Journal of Water Resource and Protection, **2013, 5, 427-439**
http://dx.doi.org/10.4236/jwarp.2013.54042 Published Online April 2013 (http://www.scirp.org/journal/jwarp)

Influence of Anthropogenic Activities of Groundwater from Hand Dug Wells within the Precarious Settlements of Southern Abidjan, Côte d'Ivoire: Case of the Slums of Anoumabo (Marcory) and Adjouffou (Port-Bouët)

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Received November 4, 2012; revised February 16, 2013; accepted February 28, 2013

ABSTRACT

This study aims to examine the quality and quantity of the groundwater resources from hand-dug wells, within two of these slums—Anoumabo (Marcory) and Adjouffou (Port-Bouët), both located in the southern part of the city. Twenty-eight representative groundwater samples were collected from different domestic wells within the study area. In addition, water samples were collected from the adjoining surface water bodies—the Ébrié lagoon and the Atlantic Ocean. The water samples were also tested for microbial indicators of fecal contamination using the conventional membrane filtration method. The groundwater samples are alkaline to acidic with pH ranging between 4.4 and 8.1. They are slightly mineralized with electrical conductivity, EC values ranging between 388 µS/cm and 1494 µS/cm. The dominant hydrochemical facies are Na-Cl, Na-SO_4, Ca-Cl and Ca-SO_4. Although, majority of the water samples have anions and cations concentrations conforming to the World Health Organization, alerting levels of nitrate contamination was recorded in the area. About 67 percent of the tested samples have nitrate values greater than the recommended WHO limit for drinking water ($NO_3 > 50$ mg/ℓ). Exceeding high nitrate concentrations in drinking water have been medically proven to be detrimental to infant health. Microbial analyses reveal bacterial contamination at varying degrees in all of the water wells. The presence of these microbial organisms in the samples is also indicative of the presence of some other disease causing pathogens, responsible for sicknesses like cholera, diarrhea, typhoid, etc. The water wells located within Anoumabo have relatively higher levels of groundwater contaminants in comparison to those located within Adjouffou. This is obviously due to the poor well designs and prevalent unhygienic and poor sanitary habits of its inhabitants. These waters though completely unsuitable for drinking and domestic purposes, can be used for irrigation purposes with very little or no sodium problems.

