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Physicochemical and Bacteriological Characterization of Drinking Water Points in Urban Areas of Kandi, Northern Benin

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Abstract

Freshwater constitutes only 2% of the world's water resources, and its quality has been compromised by anthropogenic pollution and natural contamination. This research aims to appreciate the physicochemical and bacteriological quality of various drinking water sources in the city of Kandi. Thirty water samples were collected from wells, boreholes (private and public), and the national water distribution network of Benin (SONEB). Six microbiological parameters and 19 physicochemical parameters were analyzed. The Water Quality Index (WQI) was calculated based on 11 physicochemical parameters. Hydrochemical processes were examined using Piper and Gibbs diagrams. Contamination was found in 100% of the well water samples for the six microbiological parameters; only two microbiological parameters were detected in 40% of the borehole samples and 40% of the SONEB samples. Turbidity, potassium, iron, and nitrates exceeded WHO standards in 50%, 80%, 20%, and 65% of well water samples, respectively. The temperature of all water sources was above the normal standard. The WQI was rated as excellent for 100% of the borehole water samples in dry season and for 80% in rainy season. In contrast, the WQI was poor and very poor for well water samples (50% and 5%, respectively, in dry season; and 55% and 20%, respectively, in rainy season). Piper's diagram showed heterogeneity in water type: bicarbonate calcium and magnesium facies (Ca^{2+}-Mg^{2+}-HCO_3^-) occurred in 40% and 28% during the dry and rainy seasons, respectively; chloride sulfate calcium and magnesium facies (Ca^{2+}-Mg^{2+}-Cl^--SO_4^{2-}) in 28% and 32%; chloride sodium and potassium or sulfate sodium facies (Na^+-K^+-Cl^--SO_4^{2-}) in 20% and 12%; and bicarbonate sodium and potassium facies (Na^+-K^+-HCO_3^-) in 12% and 28%. Lastly, the Gibbs diagram indicates that water-rock interactions and rock weathering were the primary factors influencing the chemical composition in the Kandi area. The results could help control sources of pollution in the city's drinking water.

Keywords

Kandi, Water Quality, Water Quality Index, Hydrogeochemical Processes, Chemical Composition

1. Introduction

Drinking water consists of any type of water, treated or untreated, intended for human consumption and domestic household purposes with minimal short- or long-term harm. Its characteristics should meet microbiological, physical, chemical, and radionuclide standards without posing a risk to health. It should be within reasonable temperature limits and free from unpleasant odors, tastes, and colors [1] [2]. Additionally, it should not contain toxins, carcinogens, pathogenic microorganisms, or other health risks [3]. Poor-quality water can lead to environmental issues, particularly for humans and animals, as its consumption can result in mortality [4] [5]. Furthermore, the use of poor-quality water, combined with insufficient drinking water, an unhealthy lifestyle, and inadequate sanitation, contributes to the deaths of 3.5 million people each year [6]. It is estimated that by 2050, 40% of the world's population will face water scarcity issues, forcing many people especially from developing countries to rely on poor-quality water [7]. In developing countries, the quality of drinking water is often compromised, with nearly 80% of diseases attributed to inadequate water and sanitation services. This has led to the death of 2.6 million people annually, including 361,000 children under the age of five [6].

Several studies have been conducted on the physicochemical and microbiological quality of drinking water. The factors affecting physicochemical quality include the use of fertilizers in crop production near water sources, the presence of livestock around water points, and industrial activities close to the catchment area of the water source. [8]-[10] have demonstrated that the non-standard concentrations of nitrates and ammonium found in analyzed water samples are attributable to fertilization with nitrogen fertilizers. Additionally, the proximity of wells to latrines, septic tanks, and illegal garbage dumping contributes to elevated levels of nitrates and ammonium in well water [11]-[13]. Furthermore, the microbiological quality of water deteriorates, particularly due to inappropriate exploitation of the resource. Factors contributing to this decline of the water quality include inadequate design of water points, lack of protection and waterproofing, poor hygienic conditions in dewatering methods, and defective coping. [14] considers that microbiological contamination can occur through re-infiltration of water drawn through cracks in the surface of a well due to inadequate waterproofing around the slab. Various studies [11]-[13] [15] have identified high concentrations of microorganisms, including total coliforms, *Escherichia coli*, fecal enterococci, and sulfite-reducing Clostridium, as indicators of fecal pollution.

In Africa, many households continue to rely on drinking water sources of questionable microbiological and physicochemical quality, such as surface water and well water, to meet their daily needs. This reliance contributes to chronic water problems and increases the prevalence of waterborne diseases [16]-[18]. Ensuring the availability of safe drinking water with minimal long-term health risks necessitates addressing environmental sanitation issues and promoting good hygiene practices in the surrounding areas. In Benin, 70% to 80% of the conditions treated in health centers are attributed to poor hygiene and basic sanitation [19] which affect water supply sources. In the town of Kandi, a significant proportion of the population faces the challenge of access to drinking water, a problem attributable to the inadequacy of conventional water supply infrastructures. The water points available to the population are located in environments that are not sufficiently sanitized. Sanitation problems in Kandi are characterized by a lack of adequate infrastructure for the management of domestic solid waste. Waste is therefore scattered or piled up in low-lying areas, often close to public wells. In addition, the town of Kandi lacks a comprehensive wastewater and excreta management system. Latrines, once filled, remain dry and are not maintained. New latrines are dug alongside the old ones. Inadequate sanitation has a detrimental effect on drinking water quality. In the city of Kandi, fewer than 25% of households benefit directly from the services of the Benin National Water Company. Consequently, the remaining 75% of the population relies on alternative sources for their water needs, including wells and boreholes, with a significant number of households consuming well water. A study on well water quality revealed considerable deterioration, showing extremely high levels of total coliforms, *E. coli*, faecal streptococci, nitrate, potassium, and iron in 100% of the well water samples analyzed from various parts of the city [11]. Very few studies have focused on water quality in the Municipality of Kandi, particularly in its urban area. The findings mentioned above, combined with a lack of data, have sparked our interest in researching the physicochemical and microbiological characteristics of various drinking water sources.

This research aims to appreciate the physicochemical and bacteriological quality of water from different water points used for drinking in urban areas. Specifically, it seeks to analyze the physicochemical and bacteriological quality of well, borehole, and SONEB water and determine the chemical processes affecting well and borehole water.

