bei is negative, then Ca^{2+} and Mg^{2+} ions in the water are exchanged for K^+ and Na^+ ions in the surrounding formations.

- If the Bei is positive then the Na^+ and K^+ ions of the water are replaced by the Mg^{2+} and Ca^{2+} ions of the surrounding formations.

- If the Bei = 0 then there is an equilibrium between the chemical compositions of the water and the surrounding soil. In the Samba Dia Quaternary aquifer, the Bei calculation reports that precisely 60.60% of the groundwater samples have a negative Bei. These negative Bei values indicate that calcium (Ca^{2+}) and magnesium (Mg^{2+}) ions in the groundwater are exchanged by potassium (K^+) and sodium (Na^+) ions in the reservoir formation. These wells are mainly located in the localities bordering the zone such as Ndangane, Djilor, Mbissel, Kobongoye, Simal, Roh, etc. On the other hand, in the wells located in the central axis of the zone, the Bei are generally positive, *i.e.*, 40.40% of the groundwater points surveyed. These Bei indicate that in this part of the aquifer, Na^+ and K^+ ions in the water are replaced by Ca^{2+} and Mg^{2+} ions in the surrounding formation.

3.2. Suitability of Groundwater for Drinking Purposes

3.2.1. Physico-Chemical Parameters

The hydrogen potential: pH is a very important parameter for assessing groundwater chemistry. It allows to evaluate the degree of acidity and alkalinity of the water in a given aquifer. The pH standard for drinking water is set between 6.5 and 8.5 [11]. The pH value measured *in situ* varies between 5.9 and

10.7 between Samba Dia and Diofior villages. The highest pH values are found in peripheral areas such as Djilass, Diofior, Ndagane, Mbissel. These values often exceed the WHO standard (8.5) and indicate excessive alkalinity, with water often unfit for consumption. On the other hand, we find low pH values of 5.90, 5.95, and 6.33 respectively at Samba Dia (P5), Ndangane (P7) and Yayeme (P13). These are wells whose pH is outside the norm in terms of acidity.

Electrical Conductivity: It expresses the capacity of a substance to conduct electric current. It is an important parameter to assess the degree of salinity of groundwater. The limit value of conductivity is set at 1500 uS/cm according to the WHO standard [11]. In our area, groundwater conductivity values vary between 107 (Djilor) and 25200 µS/cm (Ndangane) from the center of the lens to the adjacent localities. The variation in electrical conductivity in the area was associated with the Piper diagram (**Figure 4**) in order to classify the structures according to conductivity.

Total Dissolved Solids or TDS: According to the WHO specification, TDS up to 500 mg/L is the most desirable and up to 1500 mg/L the maximum allowed. Waters can be classified [26] on the basis of total dissolved solids, up to 500 mg/L as highly recommended for drinking; 500 to 1000 mg/L as permissible for drinking; up to 3000 mg/L as useful for agriculture and above 3000 mg/L as unsuitable for drinking and irrigation. In the study area, TDS varies between 78 mg/L and 14734 mg/L from Fimela (P14) to Ndangane Sambou (P8). The TDS variations of groundwater in the Samba Dia Quaternary aquifer are shown in **Table 2**.

According to the TDS-based groundwater classification [26], in the study area, 75.75% of the sampled structures (**Table 2**) contain water suitable for drinking and agriculture but to varying degrees (highly desirable water 48.5% and permissible for drinking water 27.3%). These wells are mainly located in the center of the area such as Samba Dia, Baboucar, Ndiedieng. However, 18.2% of the groundwater samples are suitable for irrigation while they are not recommended for drinking (**Table 2**). These are P1 (kobongoye), P9 (Ndangane Campement), P12 (Fimela), P13 (Yayéme), P24A (Diofior) and P26 (Djilass). These are the wells TDS vary between 1000 and 3000 mg/L. Finally, two (2) samples or 6% of the wells are considered unfit for irrigation given the very high TDS values (≥3000 mg/L). These are P8 (Ndangane Sambou) and P18B (Keur Moussa Diarra).

Table 2. Suitability of groundwater for drinking according to the TDS values.