Keywords: Anthropogenic Activities; Assessment; Groundwater; Pollution; Well

1. Introduction

Abidjan is facing great challenges in keeping up with the supply and distribution of potable water to its mushrooming inhabitants as with other big cities in the developing countries of the world. Despite its high annual precipitation of approximately 1800 mm, there still exists uneven distribution of this all important natural resources. This shortage has led to the over-abstraction and contamination of groundwater resources in some parts of the town. Recent studies show that the vast surface water bodies, the Ébrié lagoon and the Atlantic ocean, which serves as direct source of water to the population and also indirectly as recharge sources to water wells are also threatened and faced with serious pollution problems [1-4]. Though, a natural renewable resource, the geochemical quality and quantity of these waters are controlled to a very great extent by both geogenic and anthropogenic factors. In a bid to resolve this problem of water shortage, individuals, especially those within the slums of the city have gone about digging water wells to serve both domestic and agricultural purposes. These wells are mostly dug by local laymen with simple hand tools such as shovels and hoes and in some places have been cased with local materials such as used car tyres and metal drums. The quality and quantity of water obtainable from these wells is very doubtful; as they are shallow, the areas around most of the them are not sealed to prevent direct infiltration of surface contaminants, some others are dangerously located very close to sewage tanks, pig-rearing houses, bathrooms, car wash, and mechanic workshops amongst other likely pollution sources. In addition, the overall sanitation conditions prevalent within these slums are gruesome. Most of these dug wells have been shut down and abandoned due to dryness. These poverty—stricken communities locally referred to as "quartiers precaire" or "bidonville" are the hardest hit by this ordeal. Records as at 1990 showed that there exist a total of sixty-eight slums within this city; each affected in varying degrees by lack of potable water supply and unhygienic sanitation conditions. Water is the elixir of life. Its function to living organisms cannot be substituted by any other substances and as such poor quality water has grave health consequences to both plants and animals. It is a well known fact that "water is not only basic prerequisite for social stability and prosperity—it also creates new areas of life and economy". This study therefore undertakes the task of determining the quality and quantity of groundwater from the traditional hand-dug wells and the adjoining surface water bodies—the Ébrié Lagoon and the Atlantic Ocean, which also serve as means of water supply, based on hydrochemical, and microbiological data, using as case study two selected slums within the city. Abidjan, the economic and administrative capital of Côte d'Ivoire, is located in the southeastern part of country between latitudes 5˚00' and 5˚30' North and longitudes 3˚00' and 6˚00' East. It is a low-lying coastal city built around coastal lagoons on several converging peninsulas and islands, connected by bridges. It has a surface area of about 14,200 km^2 of which about 16% comprise the lagoon. The city of Abidjan, the biggest in Côte d'Ivoire, is subdivided into ten administrative communes. These are 1) Abobo; 2) Adjame; 3) Attecoube; 4) Cocody; 5) Le plateau; 6) Yopougon; 7) Treichville; 8) Koumassi; 9) Marcory and 10) Port Bouët (**Figure 1**). There exists no official record of preliminary site investigations of these settlements. They are usually located in geo-risk and geo-hazard prone zones, since; availability is the primary selection criteria. The houses are usually made from materials such as wood, canopies, plastics and in rare cases cement are habited by low income earners with little or no formal education, who cannot afford the high cost of decent accommodations. The occupants are mostly peasant farmers, security guards, iron smelters, block molders, mechanics, carpenters and petty traders. These informal settlements are characterized by, low standard of living, poor health and sanitary conditions, lack of proper waste collection and disposal systems, lack of basic social amenities like roads, drainages, electricity and potable drinking water.

2. The Study Area

Abidjan has four distinct morphological components, these are: the coastal belt, the petit—Bassam peninsula, the Ébrié lagoon and the plateau running from south to

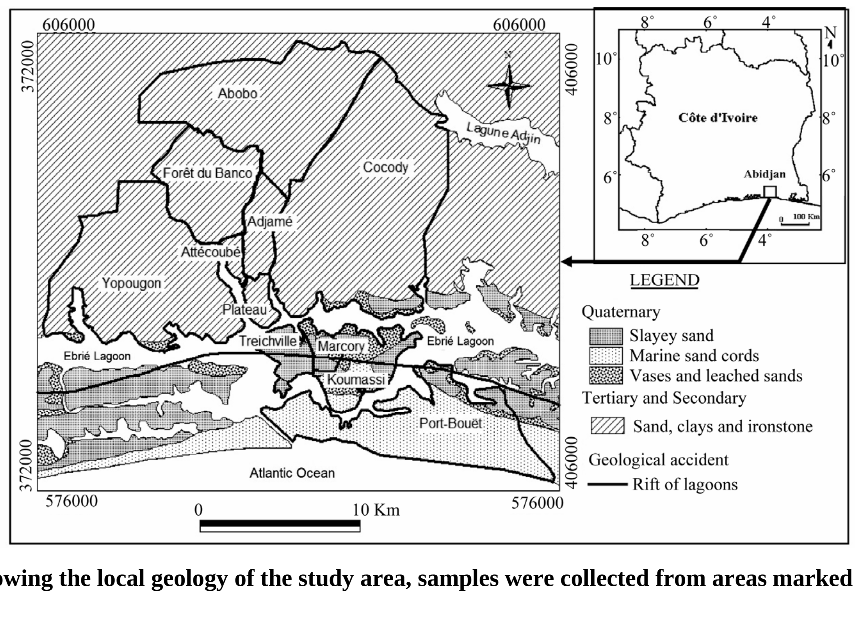


Figure 1. Map showing the local geology of the study area, samples were collected from areas marked with the red dots.

north over a distance of about 30 kilometers. This study is restricted to the precarious settlements of Anoumabo and Adjouffou, located within the communes of Marcory and Port-Bouët respectively in the southern part of Abidjan (**Figure 1**).