2. Materials and Methods

2.1. Study Area

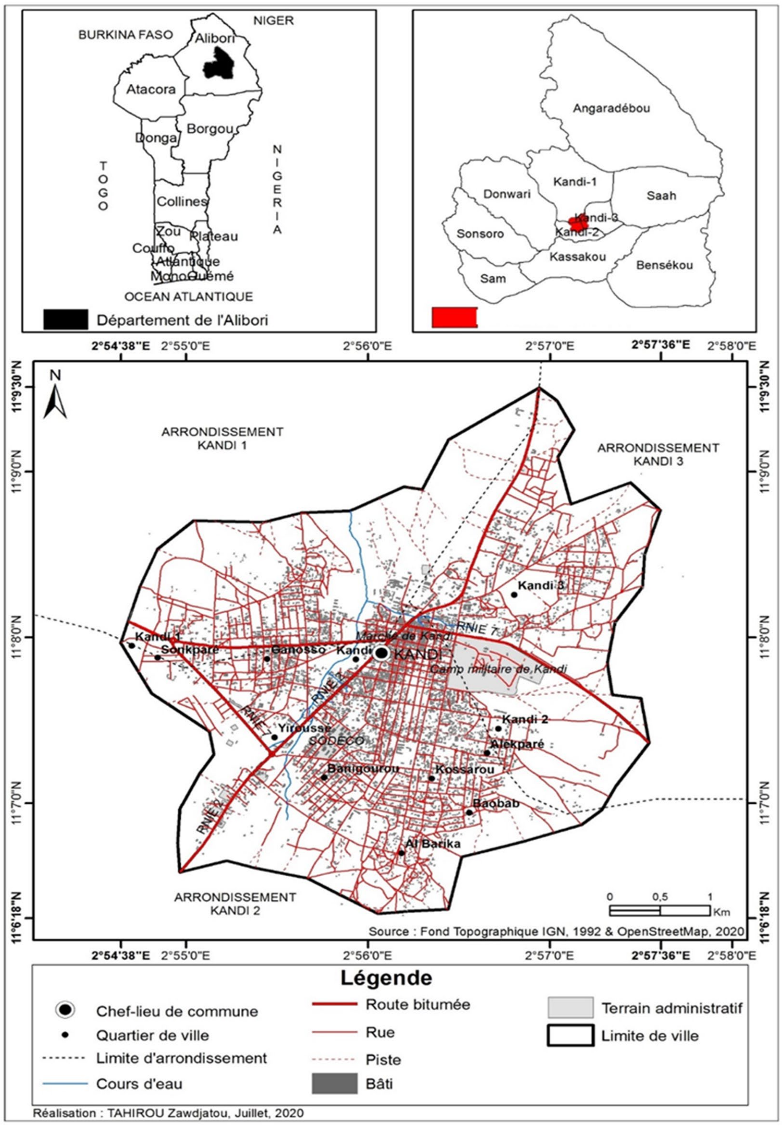


Figure 1. Map showing the geographical location of the town of Kandi [11].

The study area is located in the urban area of Kandi (2˚54'38" - 2˚58'00" E and 11˚6'18" - 11˚9'30" N), a District in the Alibori Department in northeast Benin. The urban area of Kandi covers 1437 km^2 (**Figure 1**). This city experiences a Sudanian climate with a unimodal rainfall regime, characterized by a rainy season from May to September and a single dry season from october to April. The months with the most rain are July, August and September. with 226.01 mm, 246.11 mm and 169.37 respectively over the period from 1992 to 2022. These rainy months favor the availability of water in the majority of water points. Runoff water facilitates the intrusion of waste from household waste (leachate) and wastewater into water points and accentuates their pollution. Maximum temperatures are recorded in the periods of February (37.48˚C), March (37.56˚C) and April (35.57˚C). This high temperature leads to high evaporation on water availability and therefore a high demand for water from populations, difficulty in water supply appear and households are more exposed to the problem of lack of water and water-borne diseases. The city of Kandi is characterized by presence of fine and medium ancient sandstone; breccia, silts, clay and coarse deposits along the Kandi fault. There are also conglomerates that are sometimes less productive than sandstones and favorable to drilling to a depth greater than 80 m. The water level is 5 to 15 m, the flow is 1 to 20 m^3/h and the success rate are over 80% [20]. All the water sources sampled are in this area where the boreholes are favourable. The layer "Kandi Mylonitic Complex: granitoid migmatites, granodiorites, amphibolite gneiss" is also suitable for drilling at a depth of less than 45 m; The water level is 10 to 50 m, the flow is 2 to 5 m^3/h and the success rate are 53 to 70%. The Kandi basin is divided into two main aquifers [20] [21]: the Cambro-Ordovician aquifer known as the Wèrè Formation and the terminal Ordovician/Silurian aquifer called the Kandi Formation. The Cambro-Ordovician aquifer is generally considered to be a semi-confined aquifer; nevertheless, it transitions to an unconfined aquifer in the western and southern peripheral regions of the basin where it becomes exposed. These outcropping regions correspond to the transition zone between the basin and the Pan-African Proterozoic basement formation. The aquifer is predominantly composed of coarse sandstone, exhibiting significant confinement in the southern and western regions of the basin, where it outcrops alongside Precambrian basement. The depth of the aquifer is typically between 30 and 100 metres, with the water table ranging between 5 and 45 metres below ground level when unconfined. The Cretaceous aquifer is composed of coarse-grained sandstone, and the groundwater is unconfined, exhibiting hydraulic continuity with the unconsolidated alluvial deposits that overlie the River Niger.

2.2. Sampling

2.2.1. Water Sources Sampling

The sampled water points consist of all the water points used in the city. These water points are wells, private and public boreholes and water from the network of national company (**Figure 2**). They were chosen to have a proportional spatial coverage with the population density, *i.e.* in areas with a high concentration of housing had higher sources numbers. A total of 20 wells (P1… P20), five boreholes (F1… F5), and five water point of the National Water Company of Benin (SONEB) (S1… S5) were investigated. The wells were included using direct observation with basic criteria such as proximity to garbage dumps, cesspools and latrines, existence of anti-quagmire slabs, permanent water availability, and proximity to lowland. The SONEB sampling points were selected based on their distance from the water treatment plant in order to assess the impact of the residence time on water quality. Boreholes were selected according to their attendance and the influx of the population especially in the dry season.

