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Study of the Physicochemical Quality of the Waters of the Continental Hamadien Aquifer in the Commune of Saé Saboua, Guidan Roumdji Department, Maradi Region

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Abstract

Situated in the Maradi region, the study area—the rural commune of Saé Saboua—is located about 42 km from the town of the same name. In this area, the unconfined Continental Hamadian aquifer is relied upon to meet the population's needs, notably for consumption and irrigation. However, naturally high concentrations of fluoride, nitrate, and iron are sometimes encountered in these waters, causing a public-health problem. The general objective of this study was to assess the physico-chemical quality of the waters of the Continental Hamadian aquifer for different uses. The methodological approach adopted, combining fieldwork and chemical analyses in the laboratory, made it possible, after processing all the data collected, to obtain the following results: 1) Correlations between the different lithological logs show that none of the boreholes reached bedrock, which makes it difficult to determine the aquifer thickness, but they highlight variations in thickness. 2) At the commune scale, the waters flow mainly from east to west, with a piezometric dome and two depression zones. 3) Water temperatures range from 23.6˚C to 31˚C, with neutral to acidic pH (5.7 - 7.8). All samples present conductivity values below 400 µS/cm and therefore comply with WHO potability standards. 4) The waters are soft and show no sign of anthropogenic nitrate contamination. However, iron concentrations exceed WHO guidelines at the Guidan Makada Rabo borehole. Fluoride concentrations are low and below WHO standards. 5) The suitability of the waters for irrigation, assessed by %Na and RSC, shows that all Continental Hamadian waters in the commune of Saé Saboua are of excellent quality for irrigation.

Keywords

Groundwater, Continental Hamadian, Water Quality, Saé Saboua, Maradi

1. Introduction

The globe's water stock is considerable, but the seas and oceans, made up of salt water, represent the largest percentage of that stock (about 97%). The remaining 3% comprises fresh water, two-thirds of which is stored in glaciers and is difficult to mobilize, and one-third of which is groundwater, rivers, and lakes [1]. In addition to this small proportion of fresh water, these sources face a number of factors that reduce and degrade their quality (climatic variability, overexploitation, irrigation, and livestock). In Niger, the problem of groundwater quality has two aspects: physico-chemical and bacteriological. Regarding the physico-chemical aspect, very high fluoride concentrations have been observed in various localities of the country. The main affected regions are Maradi, Zinder, and Agadez, with respective concentrations reaching 6.9 mg/L [2] [3]. Nitrate pollution, for its part, is increasingly significant in areas of rivers, goulbis, and dallols, with concentrations often exceeding the WHO guideline value (50 mg/L). Thus, very high nitrate concentrations have been observed [4]-[7]: in the Zinder region, at Bourbourwa (660 mg/L); in the Tillabéri region, at Daibery (164.2 mg/L); in the Dosso region, at Gaouna (169.8 mg/L); and in the Maradi region, in the Goulbi N'kaba valley (80.4 mg/L). Concerning the bacteriological aspect, epidemics of waterborne diseases (cholera, typhoid fever, diarrhea, and Guinea worm) have been reported; these are largely responsible for infant mortality related to water pollution by coliforms (total and fecal). All of this constitutes a major problem for the populations of Niger. Hence, this study, focusing on the quality of groundwater, aims to support the State of Niger in achieving its objectives within the framework of its sectoral Water, Hygiene, and Sanitation program. In the Maradi region, the Continental Hamadian (CH) aquifer is particularly tapped in the commune of Saé Saboua for the population's various uses. However, very high concentrations of substances such as fluoride and iron are sometimes encountered in certain boreholes, thereby harming the population. Hence this study's general objective is to assess the physico-chemical quality of the CH aquifer waters for the different uses of this rural population. More specifically, it aims to determine the piezometry and the physical and chemical parameters of the CH aquifer, to assess the suitability of the waters for consumption and irrigation, and finally to develop thematic maps for certain chemical parameters. This article is structured in three parts: generalities, materials and methods, and results and discussion.

2. Study Area

2.1. Description of the Study Area

The Rural Commune of Saé Saboua, the area of this study, is one of the five communes of the Guidan Roumdji department in the Maradi region. It is located about 42 km from the city of Maradi (the regional capital) and lies between 07˚00′00″ and 07˚30′00″ East longitude and between 13˚30′00″ and 13˚45′00″ North latitude. It covers an area of approximately 810 km^2 (**Figure 1**). The population, which is predominantly very young, totaled 136,982 inhabitants [8]. Indeed, 86.76% of the population is under 35 years old, and 54.71% is under 15 years old [9]. The population density was 169 inhabitants/km^2 in 2021. Regarding socio-economic activities, agriculture is the primary occupation of the people of Saé Saboua. The main crops grown are millet, sorghum, cowpea, peanut, and tiger nut, which places this commune first among Niger's tiger nut-producing communes. Livestock holds the second position. The hydroclimatic context is characterized by a semi-arid climate with two well-defined seasons: a long dry season from November to June and a short rainy season from June to October [10]. Rainfall recorded at the Saé Saboua station from 2010 to 2019 indicates an average of 493.76 mm/year distributed over 29 days. The relief of the study area ranges from 335 m in the lowlands (valleys) to 432 m on the plateaus. Soils in the study area are generally sandy dune soils, with silty-sandy textures in places. They form the arable and cultivated lands but are generally low in organic matter, heavily leached, and often subject to wind and water erosion.