The precarious settlement of Anoumabo is located on the Petit-Bassam peninsula. It is a low-lying zone made up of extremely marshy alluvial soils. The water level is always less than a meter underground. It is an area prone to frequent floods during rainy season. On the other hand, Adjouffou is located in Port Bouët; home to the Felix Houphouet-Boigny international airport, the main seaport as well as the state-owned refinery, CRS. It is located in the coastal belt. It is geographically located at 5˚15'20" North and 3˚57'52" West. It is a low-lying zone made up of bar sand deposits from the sea. It is very marshy. The area has an estimated population of 50,000 inhabitants. The climate of the area is generally warm and humid from equatorial. Abidjan is characterized by tropical monsoon climate (Köppen classification Am) with two long periods of wet season; between the months of May-July and September-November, punctuated by two periods of dry season; December-March and July-August. The annual average precipitation is 1800 mm. Average monthly temperatures values range between 25˚C and 32˚C.

2.1. The Local Geology of the Area

The study area geologically belongs to the sedimentary basin of cretaceous to quaternary age. It is overlain by light to brownish, coarse-grained marine bar sands.

2.2. The Hydrogeology of the Area

The sedimentary basin of Côte d'Ivoire has imbedded three principal aquifers. These are the Quaternary, the Continental Terminal (CT), and the Maastrichtian (basement) aquifers from the youngest to the oldest. The quaternary aquifer is further divided into two different aquifer layers. One composed of coarse-*grained marine sands*—the Nouakchottien and the other composed of fine sands—the Oögolien [5]. The piezometric water level in this aquifer is very low with values ranging between zero to one meter below ground level; depending on the area. This facilitates easy infiltration of rain water and other likely contaminants from the nearby surface water bodies and sewage effluents into the groundwater. It is the most vulnerable of the aquifers. It has permeability values between 10^{-3} and 4×10^{-5} m/s. There is reported vertical drainage from this aquifer into the underlying Continental Terminal, CT [5].

The Continental Terminal, CT aquifer is of Miocene to Pliocene age. Its main aquifers are the n3 and n4 layers separated by a lens of clay, which is discontinuous in some places. This is the most important aquifer in the city of Abidjan, as the city gets its potable water supply from this layer. Its hydraulic parameters are as follow: average permeability varying between 10^{-3} m/s within the fine sand layers to as low as 10^{-6} m/s depending on the facies [1]. As observed from the piezometric map of the area, groundwater flow is in an N-S direction towards the Ébrié lagoon. There is interconnectivity between this layer and the underlying Maastrichtian basement aquifer, but, the lateral extent is not known. The semi-artesian basement Maastrichtian aquifer is Upper Cretaceous in age. It comprises mainly of quartzitic fissured basement rocks. There is only one well with a depth of approximately 190 meters, located in the Locodjoro area of Abidjan that penetrates this aquifer. This is owned by a private water producing company, SADEM.

2.3. The Surface Water Bodies

The principal lagoons of Côte d'Ivoire are Grand-lahou, Ébrié lagoon and Aby lagoon, from west to east. These lagoons constitute about 1200 km^2 of the entire sedimentary basin. The Ébrié lagoon, the most important of the three has a surface area of 566 km^2, a length of 125 kilometers, a maximum width of 7 kilometers and an average depth of 5 m. It is the largest lagoon in West Africa. It receives freshwater from the Comoé, Agneby and La Mé rivers. In addition to the freshwater input from these rivers, it also receives an input of about 10% directly from precipitation. It is periodically in contact with the Atlantic Ocean through the Grand Bassam inlet in the eastern part of Abidjan and constantly via a narrow artificial channel, the Vridi channel, opened in 1951. The lagoon becomes salty during the dry season, but turns to fresh water during the rainy season. It serves both as a means of transportation, direct water supply to the populace and dumping ground for both domestic and Industrial wastes. The levels of pollution in the lagoon have been moderately high due to the discharge of untreated industrial effluents and sewages [6-7].