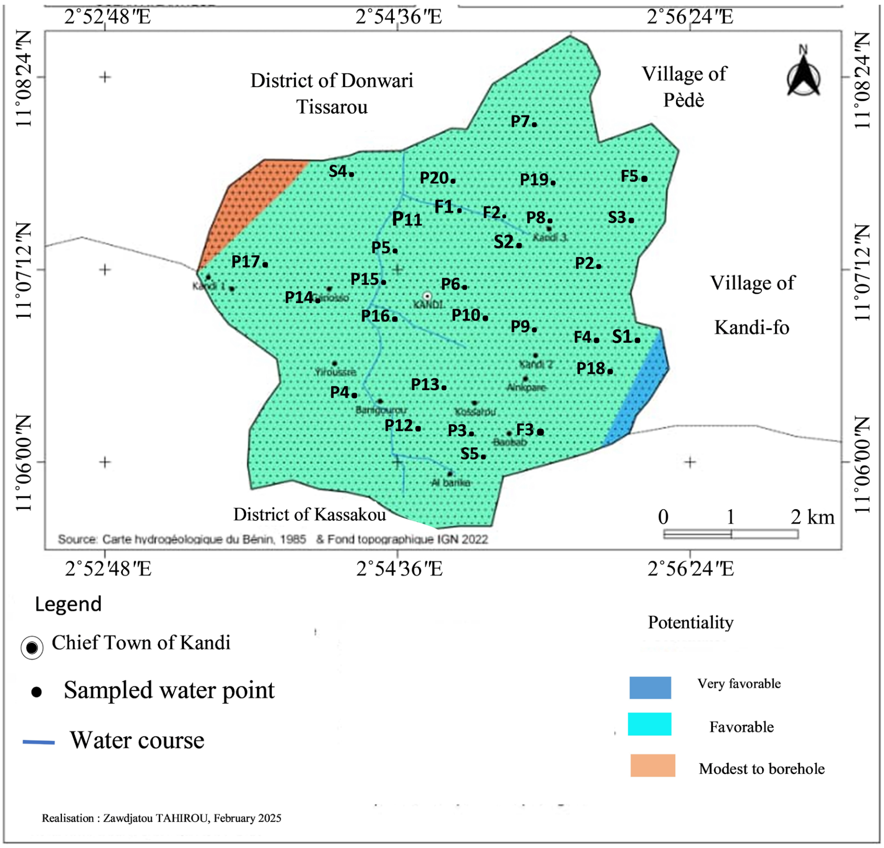


Figure 2. Spatial distribution of sampled water sources.

The sampling campaigns were carried out in the rainy season (August) and dry season (in February) using the Hounslow [22] protocol. Thirty water samples were taken twice for bacteriological analyses in the 30 sources, and 25 samples twice for the physicochemical analyses only in wells and boreholes. SONEB water was not taken for the physicochemical analysis, given the ions dynamics during the phase of water treatment. The collected samples were immediately kept in a cooling environment (4˚C) for their conservation, then transport to laboratory for analysis.

2.2.2. Laboratory Analysis

Physicochemical analyses

The electrical conductivity, pH and temperature were measured directly in the field during water sample collection using a multi-parameter device to avoid significant change over time due to transport conditions [23]. Ammonium (NH_4^+), fluorides (F^-), iron II (Fe^{2+}), nitrites (NO_2^-), nitrates (NO_3^-), sulfates (SO_4^{2-}), and orthophosphates (PO_4^{3-}) were measured using spectrophotometry, which assesses the optical density of substances based on their absorption wavelength. The volumetric titration method was employed to determine calcium (Ca^{2+}), magnesium (Mg^{2+}), chlorides (Cl^-), bicarbonates (HCO_3^-), alkalinity, and water hardness. Sodium (Na^+) and potassium (K^+) levels were assessed through potentiometry. Finally, the turbidity was measured with a nephelometer [24], which quantifies scattered light at a 90-degree angle relative to the incident light.

Bacteriological analysis

The microbiological analysis focused on detecting presumed coliforms, thermotolerant coliforms, *Escherichia coli*, fecal streptococci, sulfite reducers, and fecal enterococci. Streptococci were detected by the m-Enterococcus agar culture method after membrane filtration at 35˚C for 48 hours. Brillance E. coli Selective Agar was used as a culture medium for the detection and enumeration of *Escherichia coli* at 37˚C for 24 hours. Suspected coliforms and thermotolerant coliforms were searched for by the method of filtration and culture on agar with incubation at 35˚C for 24 hours. The search for reducing sulfitals was carried out using the membrane filtration method and incubation at 44˚C for 24 hours. The culture medium used is TSC agar. The values obtained were compared with World Health Organization (WHO) guide values [25] and the accepted standards for drinking water quality in the Republic of Benin.

2.3. Determination of water Quality index

The Water Quality Index (WQI) is calculated using the weighted arithmetic index method [26]-[29]. The relationships among those parameters is that they help to determine only the physicochemical quality status of water points. In this approach, a numerical value known as the relative weight (Wi), which is specific to each physicochemical parameter is calculated with the following equation:

$$Wi = \frac{K}{Si} \tag{1}$$

k is constant of proportionality and can also be calculated using following equation:

$$k = \frac{1}{\sum_{i=1}^{n}\left(\frac{1}{Si}\right)} \tag{2}$$

n is number of parameters and Si is maximum value of the standard norm WHO (or national water quality standard) for each parameter in mg/l, except for pH, T˚C, and electrical conductivity.

A quality assessment scale (qi) is then calculated for each parameter using the equations:

$$qi = 100\frac{V - V0}{Si - V0} \tag{3}$$

Vi and Si are respectively the estimated value and the standard permissible value of the n^{th} parameters at a sampling station.

$V0$ is ideal value of the n^{th} parameter in pure water ($V0 = 0$ for all other parameters of the drinking water except for the parameter pH (7)).

The parameters used to determine the Water Quality Index (WQI) are presented in **Table 1**.

Table 1. List of physic-chemical parameters, including their WHO drinking water standard values (Si), proportionality constants (K), and unit weight factors (Wi).

Parameters	Si	K	Wi
pH	8.5	3.56	0.41
TH	500	3.56	0.01
NO_3^-	50	3.56	0.07
SO_4^{2-}	250	3.56	0.01
K^+	12	3.56	0.3
HCO_3^-	120	3.56	0.03
Cl^-	250	3.56	0.01
Na^+	200	3.56	0.02
Mg^{2+}	50	3.56	0.07
TAC	200	3.56	0.02
Ca^{2+}	100	3.56	0.04

Source: Data processing results, February 2023.

The WQI categories are divided into five water quality states (**Table 2**) [28]-[30].

Table 2. Classification and possible use of water according to WQI value.

WQI class	Type of water	Potential use
0 - 25	Excellent quality	Drinking water, irrigation and industry
>25 - 50	Good quality	Drinking water, irrigation and industry
>50 - 75	Poor quality	Irrigation and industry
>75 - 100	Very poor quality	Irrigation and industry
>100	No-drinking water	Appropriate treatment required before

Source: Adapted from [13] [31]-[33].

In summary, the overall water quality index is calculated using the equation:

$$IQE = \frac{\sum_{i=1}^{n} qi \times Wi}{\sum_{i=1}^{n} Wi} \tag{4}$$

2.4. Piper Diagram and Gibbs

The Piper diagram is used to identify the different faces of the water points sampled. The Gibbs diagram is utilized to characterize the geochemical processes underlying the mineralization of groundwater [34]-[37]. The Gibbs diagram comprises two parts [38]: the first illustrates the relationships between total dissolved solids (TDS) and Na^+ + (Na^+ + Ca^{2+}), while the second relates TDS to Cl^- + (Cl^- + HCO_3^-).