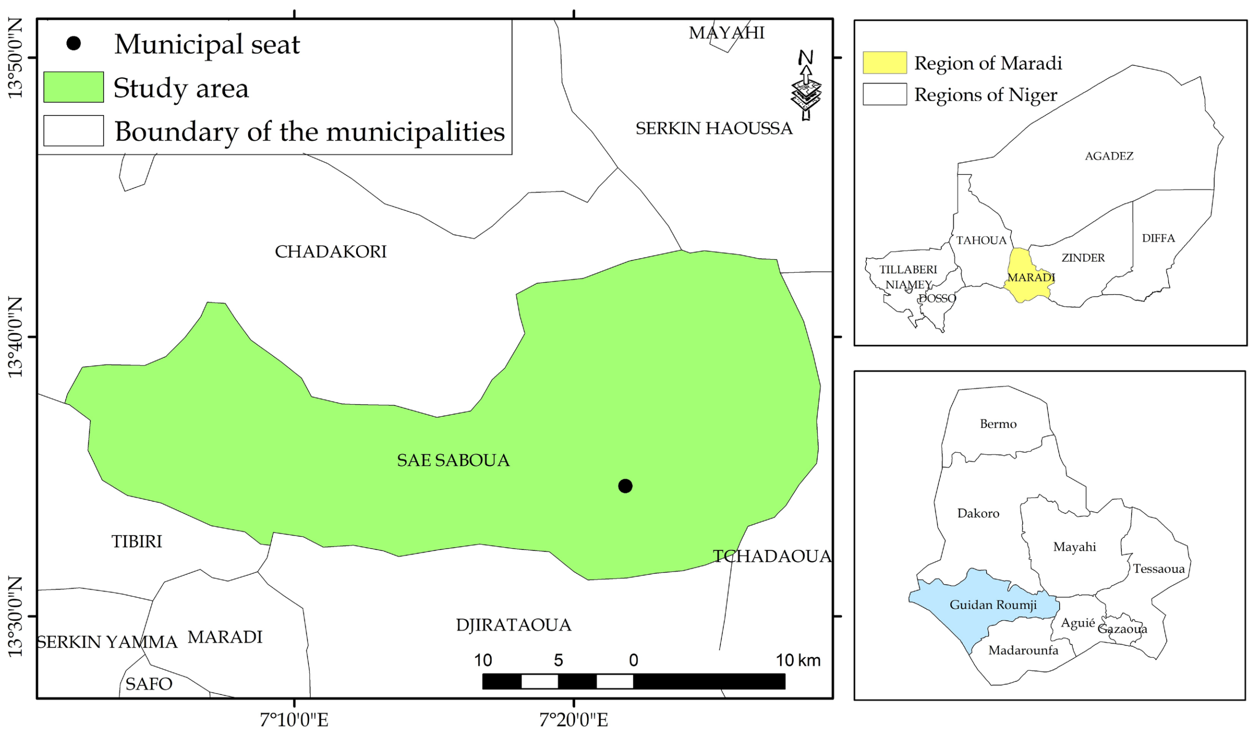

Figure 1. Location map of the study area.

2.2. Geology and Hydrogeology

The geological context of the Maradi region (**Figure 2**) is dominated by three main formations [11], listed from bottom to top: 1) the Precambrian basement, made up of igneous and metamorphic rocks. This suite of crystalline and crystallophyllian rocks is composed of granite, quartzite, and gneiss, which outcrop in the southern part of the region without a cover of weathered material. In the center and farther north, the basement disappears beneath detrital terrains assigned to the Continental Intercalaire/Hamadien [12]-[14]. 2) The Hamadian Continental (CH), composed mainly of coarse, more-or-less clayey sandstones. These deposits were not affected by the Upper Cretaceous marine transgressions encountered in the central and northern parts of the basin [15]. They correspond to fluvio-lacustrine and deltaic deposits [16]. 3) The Quaternary, consisting of recent alluvium, very weathered infill of ancient alluvium, and old alluvium derived from the erosion and deep weathering of the Precambrian formations of northern Nigeria [15]. These Quaternary formations are distinguished from the underlying Hamadian deposits by a coarser grain size of the detrital elements, especially upstream in valleys where the basement outcrops.

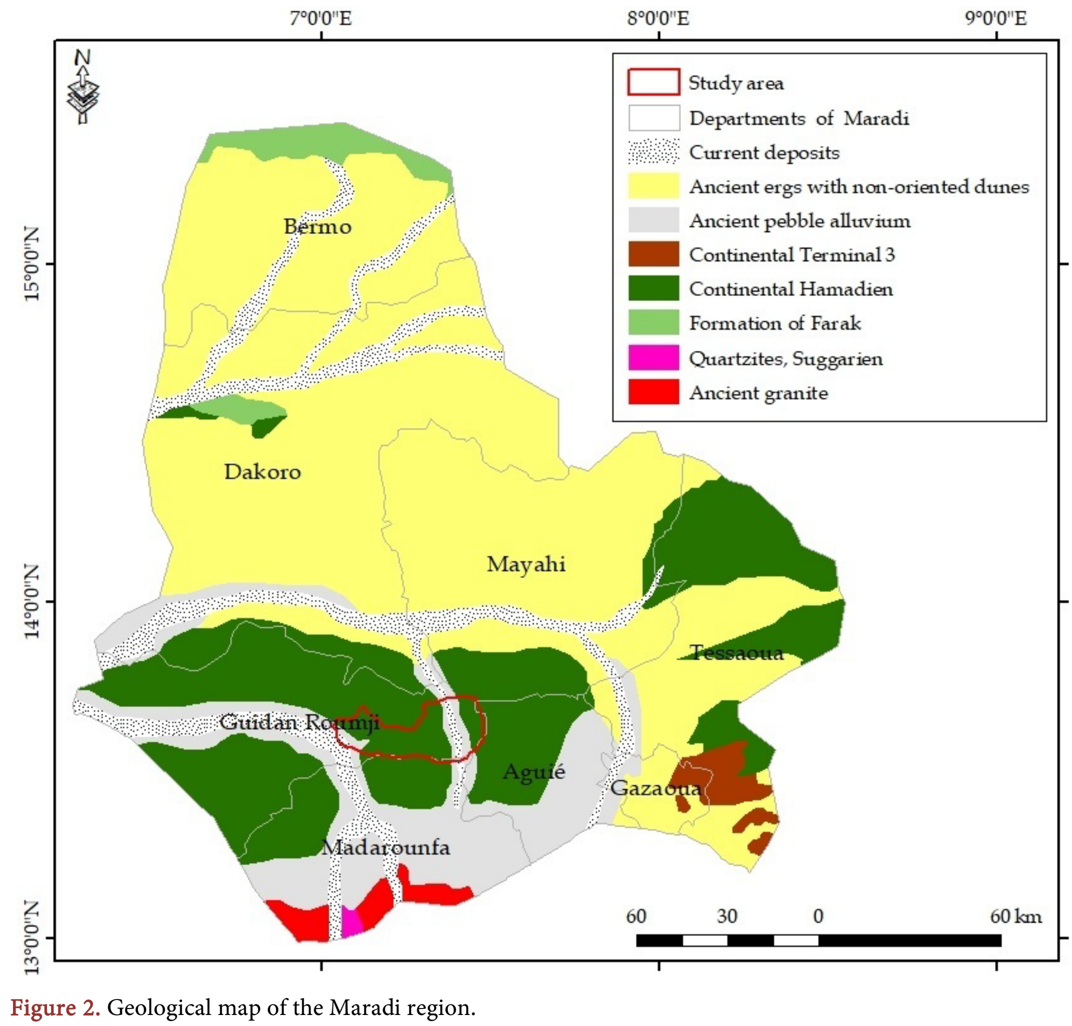

Figure 2. Geological map of the Maradi region.