3. Materials and Methods

3.1. Geochemical Sampling

A preliminary field investigation was carried out to ascertain the availability and accessibility of domestic hand-dug wells within the chosen settlements during the course of the investigation, permission to measure and collect water samples was obtained from the domestic well owners and information regarding health and sanitary matters was gathered from the occupants by way of oral interview.

The domestic wells within the area are coastal aquifers located within a 20 kilometers radius of the coastal zone. Majority of the wells within Anoumabo are poorly cased, lined in most parts with shafts consisting of used car tyres and metal drums. They are highly vulnerable to direct atmospheric pollution and contaminants infiltration from nearby sewage effluents. They are characterized by very shallow well depths (between 2 and 4 meters), large well diameters (between 40 and 98 centimeters); short distances from well top to ground surface (between 0.5 and 92 centimeters).

The sampling was done during high water period (month of May). Representative groundwater samples were collected from twenty-eight (28) already existing domestic wells—fourteen each from Anoumabo and Adjouffou respectively (**Figure 2**).

In addition, samples were collected from the Ébrié lagoon and the Atlantic Ocean (surface water). Water samples were collected using a simple rope and bucket. The water samples were directly collected into set of sterilized 250 ml polyethylene bottles and glass bottles for major ions and microbial analyses respectively. Subsequently, they were stored and transported in a thermoplastic container, cooled with ice packs to a temperature of about 4˚C before been sent to the different laboratories for further analysis. The samples for the analyses of anions were un-acidified, while, those for the analyses of the major cations were acidified with 2 drops of concentrated hydrochloric acid, HCl to a pH of about 2. This is to prevent further chemical reactions or sample degradation. Sensitive physico-chemical parameters of water such as hydrogen ion concentration, pH; temperature (˚C); redox potential, Eh (mv); dissolved oxygen, DO (‰) and electrical conductivity, EC (µS/cm) were measured *in situ* by a Hach digital pH/EC meter.

3.2. Methods of Chemical Analyses

Different analytical methods were employed in the determination of the key parameters indicative of water quality.

Cations and Anions

The major ionic composition of the samples was measured by ion chromatographic method using standard laboratory procedures. The determination of the major cation and anion concentrations of the water samples was carried out simultaneously. Samples were injected into the test column of the ion chromatograph through a 0.45 µm membrane filter.

As a rule of the thumb, samples with electrical conductivity values greater than 400 µS/cm were diluted accordingly with distilled water prior to their injection into the ion chromatograph. The dilution factor was taken into account in the computation and compilation of results.

The bicarbonate (HCO_3^-) concentration of the samples was measured by titration with 0.01 N hydrochloric acid, HCL using a Hach digital titrator within 24 hours of collection.

Samples were tested qualitatively for the presence of various heavy metals (copper (Cu); nickel (Ni); lead (Pb); uranium (U); chromium (Cr) and cadmium (Cd)) in a quick run using the flame atomic adsorption spectrometer, FAAS with a detection limit of 1 mg/l. Subsequently, based on the resulting peaks, the instrument was calibrated with standards of known concentration of samples with significant peaks to determine the exact amount of the element within the samples. The boron concentration of the samples was measured using UV-visible spectrophotometer. The samples were mixed with known quantities of buffer and Azomethin-H reagent and left in a dark room for two hours. Thereafter, the boron concentration was measured by the UV-spectrophotometer using ultra violet light at wavelength of 414 Ωm. This method has a detection limit ranging between 0.01 and 1