3. Results and Discussion

3.1. Physicochemical Quality of Water from Wells and Boreholes

The comparison of the average concentrations of cations and anions in well water (Table 3) showed the following order: $K^+ > Na^+ > Ca^{2+} > Mg^{2+}$ and $NO_3^- > HCO_3^- > Cl^- > PO_4^{3-} > SO_4^{2-} > Fe^{2+} > F^- > NO_2^-$. At the borehole level, the order is $Na^+ > K^+ > Ca^{2+} > Mg^{2+} > NH_4^+$ and $HCO_3^- > Cl^- > NO_3^- > SO_4^{2-} > PO_4^{3-} > F^- > NO_2^-$. Overall, the anions and cations concentrations in well water differ from those in the borehole water. These results indicate that some parameters in the water exceeded the WHO recommended guideline values for water potability. Therefore, all recorded temperature values are above the normal (25˚C) recommended by WHO [39] for drinking water. The water temperature is influenced by various factors, such as site altitude, sampling time, and climatic conditions at the time of sampling. Regarding the pH parameter, 100% of the values are between 6.5 and 8.5, which is the pH range recommended by WHO for drinking water. The highest pH values are recorded at the wells, particularly in wells P3, P6, P7, P16, and P18. From a health perspective, even if the water pH range ($6.5 \le pH \le 7.8$) does not pose any health risks in itself, it is conducive to the development of microorganisms (Bacteria $4.5 < pH < 9$; Yeast $2 < pH < 9$; Mold $1.5 < pH < 11$) [40]. In the event of contamination of the water table, the turbidity values recorded during this study range from 0 to 12 NTU. Overall, turbidity measurements obtained in the dry season are higher than those recorded in the rainy season due to the drop-in water level, the rise of mud and in unprotected wells from the introduction of dust raised by harmattan winds. Nearly 75% of the wells exhibit turbidity, with the highest values (exceeding the 5 NTU standard) found in wells P2, P4, P5, P6, and P8. The turbidity at the boreholes was zero or equal to 1 NTU. This is linked to the fact boreholes are protected water points located deeper and these boreholes have mechanical means of extracting water unlike wells. Notably, the wells with the highest turbidity also contain the highest iron content; this may partly explain the elevated turbidity values, which are associated with the rusty red coloration imparted to the water by iron. However, 20% of the sampled points exhibited a ferrous ion concentration greater than or equal to the 0.3 mg/l standard recommended by WHO for drinking water at least in one season (either dry or rainy). The presence of iron in groundwater has multiple origins, including pyrite (FeS2), which is commonly associated with sedimentary rocks deposited in reducing environments (such as marls and clays) as well as with metamorphic rocks. Iron can also enter groundwater from surface water, industrial effluents, or wastewater. Regarding potassium ions, 80% of well waters in the rainy season and 45% in the dry season have concentrations greater than or equal to the WHO standard of 12 mg/L, with values ranging from 1.09 to 23.09 mg/L in the rainy season and from 1.46 to 29.80 mg/L in the dry season. In contrast, boreholes water has concentrations that are 100% below the standard in both seasons. For nitrates, 65% of well waters exceed the WHO standard of 50 mg/L. Nitrate concentrations at the sampled points vary between 7 and 129.04 mg/L in the dry season and between 9.65 and 181.43 mg/L in the rainy season, with higher values observed during the rainy season. Additionally, 75% of wells have a nitrate concentration greater than or equal to 10 mg/L, which suggests that the presence of nitrates in the water is likely of anthropogenic origin [41]. The anthropogenic activities contributing to the high nitrate levels in the sampled waters, particularly in wells, include the proximity of poorly maintained and failing sanitation facilities (such as latrines, sumps, septic tanks, and soak ways) and unsanitary conditions around the wells (including stagnant water, animal droppings, and other household waste). It is noteworthy that 75% of the investigated wells are located less than 15 meters from either sanitation facilities or illegal garbage dumps (**Photo 1**), or in lowland areas. Household surveys revealed that 89% of the pit latrines built are not watertight; among this proportion, 43% are filled with water during the rainy season. The high nitrate levels during rainy periods are certainly due to the phenomenon of infiltration of leachate from rubbish dumps and domestic sewage, and also to the transfer between non-watertight latrines and nearby water points. This situation likely allows microbiological germs and nitrates to infiltrate the shallow aquifers. Consuming water with high nitrate concentrations poses health risks, particularly to infants under three months old who are bottle-fed, as well as to children, pregnant women, and individuals with a genetic deficiency in glucose-6-phosphate dehydrogenase or methemoglobinemia [41]-[45].

Table 3. Maximum, minimum, mean and standard deviation of the various physic-chemical parameters measured in dry and rainy season.

			T	pH	Cond	Turb	TH	Ca^{2+}	Mg^{2+}	Na^{+}	K^{+}	HCO_3^{-}	Cl^{-}	NO_3^{-}	SO_4^{2-}	TAC	NO^{2-}	NH_4^{+}	Fe^{2+}	PO_4^{3-}	F^{-}
			˚C	-	µS/Cm	UTN	˚F	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L
Dry season	Wells	Average	27.2	7.1	286.4	3.6	32.3	11.63	5.21	12.89	13.34	50,232	5.39	57.81	0.24	11.2	0.03	0.06	0.18	1.09	0.12
		Min	26.6	6.6	140	0.7	6	2.98	1.21	2.77	1.8	7.3	0.29	7.06	0.01	7	0	0	0	0.17	0
		Max	28.1	7.8	585	12	95	26.02	12.3	27.14	29.14	103.8	22.03	129.04	1.14	17	0.20	0.30	0.8	11.04	0.51
		Standard deviation	0.286	0.25	98.04	2.2	16.59	5.32	2.27	5.48	5.07	22.09	4.14	25.54	0.23	1.8	0.03	0.06	0.17	1.09	0.12
	Boreholes	Average	27.1	6.6	243.8	0.2	19	6	2.32	6.84	4.64	41.47	5.05	4.93	0.5	10.4	0.01	0.02	0.01	0.29	0.19
		Min	26.9	6.5	164	0	18	3.12	1.07	5.6	2.92	36.86	3.26	3.7	0	9	0	0.01	0	0.16	0.07
		Max	27.3	6.7	388	1	20	10.02	3.72	8.9	5.14	45.91	6.97	6.74	1.05	13	0.032	0.05	0.02	0.42	0.3
		Standard deviation	0.128	0.07	58.16	0.32	0.8	2.2	0.92	1.02	0.68	2.09	0.94	0.76	0.33	1.04	0.01	0.014	0.009	0.1	0.09
Rainy season	Wells	Average	26.98	7.1	298.5	2.63	31.35	14.2	7.06	18.89	15.39	67.92	7.91	72.26	0.44	11	0.04	0.07	0.2	1.06	0.12
		Min	26	6.7	160	0.3	7	2.91	2.87	4.17	1.46	11.06	0.58	9.64	0.02	7	0.003	0	0	0.15	0
		Max	27.9	7.9	590	12	93	26.84	15.61	46.91	23.09	135.32	16.73	181.43	1.69	16	0.23	0.27	0.83	11.01	0.47
		Standard deviation	0.432	0.26	99.8	1.72	15.65	5.08	3.03	10.36	4.43	25.63	3.2	37.57	0.34	1.6	0.03	0.05	0.18	1.08	0.12
	Boreholes	Average	26.7	6.7	243.6	0.6	23.6	9	3.58	13.07	5.07	56.71	10.91	8.66	0.91	10.6	0.01	0.03	0.02	0.34	0.29
		Min	26.4	6.5	160	0	16	5.72	2.53	10.48	3.64	48.87	9.08	5.08	0.3	9	0	0.01	0	0.16	0.08
		Max	27	6.9	385	1	38	10.7	5.02	16.01	6.45	63.21	13.95	11.49	1.57	13	0.031	0.05	0.06	0.42	0.56
		Standard deviation	0.2	0.15	58.72	0.48	6.72	1.3	0.76	1.93	0.9	4.504	1.25	2.3	0.32	1.12	0.007	0.001	0.01	0.08	0.11

(a) (b)

Photography: Z. Tahirou, mars, 2024.