The hydrogeology of the study area consists, from bottom to top, of four types of aquifers:

1) The discontinuous basement aquifers, located only in the southern part of the region, with poor yields;

2) The lower sandstone aquifers, located in the western part of the region, present a risk of gas emanation;

3) The Continental Hamadian aquifers, composed of clean coarse sandstones and clayey sandstones, located at depths of 21 to 350 m;

4) The superficial Quaternary aquifers, recharged by floods of the goulbi, are located at depths between 2 and 15 m in the valleys of the Goulbi Maradi and the Goulbi N'Kaba.

This study focuses on the unconfined Continental Hamadian aquifers in the study area; they constitute a strategic aquifer system in the municipality and at the regional scale, since they can reach several hundred meters in thickness and outcrop over more than 200,000 km^2 [17]. According to the same source, this aquifer has an estimated reserve of between 1,000 and 2,000 billion m^3. Local yields reach 50 m^3/h in the lower levels, with generally fresh water (350 to 600 mg/L). However, elevated concentrations of certain elements, such as fluoride, have been noted.

3. Materials and Methods

3.1. Materials

The working materials used in this study consist of multisource data and tools. These include piezometric monitoring data from piezometric campaigns (low water and high water) conducted in 2025 on wells and boreholes in the study area. Cartographic information—topographic maps (scale 1:200,000), and geological maps (scale 1:2,000,000)—as well as digital terrain models (DTMs) with a spatial resolution of 30 m, downloaded from the USGS site (http://earthexplorer.usgs.gov/), were used to determine the hydrographic network of the study area. Borehole data sheets, provided by the various drinking-water drilling campaigns, supplied data on borehole depths, piezometric levels, lithological logs, and pumping tests. All of these data contributed to the production of the various thematic maps. In addition, physico-chemical analyses of borehole water were available. Processing of all these data was carried out using ArcGIS 10.2.2 (for the development of thematic maps), ENVI Classic 5.3 (for processing satellite images), and Adobe Illustrator (for creating geological cross-sections and diagrams); software was also used for processing chemical water data. The different tools used included a GARMIN GPS for recording the geographic coordinates of the structures, a 100-m sounding probe for measuring static levels, and HANNA pH and conductivity meters for *in situ* measurements of the physico-chemical parameters of the water. The use of high-density polyethylene (HDPE) bottles with screw caps in polypropylene (PP) with a Teflon joint—X200, 500 mL—is also noted for sampling water intended for the various physico-chemical analyses. DR 3900 and DR 7100 spectrophotometers, a flame photometer, and a titrator were used to determine concentrations of major elements and some minor elements in the laboratory.

3.2. Methods

3.2.1. Sample Collection

In total, twenty (20) boreholes were included in the water sampling for chemical analyses during the month of October to November 2025. These installations are distributed throughout the municipality of Saé Saboua. For newly drilled boreholes, sampling was carried out during pumping tests. In contrast, for older installations that are in use, sampling was performed at the taps at the top of the borehole. The sampling bottles were rinsed three times with water from the borehole before collecting the sample to avoid contamination. The physical parameters of the water (pH, temperature, and EC) were measured *in situ*. Meanwhile, the bottles were placed in coolers to preserve certain constituents and to transport them safely to the laboratory of the Regional Directorate of Hydraulics of Maradi, where the physico-chemical analyses were carried out.

3.2.2. Description of the Cutting

During the drilling of water boreholes in the study area, cuttings—samples of the drilled formation—were collected every 1 m drilled, stored in metal boxes, and analyzed. Thus, the lithology of the formations encountered was described as the drilling progressed. The analysis of these data made it possible to develop the various lithostratigraphic drilling logs, which were used to establish correlations between them and to define the geometry of the CH aquifer.

3.2.3. Static Level Measurement

About thirty wells and boreholes were used as piezometers to measure static water levels in the study area. These structures are distributed throughout the commune of Saé Saboua. The static levels of the various structures (boreholes and wells) were measured using an acoustic piezometric probe, which was lowered into each structure until it contacted the water table. These measurements were taken during the high-water period, just after the rainy season (November 2025). The static level was read directly from the probe's graduated cable. These static level measurements were used to produce the piezometric map.

3.2.4. Data Processing

Cartographic data:

1) Georeferencing: The geological and topographic maps were georeferenced so they could be correctly positioned in space and used with other spatial data in ArcGIS 10.8. The operation consisted of assigning real geographic coordinates to the raster images. The different geological formations were then digitized to produce the geological map of the study area.

2) Creation of hydrogeological cross-sections: The lithological borehole logs were correlated along two profiles (A - B and C - D) to characterize the structure and geometry of the CH aquifer system. The procedure began with scaling and drawing the topographic profile, then plotting the boreholes on the profile and representing each layer with a conventional symbol. This was followed by correlation between boreholes and representation of the hydrogeological elements. Fi-

nalizing the document included providing the legend, scale, orientation, borehole names, distances, and title.

3) Piezometric maps: The geographic coordinates of the boreholes and wells used to establish the piezometric maps were derived from GPS. No leveling operation was carried out due to lack of resources. Elevations for these sites were generated using the DEM with the Arc Toolbox utility. Hydraulic heads were calculated using the formula (hydraulic head = ground elevation − depth to water level). These heads were then plotted as points on the study-area map. Interpolation was performed to display the equipotential lines, using a contour interval of 5 m. Finally, the flow directions were determined and the map was finalized.

Ionic balance:

The ionic balances of the results of the chemical analyses were calculated to verify the reliability of the analyses. An analysis is considered reliable if the ionic balance is between −6% and +6%. It is defined by the following equation:

$$Bi(\%) = \frac{\sum \text{cations} - \sum \text{anions}}{\sum \text{cations} + \sum \text{anions}} \times 100$$

With the Bi: ionic balance expressed in % concentrations of cations and anions in meq/L.

Water hardness:

The main ions responsible for water hardness are calcium (Ca^{2+}) and magnesium (Mg^{2+}). Water hardness is evaluated by the hydrotimetric titre, which reflects the water's capacity to react with soap [18] [19]. It is expressed in ppm of calcium carbonate ($CaCO_3$) or in French degrees (˚f). One French degree (˚f) is equal to 10 mg/L of $CaCO_3$. It is calculated by the formula below.

$$°th = \text{Ca}^{2+} \times \frac{\text{CaCO}_3}{\text{Ca}} + \text{M}_\text{g}{}^{2+} \times \frac{\text{CaCO}_3}{\text{M}_\text{g}}$$

With the $°th$ hydrotimetric title in ˚f or in ppm of $CaCO_3$; Ca, Mg, C, and O: molar mass, in g/mol and Ca^{2+} and Mg^{2+} in mg/L.