Water class	TDS Variation (mg/L)	Number of samples	% of samples
Desirable for drinking	De 0 à 500	16	48.5
Permissible for drinking	500 - 1000	09	27.3
Suitable for irrigation	1000 - 3000	06	18.2
Unfit for drinking and irrigation	≥3000	02	6

3.2.2. Major Ions

In the study area, chemical analysis shows that the dominant cation in groundwater is Na^+ while the dominant anion is chloride (Cl^-). Chloride in groundwater may originate from various sources including the dissolution of halite. The high Na^+ concentration (beyond 20 mg/L) in the water may cause health hazards *i.e.* high blood pressure, heart disease, kidney problem, etc [27]. The chloride concentration varies from 13.26 mg/L in Fimela to 8184.25 mg/L in P8 of Ndagane. To be usable for drinking, the chloride concentration must not exceed 250 mg/L according to WHO recommendations [11]. The hydrochemical examination of the samples shows that out of the 33 samples, 10 exceed the concentration limit prescribed by the WHO (250 mg/L). These wells are often located in neighboring localities such as Ndangane, Djilass, Diofior, Kobongoye etc.… Nitrates are also among the major anions in the groundwater of the area. The recommended nitrate standard for drinking water is 50 gm/L [11]. For this area, nitrate concentrations range from 2.99 mg/L at Mbissel to 883.8 at Yayéme. 42.42% of groundwater samples (14 wells) exceeded the WHO drinking standard. This excess of nitrates often indicates anthropogenic pollution around several structures located in Yayéme, Samba Dia, Fimela, Keur Moussa Diarra … The use of high nitrate water for drinking reduces the oxygen carrying capacity of the blood and can lead to "blue disease" (methemoglobinemia) in babies [28] [29] [30] [31]. This may be due to the reduction of nitrate to nitrite which reacts with hemoglobin in the blood to form methemoglobin. The elevated NO_3^- concentrations observed in some localities in the study area are mainly due to anthropogenic sources such as leaking septic tanks, sewage, improper disposal of domestic waste, animal and human waste stored around wells, use of fertilizers and pesticides for fertilizing croplands.

Sulfate (SO_4^{2-}) is also among the major anions present in the groundwater of the Samba Dia Quaternary aquifer. Sulfate concentrations in the study area range from 0.95 mg/L to 557 mg/L from Fimela to Ndangane while the WHO recommended standard is limited to 400 mg/L. When the sulfate concentration exceeds the maximum allowable limit (400 mg/L), it becomes unstable and causes a laxative effect on the human system with the excess of magnesium in the groundwater [32]. Excess sulfate is found in only one well in the area, namely at Ndangane (P8) (557 mg/L). Sodium being the dominant cation in the area varies from 9.85 mg/L at Fimela to 4472 mg/L at Ndangane. The maximum allowable limit of sodium in drinking water is 200 mg/L. Based on this classification, 24.25% of the groundwater samples have excess sodium. Calcium is one of the most abundant substances in natural water. In this study, calcium content ranged from 5.76 mg/L in Djilor (P10) to 467.71 mg/L in Djilass (P26). The permissible limit for calcium concentration in drinking water is 75 mg/L. Therefore, 24.24% of the water samples taken from the wells have a calcium surplus. Magnesium is also among the major ions found in the groundwater of the study area. The concentration of magnesium in the area varies from 0.83 mg/L in Fimela to 494.96 mg/L in Ndangane (P8), while the limit indicated by the [11] for drinking water is set at 50 mg/L. Based on this classification, 9% of the groundwater samples do not meet the potability standards for magnesium content. These are wells located in the villages of Ndangane (P8), Keur Moussa Diarra (P18B) and Yayéme (P13). For Potassium (K^+), the concentrations recorded in the area vary between 0.30 mg/L at Sorobougou (P 29) and 209.7 mg/L at Ndangane (P8). The maximum permissible potassium limit for drinking water is 12 mg/L [11]. In the Samba Dia Quaternary aquifer, 24.24% of the groundwater samples exceeded the potassium level set by the WHO.

3.3. Groundwater Suitability for Irrigation

Groundwater pumped for irrigation contains a very significant number of chemical constituents either from the natural environment or from anthropogenic activities. These chemical constituents can affect soil fertility and reduce crop yields [33]. The use of groundwater for irrigation introduces salts into the root zone. Plant roots absorb water but only à small amount of salt from the soil solution. Similarly, water evaporates from the soil surface while salts remain on the surface. This process leads to a progressive accumulation of salt in the root zone of the plants creating a risk of salinity, water deficiency and increased toxicity in the turn of the plants [34]. Knowledge of irrigation water quantity is essential to understand what management approaches are needed for long-term productivity [34]. The assessment of groundwater quality in relation to irrigation can be done by several criteria. Among the parameters we chose to work with the sodium absorption ratio SAR, the percentage of sodium %Na, and the Ca/Mg ratio. **Table 3** shows the variation of these different parameters of groundwater for irrigation in the study area. The examination of these indicators will be accompanied by the analysis of Wilcox diagrams and the groundwater suitability diagram in relation to SAR, also known as Richards' salinity diagram [35].