Photo 1. Well located near a garbage dump in Ganssoso (a); and Well located near the waste water from the toilet Keferi (b).

3.2. Water Quality Index

The WQI values for water from different sources vary between the dry and rainy seasons (Figure 3).

The WQI was excellent for 100% of the borehole water samples in dry season and for 80% of the samples in rainy season. However, the WQI was poor and very poor for well water samples, with 50% and 5%, respectively, in dry season, and 55% and 20%, respectively, in rainy season. In all water points, the WQI values from one season to another varied. These variations are intrinsic to each water point. These results corroborate those found by [13] which indicates that the WQI values of the sampled water points do not depend on the season.

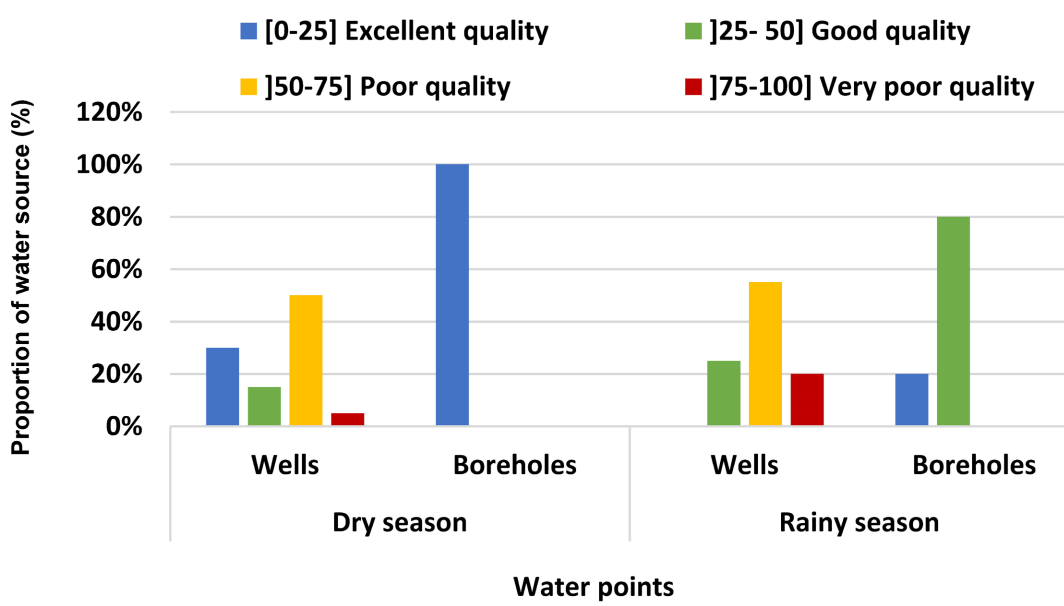


Figure 3. Proportions of different water points according to water quality classes.

3.3. Hydrochemical Facies of Waters

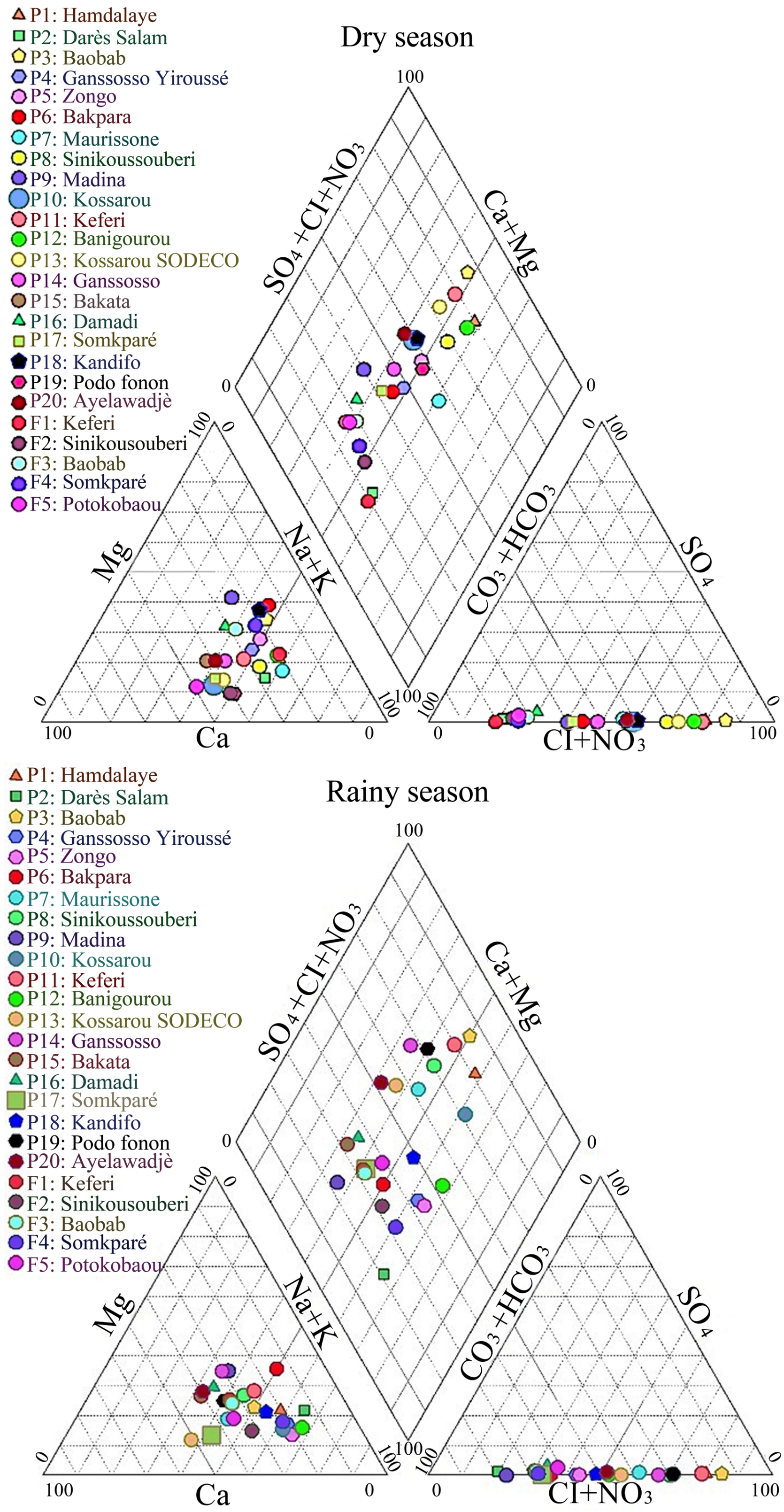


Figure 4. Hydrochemical facies.