The results of the water hardness allow it to be classified [16] into several groups (**Table 1**).

Table 1. Classification of waters based on their calcium and magnesium hardness.

Nature of the waters	Soft water	Moderately hard water	Hard water	Very hard water
Value of ˚th	˚th < 6˚f	6˚f < ˚th < 12˚f	12˚f < ˚th < 18˚f	˚th > 18˚f

Suitability of water for human consumption and irrigation:

The suitability of water for human consumption is determined by comparing the concentrations in mg/L of undesirable ions and the values of the physical parameters of the water to the WHO drinking water standards. As for the suitability of groundwater for irrigation, it is assessed using the residual sodium carbonate (RSC) method. The RSC is determined by the following equation:

$$RSC = (CO_3 + HCO_3) - (Ca + Mg)$$

With CO_3, HCO_3, Ca and Mg: concentrations in meq/L.

The value of the RSC, as calculated, allows for a classification [20] into three categories of water (**Table 2**).

Table 2. Classification of water suitability for irrigation based on RSC values.

RSC Value	Suitability of water for irrigation
] ← – 1.25]	water of good quality for irrigation
] 1.25 – 2.50 [	medium quality water for irrigation
[2.50 – → [	salty and unsuitable water for irrigation

The Wilcox diagram is used to validate the results of the SAR. Wilcox also allows for the classification of waters based on their suitability for irrigation into five categories: excellent, good, permissible, marginal, and poor. It is developed based on the values of electrical conductivity or TDS on the x-axis and the percentage of sodium in the waters, given by the formula below.

$$Na(\%) = \frac{Na}{Ca + Mg + Na + K} \times 100$$

With Na, Ca, Mg, and K: concentrations of sodium, calcium, magnesium, and potassium in meq/L.

4. Results

4.1. Overall Aquifer Configuration

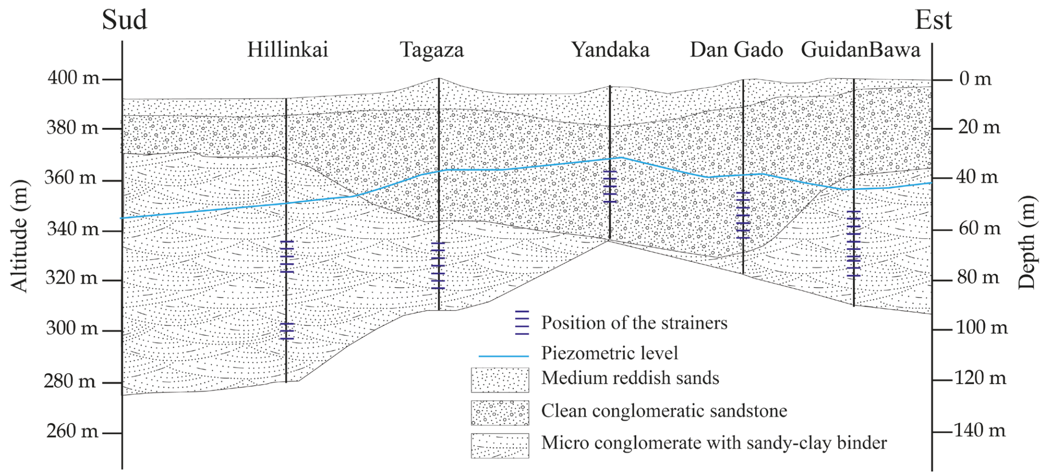

Figure 3. Hydrogeological cross-section oriented southeast.

The geometry of the aquifers in the study area is defined based on lithostratigraphic correlations between the different lithological logs. Thus, the SE-oriented section (**Figure 3**) highlights the different layers crossed by the boreholes. It should be noted that no borehole has reached the bedrock in the study area; therefore, it is difficult to determine the exact thickness of the CH aquifer in the area. The hydrogeological section shows a lateral continuity of the formations, mainly composed of sands, gravels, and microconglomerates, with thicknesses that vary laterally. The presence of the gravel layer on either side of the Yandaka and Dan Gado boreholes indicates that it could exist beneath these boreholes, which have not visibly reached it. This configuration gives the aquifer a multilayered geometry favorable for the storage and circulation of groundwater.

4.2. Piezometry

Piezometry is a fundamental tool for the proper understanding and functioning of aquifers and their underground hydrodynamics. The calculated piezometric levels range from 320 m to 420 m, from north to south and from east to west (Figure 4). The waters generally flow from east to west across the municipality. This means that the eastern zone is a recharge area and the western part is a discharge area. Furthermore, concentric anomalies in the isopiestic lines are also observed on the southeast and northeast sides, corresponding to a piezometric dome, indicating a recharge zone. Two depression zones were also observed, close to the piezometric dome area: the first in the southwest and the second in the northeast part relative to the dome.