3.3.1. Percent Sodium

The assessment of sodium concentration is important for irrigation because Na^+ reacts with the soil by reducing its permeability and structure. Indeed, when the sodium ion concentration is high in irrigation water, Na^+ tends to be absorbed by clay particles, displacing magnesium and calcium ions. This process of exchanging sodium in water for Ca^{2+} and Mg^{2+} in soils reduces permeability and ultimately results in soil with poor internal drainage. In the agricultural field, the measurement of the sodium adsorption rate gives a clear idea of the sustainability of the water used for agricultural irrigation. In addition, using a high percentage of welded water for irrigation can stunt plant growth and reduce soil permeability [36]. The percentage of sodium is given by the following "Equation (1)":

$$\%N = \frac{\left[Na^+ + K^+\right]}{\left[Ca^{2+} + Mg^{2+} + Na^+ + K^+\right]} \times 100 \quad (1)$$

where the concentration of ions is expressed in meq/L.

Table 3. Variation of irrigation suitability indices in the area.

Wells	Localities	% Na	SAR	Ca^{2+}/Mg^{2+} (meq/L)
P1	Kobongoye 2 (E)	68.39	7.23	1.25
P2	Kobongoye 2	44.8	1.30	5.27
P3	Kobongoye 1	57.29	2.02	1.92
P4	Samba Dia F	39.73	1.39	4.13
P5	Samba Dia msq	41.65	1.89	3.04
P6	Baboucar	39.77	0.92	7.38
P7	Ndangane 1	9.31	2.53	4.83
P8	Ndangane 2	78.55	37.22	0.34
P9	Ndangane camp	77.50	11.46	4.25
P10	Djilor 2	66.03	1.55	4.14
P11	Simal	70.50	4.90	1.58
P12	Fimela	63.37	6.91	3.10
P13	Yayeme	61.32	6.31	1.50
P14	Fimela Jrd	50.55	0.90	5.42
P15	Samba dia Sud	02.29	5.06	2.91
P16	Ndiedieng	47.85	1.07	3.56
P17	Samba Diallo	68.88	4.91	4.84
P18A	K. Moussa Diarra A	56.75	1.46	6.11
P18B	K Moussa Diarra B	42.75	5.67	2.58
P19	Soumbel	47.72	2.61	3.20
P20	Ndimbiding	81.87	8.04	3.04
P21	Mbissel 2	43.58	2.08	2.06
P22	Fadial	36.76	0.70	6.16
P23	Samba Dia Mka	38.26	1.34	9.20
P24A	Difior 1	51.48	6.10	18.87
P24B	Difior 2	52.8	1.65	4.36
P25	Roh	66.24	4.27	2.54
P26	Djilass	42.89	5.30	15.18
P27	Ngarigne Jim 1	63.22	4.10	8.93
P28	Ngarigne Jim 2	63.35	4.17	5.51
P29	Sorobougou	69.39	2.38	1.94
P30	Mbissel 1	67.72	4.98	2.05
P31	Ngarigne Nanoh	63.25	0.17	1.67

Table 4 shows the classification of groundwater types according to the percentage of sodium based on the criteria set by [11].

Table 4. Classification of groundwater according to the percentage of Na [11].

Water class	Variation %Na	Number of samples	% of samples
Excellent	<20	2	6
good	20 - 40	4	12.2
Eligible	40 - 60	12	36.4
Doubtful	60 - 80	14	42.4
Unsuitable	≥80	1	3

In the study area; the percentage of sodium (% Na) varies between 2.29 at Samba Dia (P15) and 81.5 at Ndimbiding (P20) (**Table 3**). According to the standards indicated by [11], 6% of the groundwater samples are in the excellent category for irrigation, 12.2% of the samples are classified as good for irrigation and 36.36 of the groundwater is considered admissible for agriculture. These structures are mainly located in the center of the area such as Samba Dia, Samba Diallo, Baboucar, Ndiedieng, etc., and in some peripheral localities such as Diofior village, Djilor 2 and Ngarigne Jim1.