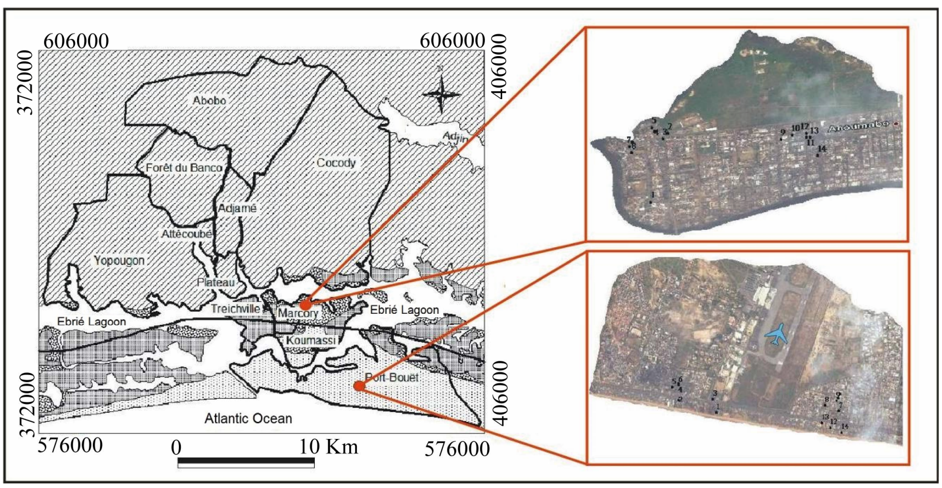


Figure 2. Groundwater sampling points.

mg/ℓ borate.

A qualitative analysis for the presence of trichloroethene (TCE) and tetrachloroethene (PCE) in the samples was done in the GC/MS SCAN mode of the gas chromatography-mass spectrometer, GC-MS; using the purge and trap method with TCE and PCE known standards of 7 µl and 8 µl respectively.

3.3. Methods of Microbial Analyses

Traditionally, indicator micro-organisms have been used to suggest the presence of pathogens. Each water sample was analyzed for indicator bacteria of unhygienic conditions. These are *Fecal coliform*, *Total coliform* and *Fecal streptococci*. Fecal indicators though have no real health significance, they are effective indicators of the hygienic quality of water and the presence of other disease-causing pathogens. They were used in the determination of fecal pollution in the areas under study. *Fecal coliforms*—these are thermo-tolerant, gram-negative bacteria present in the gut or the feces of warm-blooded animals. They are more closely related to fecal or sewage pollution and generally do not replicate in water environment. They are indicator bacteria used for the assessment of fecal pollution in raw water sources. Their presence may indicate recent and possibly dangerous contamination [8-10]. Their presence in the water samples were detected by the standard membrane filtration technique, using mFC culture medium and incubation for 24 hours at 44.5˚C. *Total coliform*, some of the members of this group are conclusively of fecal origin, while, others may replicate in suitable water environments. They are not to detect fecal pollution but are used primarily to assess the general sanitary quality of already disinfected drinking water. The method of detection was by membrane filtration using LES Endo agar and incubation for 24 hours at 37˚C. *Fecal streptococci* or *enterococci* are gram-positive bacteria. They are more closely related to fecal pollution than the *Total coliform* because their normal habitat is the intestinal tract of human and animals. They are used in sanitary evaluation as a supplement to *Fecal coliforms* for a precise determination of sources of contamination. They tend to be more resistant than *Fecal coliform* (gram-negative). The method of detection was by membrane filtration using m-enterococcus agar and incubation for 24 hours at 44˚C.

The first check of the accuracy of any analysis of the chemical composition of water is the calculation of its charge balance. This stems from a known fact that water is uncharged and obeys the principle of electro-neutrality which states that "total charge of cations and anions balance each other".