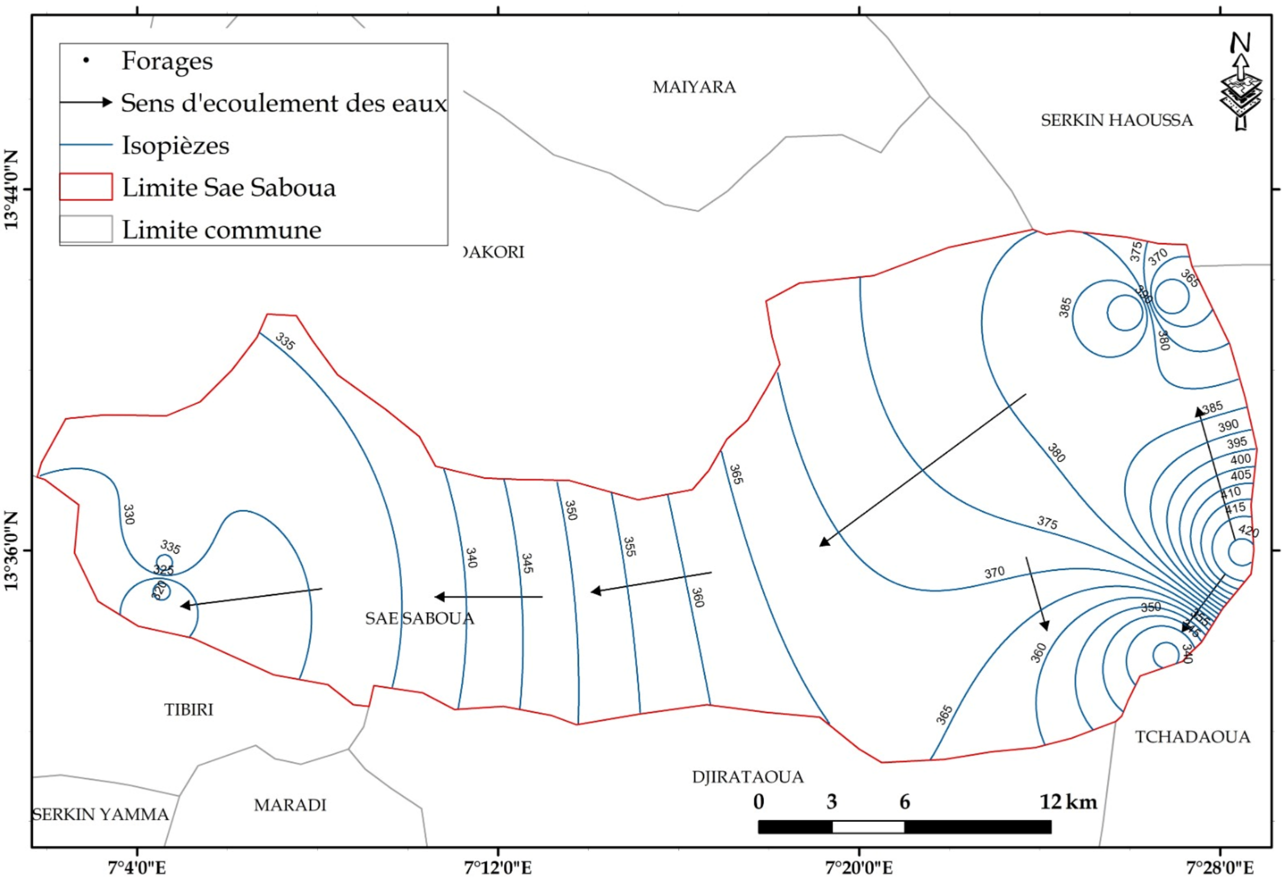

Figure 4. Piezometric map of the study area.

4.3. Physicochemical Quality of Water for Consumption

The quality of water intended for consumption, within the framework of this study, is evaluated based on the interpretation of the results of physicochemical analyses of the water from the Continental Hamadien aquifer in the municipality of Saé Saboua (**Table 3**). The results of the ionic balances show, for all the analyzed samples, values ranging between −6% and 6%, thus demonstrating the reliability of the analytical results.

Table 3. Results of physicochemical analyses.

Sites	T	pH	EC	Ca	Mg	Na	K	Fet	HCO_3	Cl	SO_4	NO_3	NO_2	F
	(˚C)		(µs/cm)	(mg/L)										
Dan Amina		6.4	142	16	2	4	9	0.2	67	1	0.03	11	0.02	0.03
Dan Boulde	29.2	5.88	82.96	7.2	0.72	25	5	0.08	30.5	19	0	41.8	0.02	0
Dan Dabo		6.3	147	16	6	3	10	0	85	1	0.02	7	0.02	0.1
Dan Gado B	31.9	7.79	168.1	43.2	2.64	3	7.39	0.06	95.16	27	0		0.01	0.26
Garin Kapini 3		6	71	5	1	5	5	0	43	0.3	0.03	6	0	0.1
Dogon Krya		5.7	101	6	2	6	6	0.1	28	1	0.01	19	0.01	0
Guidan Bwa 4	30.9	5.82	76	7.2	1.92	10	5.65	0	39.04	18	0	3.52	0.01	0.28
Guidan Kalgo	29.1	6.16	127.6	10.8	0.96	2.5	8	0.06	32.94	11	1	3.92	0.52	0.08
Guidan Mkd R	31.8	7.78	114.7	28.8	1.2	2.5	14.34	0.36	57.34	38	1		0.01	0.02
Guidan M 2		6.3	122	13	3	4	8	0	79	1	0.03	6	0.01	0.1
Hilin Kai		7.5	217	24	1	16	8	0.01	143	2	0.02	0.5	0.01	0.3
Kakin	30.8	5.94	101.5	14	0.96	10	8.71	0.18	57.34	22	0	0	0.02	0.59
Karambi Tsfa	23.6	6.14	311.5	21.6	6.96	30.4	19.39	0.03	101.26	48	7	0	0.02	0.13
Rouga Ktg		6.6	153	18	2	5	9	0.1	98	1	0.02	5	0.05	0.3
Saé Tsofoua	28.6	7.25	230	28	0.24	4	12.72	0.02	120.78	4	0	7.48	0.03	0.04
Sarkin K Kane	28.2	6.01	98.55	14	1.2	10	5	0	53.68	21	0	3.96	0.02	0
Wangarawa	28.4	5.72	131.8	14	0.72	20	6.52	0.03	48.8	21	1	31.68	0.02	0.69
Yandaka 2		6.3	141	15	2	3	9	0	58	1	0.03	16	0.02	0.1
Yandoto Al	28.1	7.18	100	4.4	1.68	5	11.8	0.03	24.4	9	0	13.2	0.43	0
Zangon Bale	28.3	5.92	219.6	18	3.84	20	4.75	0.02	82.96	28	0	2.8	0.01	0.2

4.3.1. Physical Parameters of Water

The physical parameters (hydrogen potential, electrical conductivity, and temperature) of the waters measured *in situ* show that the temperature values of the waters from the Continental Hamadien in the study area vary between 23.6˚C and 31˚C, with an average of 29.08˚C and a standard deviation of 2.23˚C. They reflect the average atmospheric temperature [21]. The pH values of the waters range between 5.7 and 7.8 pH units, with an average of 6.43 pH units and a standard deviation of 0.68 pH units. The statistical analysis of the pH results shows that 18.70%

of the samples have a pH below 6.5, 5% have a pH between 6.5 and 7, and 25% have a pH above 7. Electrical conductivity allows for the assessment of the amount of dissolved salts in the water and, consequently, its degree of mineralization [22]. The values of electrical conductivity range between 71 and 311.50 µS/cm, indicating that the mineralization is low in the waters of the study area. These conductivity values comply with the WHO drinking water standard (below 400 µS/cm). The statistical analysis of the conductivity values shows that 25% of the structures have a conductivity below 100 µS/cm, 55% are between 100 and 200 µS/cm, 15% are between 200 and 300 µS/cm, and 5% are above 300 µS/cm.

4.3.2. Chemical Parameters of Water

Water hardness:

The hardness of the waters from the CH of Saé Saboua aquifer, determined by the hydrotimetric title, varies between 1.6 and 11.9°f. It classifies the waters of this aquifer (**Figure 5**); according to the adapted classification [16], two categories of hardness are defined: Very soft waters (75%) and soft waters (25%). The spatial distribution of water hardness values (**Figure 5**) indicates that the majority of very soft waters are located in the western part of the municipality, with the exception of the waters from the village of Guidan Bawa, situated in the extreme east of the municipality. Regarding soft waters, they do not show any particular distribution. Hard water causes a number of inconveniences: scaling of pipes and water heaters, excessive soap consumption during domestic use (low foaming), longer cooking times for vegetables, and the deposition of scale at the bottom of pots and pans when they are brought to a boil [19] [23].