However, groundwater samples whose suitability for irrigation is doubtful and requires precautions represent 42.4%, while water that is completely unsuitable and not recommended for irrigation is evaluated at 3% of the samples taken. These types of water are mainly located in the peripheral villages of the zone (Ndangane, Djilass, Diofior, Simal, Mbissel…)

3.3.2. The Wilcox Diagram

The Wilcox diagram [37], based on the percentage of sodium and electrical conductivity, is also an effective and widely used indicator for assessing the use of groundwater for agricultural irrigation purposes. On the basis of the variation of the percentage of sodium in relation to the conductivity, the Wilcox diagram is subdivided into four classes, each indicating a given type of water. Examination of the Wilcox diagram (**Figure 5**) reports that 42.4% of the sampled structures contain groundwater with excellent suitability for irrigation, about 06% of the samples are classified as good for agricultural use and 30.3% of the sampled groundwater is classified as suitable for agricultural use. So, there are about 79% of the sampled groundwater suitable for agricultural irrigation to different degrees (**Figure 5**). However, the other part of the groundwater samples is not recommended for irrigation as it is made up of water of poor to bad quality with the following distribution: 06% of samples of poor class and 15.2% of samples classified as poor and not suitable for irrigation.

3.3.3. SAR: Sodium Adsorption Ratio

In addition to electrical conductivity and Wilcox classification by percent sodium, the sodium absorption ratio is another very suitable parameter for measuring the suitability of groundwater for irrigation. The sodium absorption ratio (SAR) is given by the following "Equation (2)" where ion concentrations are expressed in meq/L [35].

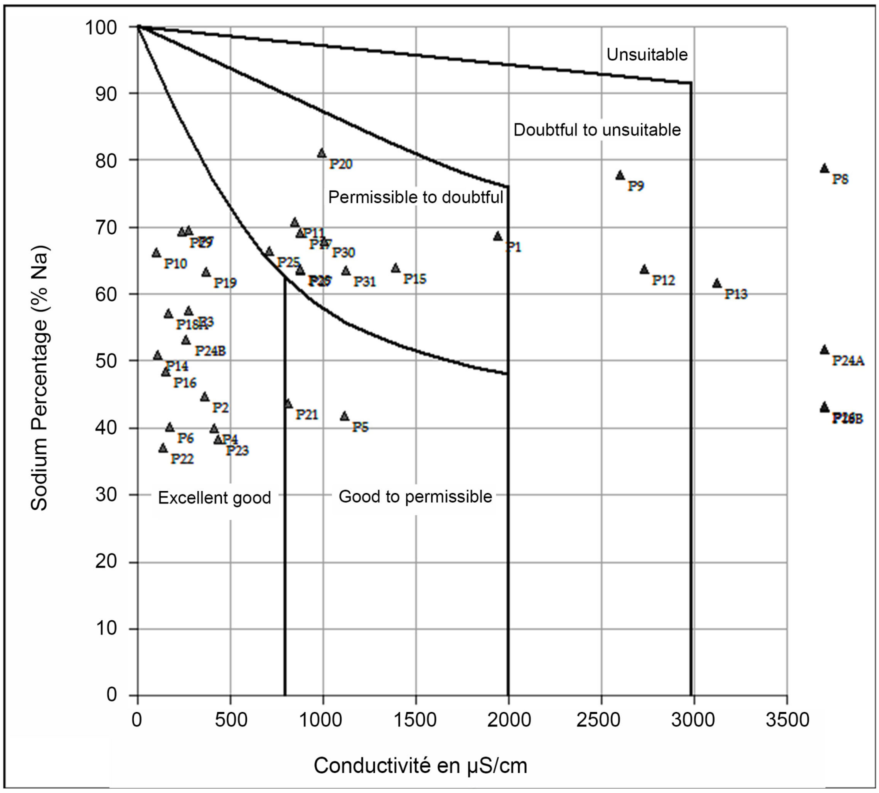

Figure 5. Suitability of groundwater for irrigation in Wilcox diagram.