The Piper diagram [46] illustrates the classification of different hydrochemical facies of water. Changes in the chemical composition of groundwater are related to ion exchange, dissolution or alteration of rocks, contamination by humans, or saline intrusion [13]. Aquifers, due to their mineral compositions, can affect the quality of groundwater. **Figure 4** illustrates several hydrochemical facies of well and borehole waters, highlighting the heterogeneity in water type (**Table 4**). This heterogeneity in water type in Kandi was previously observed in 2017 by M. K. Zouari [47]. In the dry season, the dominant facies are Ca^{2+}-Mg^{2+}-HCO_3^- (40%) and Ca^{2+}-Mg^{2+}-Cl^--SO_4^{2-} (28%), In the rainy season, the dominant facies are Ca^{2+}-Mg^{2+}-Cl^--SO_4^{2-} (32%), (Ca^{2+}-Mg^{2+}-HCO_3^- (28%) and Na^+-K^+-HCO_3^- (28%).

From the dry season to the rainy season, the chemical composition of the waters underwent changes that affected the facies of some wells and boreholes. As a result, 36 % of the water points migrated from one facies to another. However, the water samples from the boreholes, in both seasons, primarily displayed a Ca^{2+}-Mg^{2+}-HCO_3^- (60%) and Na^+-K^+-HCO_3^- (40%).

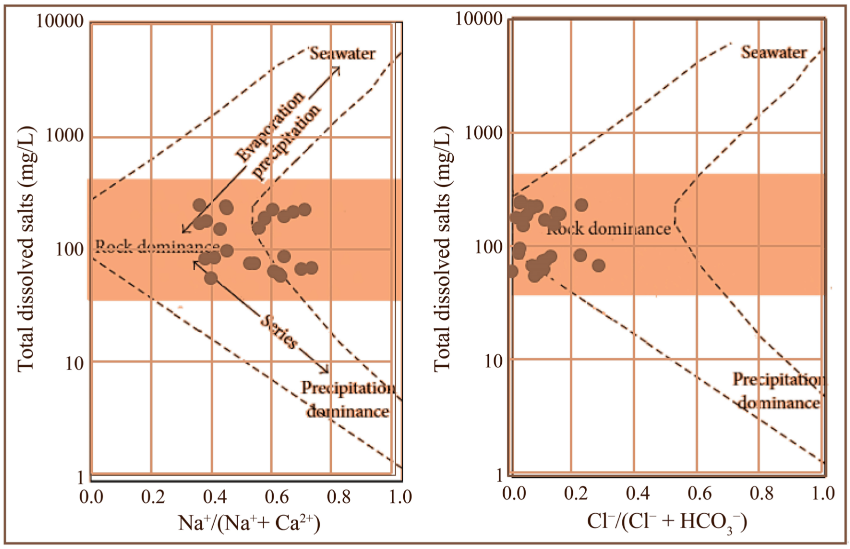
Table 4. Distribution of different water samples in hydrochemical facies.

Facies	Dry season	Rainy season
	Water points	
Bicarbonate calcium and magnesium (Ca^{2+}-Mg^{2+}-HCO_3^-)	P4; P6; P9; P14; P15; P16; P17; F3; F4; F5	P9; P15; P16; P17; F1; F3; F5
Calcium and magnesium sulfate chlorides (Ca^{2+}-Mg^{2+}-Cl^--SO_4^{2-})	P3; P10; P11; P12; P13; P18; P20	P3; P7; P8; P11; P13; P14; P19; P20
Sodium and potassium chloride or sodium sulfate (Na^+-K^+-Cl^--SO_4^{2-})	P1; P5; P7; P8; P19	P1; P10; P12
Bicarbonate sodium and potassium (Na^+-K^+-HCO_3^-)	P2; F1; F2	P2; P4; P5; P6; P18; F2; F4

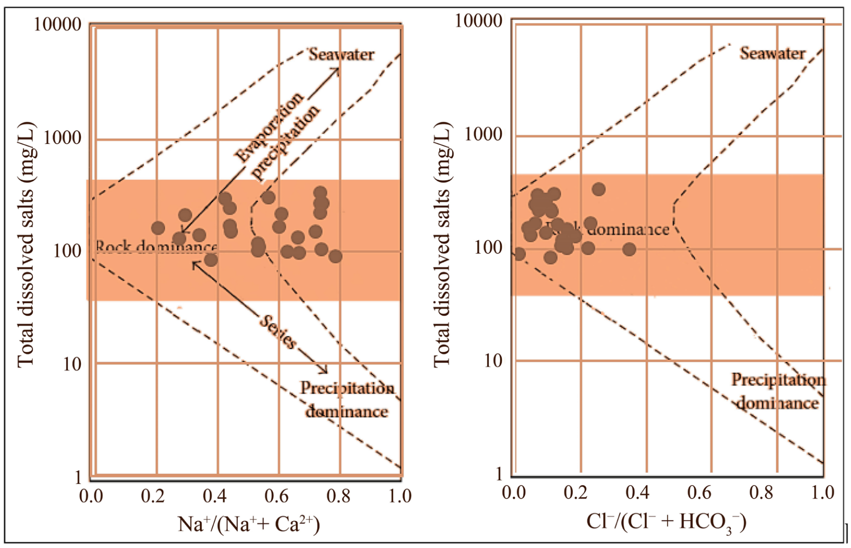
Source: data processing results.

3.4. Gibbs Diagram

The Gibbs diagram [48] (**Figure 5**) illustrates the ratios of $Na^+/(Na^+ + Ca^{2+})$ and $Cl^-/(Cl^- + HCO_3^-)$ as a function of TDS. Across all seasons, all water samples are located in a zone of rock alteration (water-rock interaction). The values of the first Gibbs ratio (weight of cations) in the dry and rainy seasons vary from 0.35 to 0.73, with an average of 0.53 ± 0.10, and from 0.20 to 0.78, with an average of 0.54 ± 0.14, respectively. The second Gibbs ratio (weight of anions) shows values ranging from 0.008 to 0.28, with an average of 0.10 ± 0.05 in the dry season, and from 0.1 to 0.34, with an average of 0.12 ± 0.05 in the rainy season. Across all seasons, groundwater samples indicate a zone dominated by rock weathering. This result suggests that water-rock interactions and rock weathering are the main factors controlling the chemical composition in the study area. However, according to [49] and [50], while Gibbs diagrams can suggest the natural origins of waters, they do not indicate the influence of anthropogenic activities on water quality. Therefore, the application of other complementary techniques, such as ionic ratios, can help address this limitation.