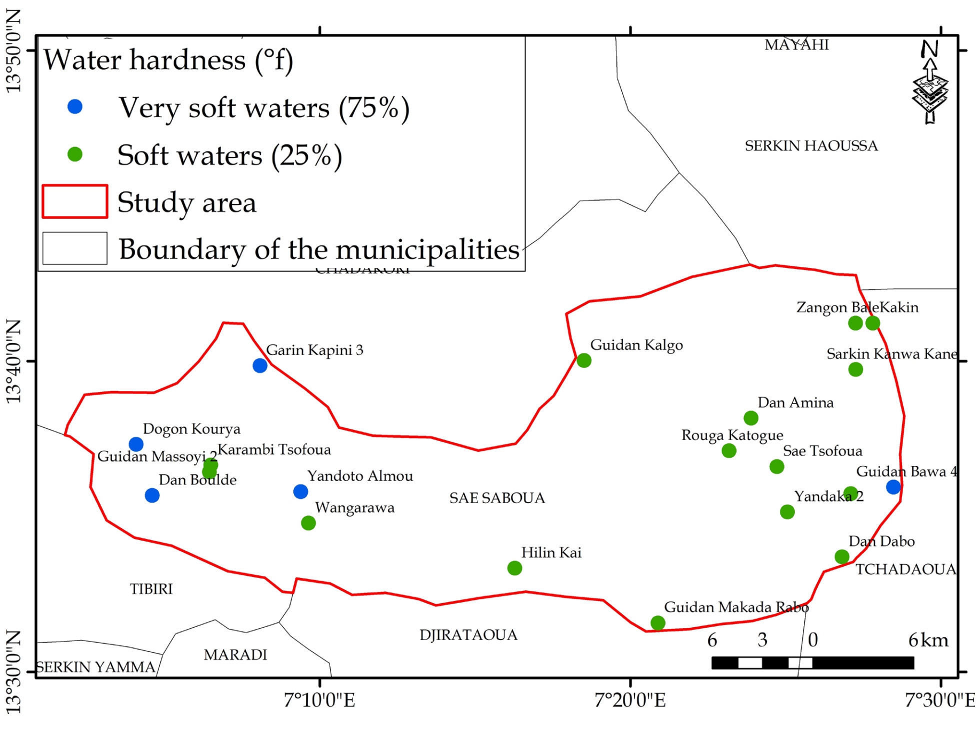

Figure 5. Spatial distribution of different water hardness levels.

Fluorine:

The fluoride levels in the study area range from 0 to 0.69 mg/L. More than 70% of the samples have values below 0.25 mg/L, 20% of the samples have values between 0.25 mg/L and 0.30 mg/L, and 10% have values between 0.30 mg/L and 0.69 mg/L (Figure 6). All the fluoride content values of the waters in the study area comply with WHO standards (1.5 mg/L). Excess fluoride in drinking water can be toxic and cause dental caries or even dental or skeletal fluorosis at high doses [16] [24] [25].

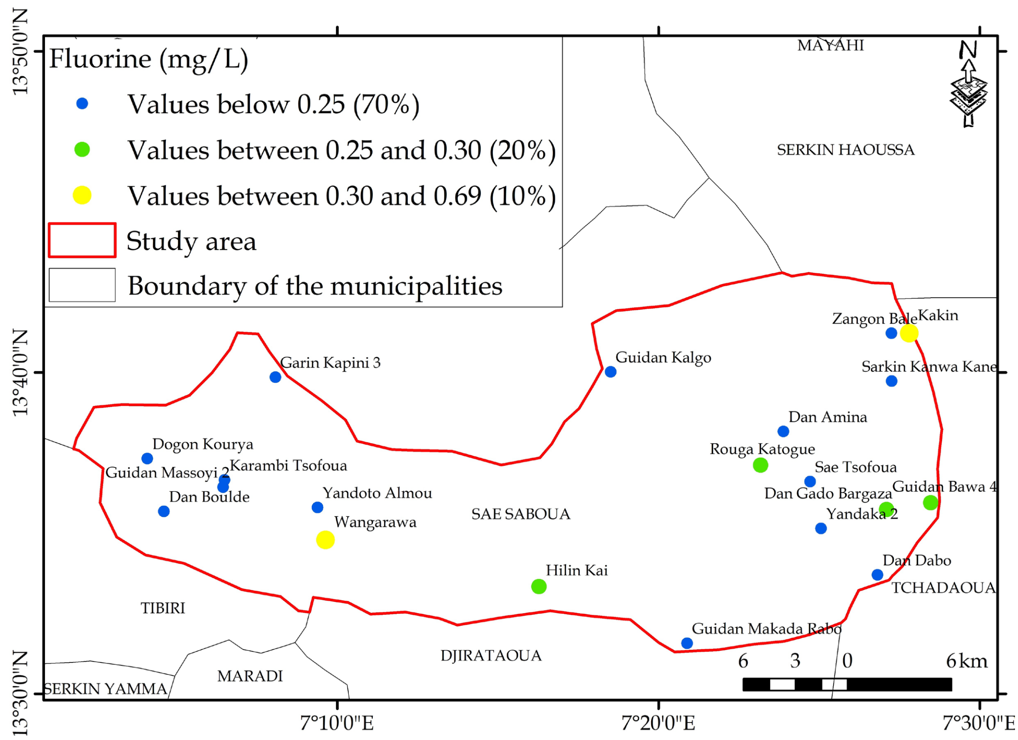

Figure 6. Spatial variation of fluoride levels.

Nitrates:

The presence of nitrates in drinking water is mainly attributable to anthropogenic activities [26]. Deficient septic systems, as well as the decomposition of plant and animal matter, can also be a source of nitrate pollution in water [27]. Nitrate levels range from 0.0 mg/L to 41.8 mg/L in the waters of the CH aquifer in the municipality of Saé Saboua. One hundred percent of the waters from this aquifer have nitrate levels below the WHO standard (50 mg/L), thus giving these waters excellent quality for nitrates. The most dominant structures are those with values below 20 mg/L; they represent 90% of the samples. The maximum value is observed in the Dan Boulde borehole (41.5 mg/L), and seems to be linked to intense anthropogenic activities in this area. It is therefore necessary to take precautions to limit this anthropogenic pollution.