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

The SAR values are useful for the calculation in which the irrigation water tends to participate in the soil cation exchange. In principle, if the irrigated water becomes enriched in Na^{+} and depleted in Ca^{2+}, the ion exchange system can be saturated in Na^{+} and destroy the soil structure due to the dispersion of clay particles. This causes deflocculation of the soil, which becomes relatively impermeable and makes the land uncultivable or difficult to cultivate. When the rate of Sodium absorption is very high, there is a threat to the rate of water infiltration so the land is more suitable for irrigation the lower the SAR [38]. Table 5 shows the classification of groundwater based on SAR according to WHO and at the same time provides an inventory of groundwater samples in the area suitable or unsuitable for agriculture. For the case of this study, the SAR value varies between 0.17 at P31 and 37.22 at P8 of Ndangane Sambou (Table 3). In all localities where the SAR is higher than 5, the study indicates a real risk of alkalinization of groundwater. According to the SAR-based classification, 94 % of the groundwater samples are categorized as excellent for agricultural use and 3% of the structures contain water of good quality for irrigation. On the other hand, there is a small part (3%) of the samples that is not recommended for irrigation with a SAR value strictly higher than 26 (Table 5).

Table 5. Classification of groundwater by sodium adsorption ratio [11].

Water classes	SAR value	Number of samples	% of samples
Excellent	≤10	31	94
Good	10 - 18	01	3
Doubtful	18 - 26	00	00
Unsuitable	≥26	01	3

3.3.4. Richards's Salinity Diagram

The irrigation water classification diagram or salinity diagram [35] is a representation of the sodium absorption ratio (SAR) versus electrical conductivity (EC) (**Figure 6**). The diagram is subdivided into four classes from C1 to C4 to judge the use of groundwater for irrigation. For a conductivity of 25˚C the groundwater in the area is distributed between the four classes. Classes C1, C2 and C3 are characterized by very good water suitability for irrigation. These are classes in which the sodium absorption ratio (SAR) is lower. The groundwater contained in these classes is highly recommended for agriculture and can be used without specific control. This category represents more than 75% of the groundwater samples studied in the area. These structures are mainly located in the central localities of the zone such as Samba Diallo, Baboucar, Samba Diallo, Ndiedieng, Fimela… and some structures located in the periphery such as Diofior village, Djilor garden among others. On the other hand, class C4 groups together groundwater that is less suitable for irrigation. It is characterized by a higher SAR than in the previous classes and a very high conductivity. The groundwater in this part is almost impractical for irrigation unless quality control devices are put in place to monitor the variation of chemical parameters. This category of groundwater constitutes the peripheral part of the Quaternary aquifer in the area and the localities at the "tannes". These types of water can be found in Ndangane, Diofior center, Djilass, Roh, Simal, Nguerigne … They represent about 24% of the structures listed above.

3.3.5. The Ca/Mg

Calcium and magnesium behave differently in groundwater and high magnesium concentrations are not desirable in irrigation water. This is because magnesium uptake at cation exchange sites in the soil causes the dispersion of soil aggregates and deterioration of soil structure, especially when the waters are very high in Na^+ and highly saline [3] [39]. If the Ca/ Mg ratio is less than or equal to 1, the uptake and transport of calcium from the soil water to the aerial parts of the plants are slowed by the increase in magnesium. In addition, the increase in Na^+ generated by this effect can affect soil quality and plant growth [3]. In short, if the Ca/Mg ratio ≤ 1, groundwater is unsuitable for irrigation and if the Ca/Mg ratio ≥ 1, groundwater is suitable for irrigation [11]. In the study area, the Ca/Mg ratio varies between 0.34 and 18.87 meq/L between P8 of Ndangane and P24A of Keur Moussa Diarra. Analysis of **Table 3** shows that the Ca/Mg ratio is