(a)



(b)

Figure 5. Gibbs Diagram of the sampling water on the City of Kandi: (a) dry season; (b) rainy season.

Across all seasons, all water samples are located in a zone of rock alteration (water-rock interaction). The values of the first Gibbs ratio (weight of cations) in the dry and rainy seasons vary from 0.35 to 0.73, with an average of 0.53 ± 0.10, and from 0.20 to 0.78, with an average of 0.54 ± 0.14, respectively. The second Gibbs ratio (weight of anions) shows values ranging from 0.008 to 0.28, with an average of 0.10 ± 0.05 in the dry season, and from 0.1 to 0.34, with an average of

0.12 ± 0.05 in the rainy season. Across all seasons, groundwater samples indicate a zone dominated by rock weathering. This result suggests that water-rock interactions and rock weathering are the main factors controlling the chemical composition in the study area. However, according to [49] and [50], while Gibbs diagrams can suggest the natural origins of waters, they do not indicate the influence of anthropogenic activities on water quality. Therefore, the application of other complementary techniques, such as ionic ratios, hierarchical ascending classification, can help address this limitation.

3.5. Ion Exchange

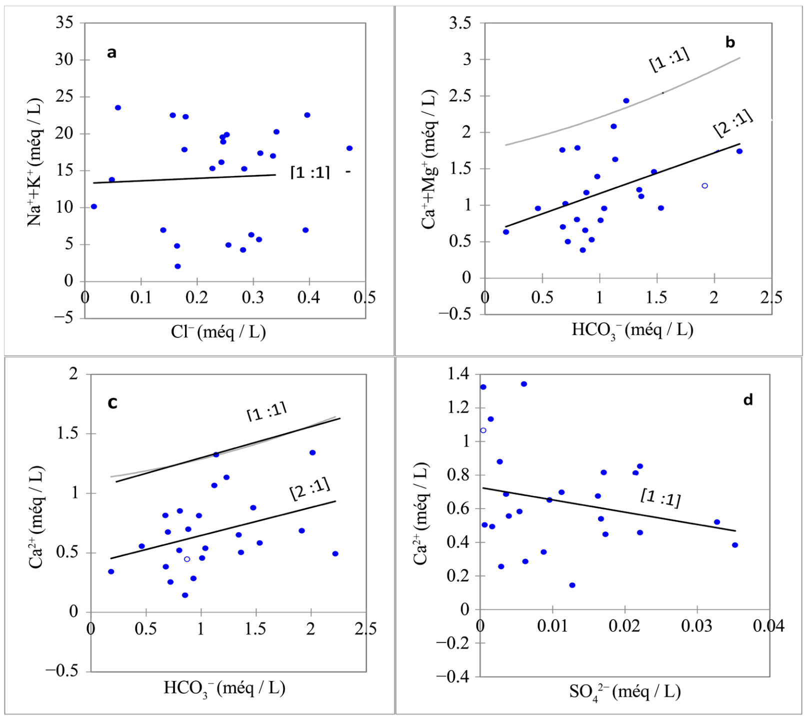


Figure 6. Relationship between major ions: (Na^+ + K^+) vs Cl^- (a), (Ca^{2+} + Mg^{2+}) vs HCO_3^- (b), (Ca^{2+}) vs (HCO_3^-) (c) and (SO_4^{2-}) vs (Ca^{2+}) (d).

The diagram in **Figure 6(a)** shows that the point cloud is distributed on either side of the 1:1 slope line, with the points below (36%) further away than those above. This suggests that there is no dissolution of halite but rather ion exchange through the release of Na^+ and the fixation of Ca^{2+}; similar results were obtained in the groundwater of the basement aquifers at Natitingou in Benin [51]. The origin of the dissolution of carbonate minerals into ions in groundwater can be highlighted by the (Ca^{2+} + Mg^{2+}) and (Ca^{2+}) versus (HCO_3^-) diagrams [50]. If the dissolution of carbonate minerals such as dolomite ($CaMgCO_3$) and calcite ($CaCO_3$) is responsible for the presence of Ca^{2+}, Mg^{2+}, and HCO_3^- ions in the water table, the point cloud forming the diagrams should align along the lines of slopes 1:1 and 2:1. **Figure 6(b)** and **Figure 6(c)** show scattered point clouds completely below the 1:1 slope line, with some points close to the 2:1 slope line. Thus, a certain relative dominance of the bicarbonate ion over the Ca^{2+} + Mg^{2+} ions is suggested, indicating the influence of the dissolution of carbonate minerals (calcite and dolomite) in a portion 56% of the samples, with the remainder attributed to ion exchanges. These results are similar to those obtained in the groundwater of the Kandi Basin [52] and in the groundwater of the alluvial-diluvial plain of southwestern Shandong Province and the Yishu River Basin in China [53]. As with the previously mentioned ions, the origin of SO_4^{2-} and Ca^{2+} ions in groundwater can be highlighted using the SO_4^{2-} versus Ca^{2+} diagram [49]. If gypsum dissolution ($CaSO_4 \cdot 2H_2O$) is responsible for these ions in the water, the scatter plot of the diagram will align along the 1:1 slope line. The results from the analyses showed a scattered plot around the 1:1 slope line (**Figure 6(d)**), which suggests that gypsum dissolution does not control the presence of SO_4^{2-} and Ca^{2+} ions in the sampled waters. Instead, these ions could result from ion exchange (for points above the line) and reverse ion exchange (for points below the line) processes [54].

3.6. Bacteriological Quality of Water from Different Water Point

To ensure the safety of drinking water supply and the management of health risks, it is essential to detect episodes of contamination in water sources (**Table 5**) due to their vulnerability to inadequate household practices [55].

Table 5. Seasonal mean, maximum and minimum values of microbiological parameters.

Dry Season										
		SONEB network			**Borehole**			**Wells**		
Bacteriological parameters (CFU/100 ml)	WHO standards	Average	Max	Min	Average	Max	Min	Average	Max	Min
Presumed coliforms	0	4	13	0	11.8	31	0	178455	622000	6011
Thermotolerant coliforms	0	2.8	8	0	8.6	26	0	102390	411700	5209
Escherichia coli	0	0	0	0	0	0	0	6876	42822	102
Fecal streptococci	0	0	0	0	0	0	0	3433	21077	59
Sulfite-reducers	0	0	0	0	0	0	0	3.1	16	0
Fecal enterococci	0	0	0	0	0	0	0	207	720	19
Rainy Season										
		SONEB network			**Boreholes**			**Wells**		
Bacteriological parameters (CFU/100 ml)	WHO standards	Average	Max	Min	Average	Max	Min	Average	Max	Min
Presumed coliforms	0	7	21	0	12.8	36	0	186731	671000	10200
Thermotolerant coliforms	0	5.2	17	0	9.8	28	0	163177	594839	8404
Escherichia coli	0	0	0	0	0	0	0	8091	59000	98
Fecal streptococci	0	0	0	0	0	0	0	3162	9180	101
Sulfite-reducers	0	0	0	0	0	0	0	12	29	0
Fecal enterococci	0	0	0	0	0.4	0	0	316	948	20

Source: Data processing results.