Nitrites:

The nitrite concentrations in the waters range from 0 to 0.52 mg/L. More than

90% of these waters have nitrite concentrations below 0.2 mg/L. However, the villages of Guidan Kalgo and Yondo Almou, representing the remaining 10 %, have concentrations of 0.43 mg/L and 0.52 mg/L, respectively. These samples therefore do not comply with the WHO standard (0.2 mg/L).

Iron:

Iron levels range from 0.01 to 0.36 mg/L. The limit value for iron in drinking water is estimated to be 0.2 mg/L [28]. Eighty-five percent of the waters from the CH aquifer have values below 0.1 mg/L, 10% of the values are between 0.1 and 0.3 mg/L, and finally, 5% are above 0.3 mg/L but below 0.36 mg/L (**Figure 7**). Iron, apart from its undesirable nature (stains clothes, darkens dough), would also be involved in certain cardiovascular diseases and cancers at higher levels.

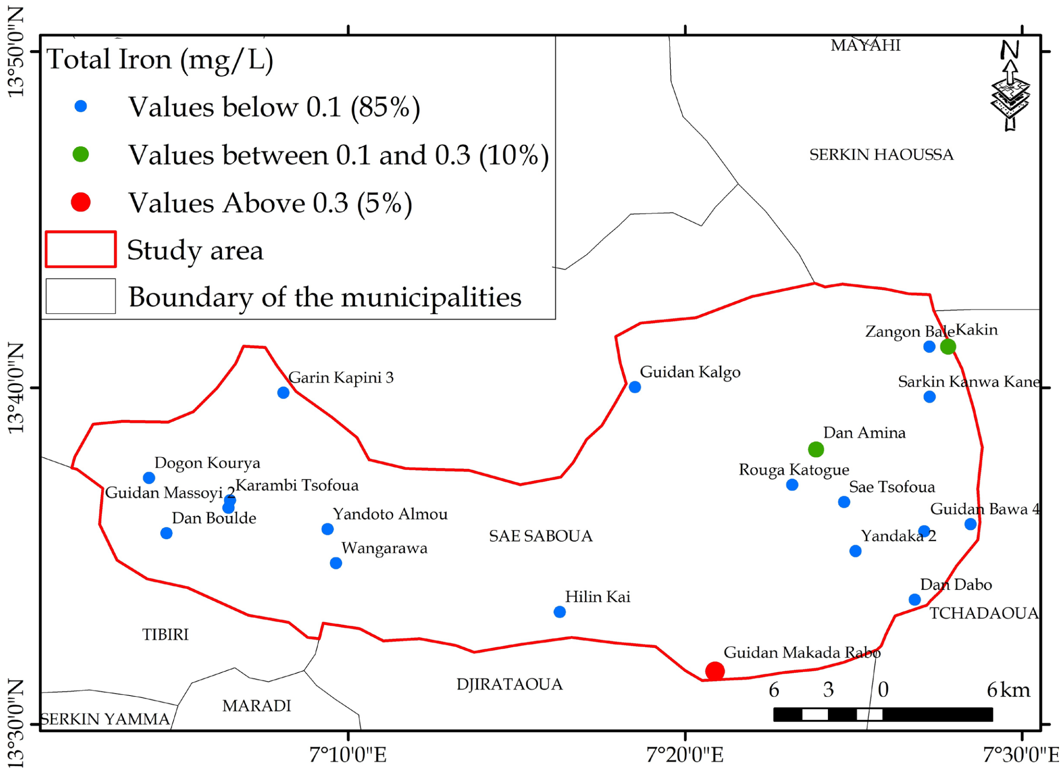

Figure 7. Spatial variation of iron content.

4.4. Suitability of Water for Irrigation

The evaluation of water suitability for irrigation can be carried out using several methods [20] [29] [30]. In this study, residual sodium carbonate (RSC) and sodium percentage were used for this task. The RSC values obtained for the waters range between −0.82 and 1.06. All of these values are grouped into a single class of water quality for irrigation (**Figure 8**): that of good quality water for irrigation. This is corroborated by the Wilcox diagram, which allows for the classification of water based on its suitability for irrigation. Thus, the waters of the Continental Hamadien aquifer system in the municipality of Saé Saboua, plotted on the Wilcox diagram (**Figure 8**), allow us to observe and deduce that all the waters are of excellent quality for irrigation. This corroborates the quality defined for these same waters by the residual sodium carbonate method.

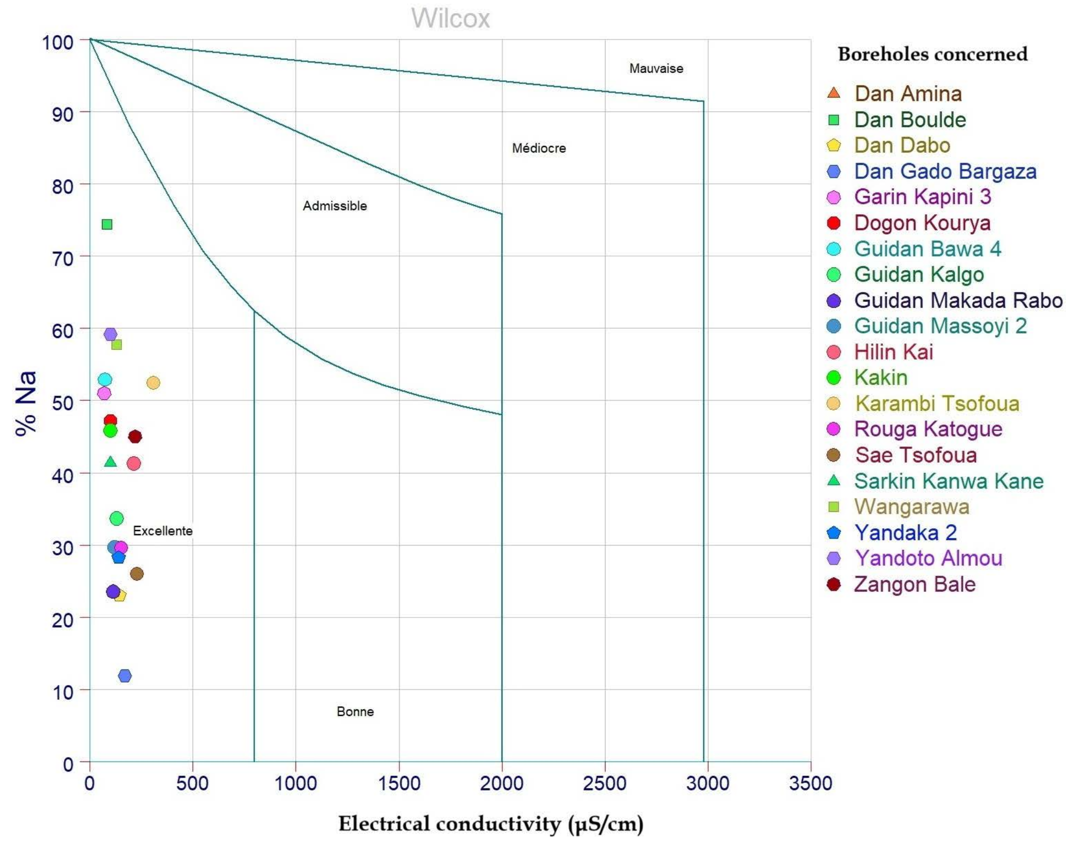

Figure 8. Map of the area's water suitability for irrigation (Wilcox Diagram).