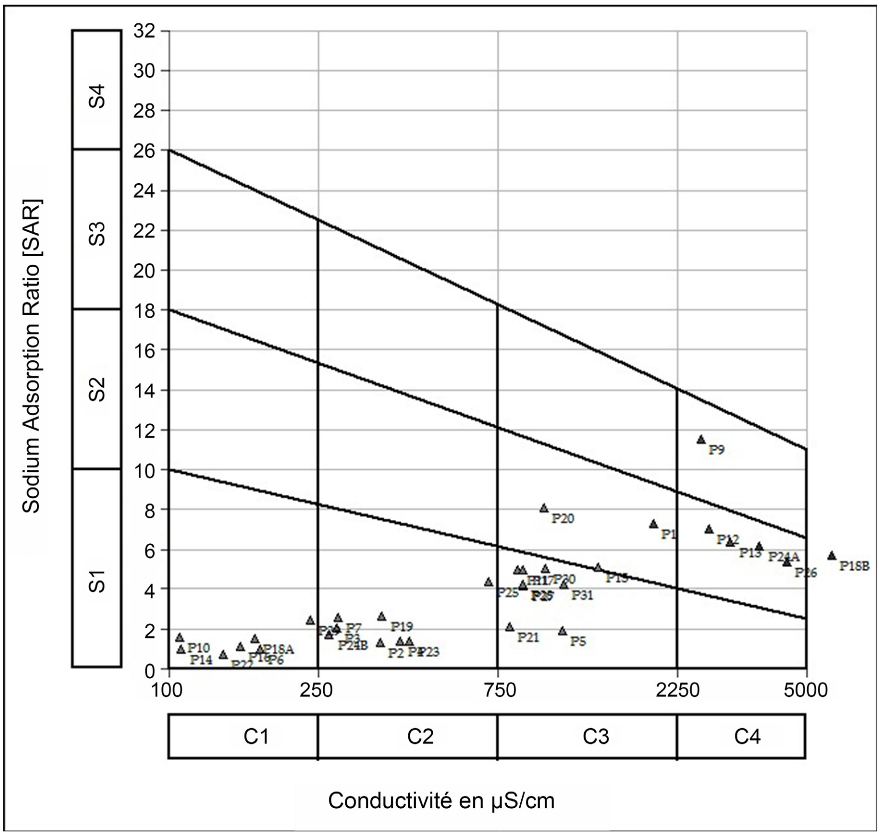

Figure 6. USSL classification of groundwater. C: Salinity Hazard; C1: Low, C2: Medium, C3: High, C4: Very high; S: Sodium Hazard; S1: Low, S2: Medium, S3: High, S4: Very high.

strictly greater than 1 for all groundwater samples except P8 at Ndangane Sambou (0.34 Meq/L). These variations in concentration showing a dominance of calcium over magnesium in the groundwater indicate that most of the groundwater, 96.96% (except P8) is suitable for agricultural irrigation (**Table 3**).

4. Conclusion

The hydrogeochemical study of the Quaternary aquifer of the Samba Dia area allowed us to assess groundwater use for consumption and water supply for irrigation. The study of groundwater quality for drinking and irrigation purposes is mainly based on the range of water potability showed by the WHO. Examining the analytical data characterized by physicochemical parameters and major chemical constituents revealed that most of the groundwater is suitable for human consumption. The pH, electrical conductivity, and TDS show that nearly 75% of the groundwater samples are fit for consumption according to the WHO standards (**Table 1**). Moreover, the dominant ions show drinking suitability rates respectively established: 69.69% for Cl, 57.58% according to nitrates, 96.96% according to sulfates, 75.75% for Na content and 90.91% suitability based on magnesium contents. The concentrations of potassium K^+ and calcium Ca^{2+} indicate that 75.76% of the groundwater samples are suitable for drinking. To qualify the suitability of the groundwater for irrigation, we studied several parameters compared with the WHO standards. The percentage of Na reveals that 54.54% of the groundwater samples can be used for irrigation with no risk. On the other hand, 42.4% of these samples have doubtful suitability for agriculture, and the use requires precautions. Based on %Na, the Wilcox diagram is established and shows that about 79% of the waters of the sampling site are suitable for irrigation. The sodium absorption ratio SAR calculation gives low values, which justify the reliability of the irrigation waters up to 96.96% of the works. The salinity diagram of the water based on SAR and electrical conductivity shows that more than 75% are grouped in classes C1, C2 and C3, which are characteristic of a good aptitude for irrigation. Finally, the Ca/Mg ratio gives values greater than 1 for all the structures, *i.e.*, 96.96%, except for well P8 at Ndangane. This shows that the rest of the wells (32 out of 33) are of good quality for agriculture. This study reports that the overwhelming majority of groundwater in the area is suitable for consumption and irrigation. However, some wells, especially in the periphery and towards the "tannes", show signs of excessive salinity. In contrast, increased nitrate content characterized others, constituting a pollution threat to the water table. This deserves a study of the geochemical processes that govern the mineralization of the water table in order to manage and or remove such a threat at these water tables in all its forms.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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