The presence of *Escherichia coli* and fecal streptococci in well water samples is a clear indicator of fecal pollution. Although these wells are located in different neighborhoods, the high concentrations of microbiological contaminants suggest a pervasive and ongoing pollution of the well water. The causes of this pollution are varied, including the environmental conditions around the wells (proximity to toilet facilities, household waste disposal sites, wastewater and runoff receptacles) and risky behaviors among the local population (such as the use of dirty water collection equipment and allowing children to introduce unclean objects into unprotected wells).Furthermore, the presumed coliforms and thermotolerant coliforms detected in the two SONEB subscribers farthest from the network may be linked to one-off contamination at the Subscribers due to breaks in the network pipes, which can allow microorganisms to intrude. This may also be attributed to the presence of biofilms within the pipes. According to [56], a breakdown in the integrity of the network, such as a pipe break or leak, can lead to the intrusion of microbes through short-term pressure transients. Drinking water distribution systems are challenging environments with oligotrophic conditions where residual disinfectants are commonly maintained. Despite this, microorganisms can survive and adhere to the internal surfaces of pipes, forming biofilms that may compromise water quality [57] [58]. Indeed, biofilms consist of clusters of microorganisms, typically encased in a matrix of extracellular polymeric substances that contain both organic and inorganic matter. These biofilms form naturally in all drinking water distribution networks and can harbor pathogenic germs (such as Legionella and fecal coliforms) [59]-[62]. According to [63], the degradation of residual chlorine in a distribution network is associated with the presence of biofilms or corrosion tubercles, which are subject to the oxidizing action of chlorine on walls of pipes (the wall effect) and natural organic matter. Additionally, the time required to transport water from the treatment station to the last subscribers, along with the length of the pipes, can contribute to the degradation of residual chlorine in the network. The results of the studies conducted by [64]-[66] indicated that various factors such as the length of the water distribution pipes, the time taken to transport water to each subscriber, the pressure, and the speed of water flow can influence the free residual chlorine content in drinking water. Identical pathogens, specifically presumed coliforms and thermotolerant coliforms, were detected at both a private (F1) and public (F5) boreholes. In both instances, the identified causes were linked to a lack of maintenance of these structures. Water from the borehole (F1) originates from a storage tank that has almost never been cleaned since its installation. The pathogens detected in this source could be associated with the presence of biofilms, which provide support and protection for bacterial colonies in the catchment and storage structures (tanks) used by households. In the case of public borehole F5, where water comes directly from the pump, the presence of bacteria can be attributed to several factors. A poorly cleaned coping allows the accumulation of sludge deposits at the pump head and facilitates the infiltration of contaminants. In addition, the periodic repair and maintenance work required for the operation of the pump can facilitate the penetration of bacteria into the borehole. [13] highlights that poorly maintained pump head systems are significant contributors to the infiltration of contaminated wastewater into boreholes. In contrast, other unpolluted water sources show no bacterial presence, which can be attributed to the maintenance of these structures and the greater depth of these sources averaging over 40 meters along with the filtering capacity and physical structure of the soil, its granulometry, and the hydrodynamics of the groundwater. These results agree with [67] which estimates that depending on the geomorphological characteristics of an area, the speed of progression of the pollutant load depends on the hydrodynamics of the groundwater, the physical structure of the soil, and its particle [68]-[70] estimate that the extension of pollution, from a point of contamination (latrines, illegal dumping, etc.) to groundwater, depends on the speed and direction of circulation waters. Furthermore, the urban population is well aware of the causal link between the drop-in water level and its physical quality, which is characterized by high turbidity, color changes, and even odor. Households often introduce disinfectant products (such as calcium hypochlorite, Aquatab tablets, and alum) into the water to improve its quality (making it drinkable). However, this intervention can yield either positive effects (eliminating germs) or negative effects (forming trihalomethanes) on water quality.

4. Conclusions

This study demonstrated that well water in the city of Kandi is heavily contaminated by microbiological germs with levels 100 to 1000 times higher than the WHO standard (0 CFU/100 ml) in both seasons. In contrast, borehole water samples and those from the SONEB network only contained presumed coliforms and thermotolerant coliforms in low concentrations. Physicochemical level, all water points studied (boreholes and wells) exhibited an average mineralization ranging from 140 to 590 µS/cm and slight acidity, with average pH levels of 6.6 for boreholes and 7.1 for wells. Well water showed exceedingly high levels of nitrates (65% above the WHO standard of 50 mg/l) and potassium (80% above the standard of 12 mg/l). The Piper diagram indicates heterogeneity in water types. In the dry season, the dominant facies are Ca^{2+}-Mg^{2+}-HCO_3^- (40%) and Ca^{2+}-Mg^{2+}-Cl^--SO_4^{2-} (28%), In the rainy season, the dominant facies are Ca^{2+}-Mg^{2+}-Cl^--SO_4^{2-} (32%), Ca^{2+}-Mg^{2+}-HCO_3^- (28%) and Na^+-K^+-HCO_3^- (28%). The Gibbs diagram indicates that water-rock interactions and rock weathering primarily control the chemical composition in the study area. The ionic relationships of ($Na^+ + K^+$) versus Cl^- suggest that there is no dissolution of halite, but rather ion exchange through the release of Na^+ and fixation of Ca^{2+}. Furthermore, the diagrams ($Ca^{2+} + Mg^{2+}$) and (Ca^{2+}) versus (HCO_3^-) indicate a relative dominance of the bicarbonate ion compared to $Ca^{2+} + Mg^{2+}$ ions, suggesting the influence of carbonate mineral dissolution (calcite $CaCO_3$ and dolomite $CaMgCO_3$) for 56% of the samples. The SO_4^{2-} versus Ca^{2+} diagram indicates that the dissolution of gypsum ($CaSO_4 \cdot 2H_2O$) does not control the presence of SO_4^{2-} and Ca^{2+} ions in the sampled waters; these ions likely originate from ion exchange and reverse ion exchange processes. Finally, the assessment of the suitability of the water for consumption indicates that borehole waters belong mainly to the excellent quality classes, with 100% in the dry season and 80% in the rainy season.

Given these findings of deteriorating drinking water quality, it would be prudent to review the situation of water points in relation to toilets, household waste and sewage, and above all, households should disinfect water from wells and boreholes with chlorine before drinking. We suggest that the authorities extend the SONEB water networks in the neighbourhoods, increase the frequency of water sampling and analysis at the subscriber level in order to adjust treatment products, and set up a toll-free number to report network malfunctions.

Conflicts of Interest

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

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