5. Discussion

The hydrogeological cross-section of profiles (A - B), oriented southeast, highlights formations such as sands, microconglomerates, conglomerates, gravel, and clay, intersected by the various boreholes. The configuration and lateral continuity of the formations toward the southeast suggest a multilayer geometry for the aquifer. These results are consistent with those of previous studies in the Maradi region [31] [32]. The same types of formations are found in the regions of Tahoua and Dosso for the CH [16]. The piezometry of the study area indicates a generalized flow of groundwater oriented from east to west, with isopiestic lines that narrow in the eastern part and form concentric circles around certain boreholes. These water flow directions are identical to those obtained by several studies [7] [16] [31] at the scale of the Iullemeden basin sensu stricto for the Continental Hamadien. Two anomalies were observed: the first shows piezometric values increasing from the outside to the inside, indicating a piezometric dome and, consequently, a recharge area; the second shows piezometric values decreasing from the outside to the inside in two locations, indicating an overexploitation area or a depression. These depressions could be due to intensive pumping activities. The temperature values recorded at the level of the Continental Hamadian waters in the study area range between 23.6˚C and 31.8˚C. These values are similar to the average atmospheric temperatures observed in the arid and semi-arid zones of West Africa [21]. They are also similar to those recorded by previous studies [7] [31] [33] [34] in certain unconfined aquifers in Niger. However, they are slightly higher than the temperatures of the effluents from the city of Nouakchott, which range between 23˚C and 26.3˚C [35], and those obtained by [23] and [36] for the drinking water of the city of Aboisso. The pH values of the groundwater range between 5.7 and 7.8 pH units. The pH results show that 75% of the waters are acidic. This trend toward acidity indicates that the aquifer is in contact with CO_2 from the atmosphere and soils [37] and is therefore free. Similar results were obtained in the Tahoua region by [24], in the Zinder region at the level of Korama [25], in Maradi by [21], and in other regions of Côte d'Ivoire [38]. This predominantly acidic nature of the water gives it a corrosive quality toward drilling equipment, extraction means, and water pipes, consequently requiring equipment materials made of stainless steel or PVC. Electrical conductivity allows for the assessment of the amount of dissolved salts in the water and thus its mineralization. The electrical conductivity values in the study area range between 71 µS/cm and 311.50 µS/cm, with an average of 142.82 µS/cm; 100% of the samples have levels below 500 $\mu S \cdot cm^{-1}$. These results indicate that the waters are weakly mineralized. They are close to those found by [39] in Dallol Maouri and consistent with those of [25] [32], and [40]. Electrical conductivity depends on the loads of endogenous and exogenous organic matter, which generate salts after decomposition and mineralization, and is also influenced by the evaporation phenomenon that concentrates these salts in the water; it also varies according to the geological substrate traversed [41] [42]. The conductivities obtained in this area are significantly lower than those recorded by [43] for the waters of the northern Sahara aquifers (El Oued aquifers in Algeria), which range between 2,170 and 47,150 µS/cm, or even those of the groundwater in the Biskra region [44]. The waters of the Continental Hamadian in the municipality of Saé Saboua exhibit two classes of hardness. Approximately 25% of the waters are very soft, concentrated in the western part of the area, and 75% are soft, dispersed throughout the entire municipality. All the ˚f values are below 14 ˚f, ranging from 1.6 ˚f to 11.9 ˚f, and are distributed heterogeneously throughout the entire municipality. These results are similar to those of [31] in the Maradi region and for the CH aquifer. It should be noted that very soft waters, which represent a small percentage in the area, could promote the corrosion of certain metals such as copper, zinc, lead, and cadmium, which may end up in the distribution network water. The nitrate levels in the waters of the CH of the commune of Saé Saboua are relatively low and below the WHO standard (50 mg/L). The maximum concentration of nitrates is 41.8 mg/L. The origin of these nitrates would be linked to anthropogenic activities in the area [31] [45]. These results are similar to those found by [7]. Iron levels range from 0 to 0.36 mg/L. These low levels seem to indicate the absence of a source likely to introduce iron into the waters [32]. Nevertheless, the Dan Amina borehole records a value of 0.20 mg/L, just at the limit of the standard, and the Guidan Makada Rabot borehole shows a content of 0.36 mg/L, exceeding the standard; this value is likely due to leaching of the soils or corrosion of certain drilling materials [46]. For fluoride, the concentrations range from 0 to 0.69 mg/L; all the waters from the CH exhibit very low fluoride levels and therefore comply with the WHO guideline (1.5 mg/L). The evaluation of the suitability of water for irrigation conducted using the RSC and Wilcox methods [29] [30] [47] shows that all water samples have values below 1.25 for RSC. These values are grouped into a single class of water suitability for irrigation, namely, the class of good quality water for irrigation. The Wilcox diagram, used to validate the RSC results, confirms that all waters appear excellent for irrigation.

6. Conclusion

This study focused on the analysis of the physicochemical parameters of the waters of the CH of the commune of Saé Saboua in order to improve understanding of the physicochemical characteristics of these waters. Thus, in light of the above, it appears that the hydrogeological correlation sections highlight the following sedimentary formations: sands, microconglomerates, conglomerates, gravels, and clays. This has allowed for the observation of a multilayer aquifer for the CH. The observed water flow directions at the municipal scale show a general east-west flow direction. The water temperatures reflect those of the average atmospheric temperatures, with neutral to slightly acidic waters. The waters of these aquifers are very low in minerals. The analysis of the chemical parameters of the water indicated that more than 90% of the samples analyzed are of excellent quality for consumption. The remaining less than 10 % are considered poor quality due to their high iron and nitrite levels compared with WHO guidelines. The RSC values obtained are compatible with excellent water quality for irrigation.

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Conflicts of Interest

The all authors declare no conflict of interest in this publication.

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