The charge balance of the analytical data was calculated using the formula:

$$\text{Error of ion balance, EB} = \frac{\sum(\text{cations} - \text{anions})}{\sum(\text{cations} + \text{anions})} \times 100\%$$

During this study, the total hardness of the water samples was calculated with the formula according to Klut and Olszewski (1945) and classified accordingly:

$$\text{dH}(\text{GH}) = \text{meq}/\ell\left(\text{Ca}^{2+} + \text{Mg}^{2+}\right) * 2.8$$

where $1\ \text{dH} = 17.848\ \text{CaCO}_3\ \text{mg}/\ell$

The carbon dioxide concentration of the samples was calculated using Tillmann's equilibrium equation of the carbonate system:

$$\left[\text{CO}_{2(g)}\right] = K_T\left[\text{HCO}_3^-\right]^2 * \left[\text{Ca}^{2+}\right]$$

where $\left[\text{HCO}_3^-\right]$ is the concentration of the freely dissolved carbonic acid in water (mg/ℓ or $mmol/\ell$); $\left[\text{Ca}^{2+}\right]$ is the concentration of calcium ion and K_T is the temperature dependent Tillmanns constant.

4. Results and Discussion

Water quality is normally expressed in terms of four basic categories: physical, chemical and biological. Each of these afore-mentioned categories contains limitless potential pollutants, but, for this study only few key parameters sufficient to serve as indicators of pollution were analyzed. Geochemical analysis is carried out on thirty water samples with an aim to determining their quality and suitability for different uses. Twenty-eight of the samples were groundwater samples from hand-dug wells within the Anoumabo and Adjouffou communities in southern Abidjan, while two of them were from the adjoining surface water bodies—Ébrié lagoon and Atlantic Ocean respectively.

4.1. The Surface Water

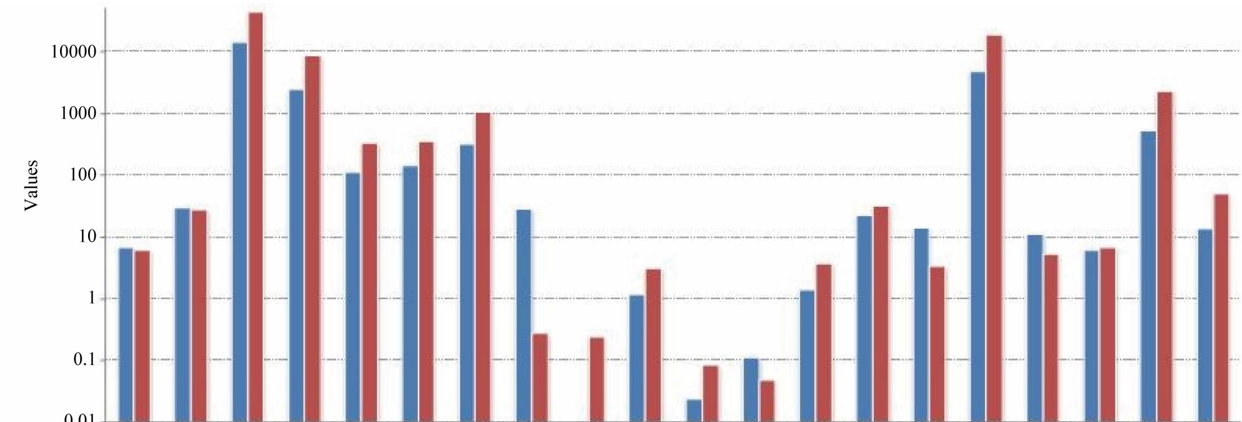
Quality assessment was carried out on water samples from the surface environment. These are the Ébrié lagoon and the Atlantic Ocean. The analytical results for the Ébrié lagoon shows a rather high electrical conductivity value of $14.6\ \text{mS/cm}$, a temperature of 30.5˚C, a hydrogen ion concentration, pH of 6.9 and an alkalinity value of 16 as $\text{CaCO}_3\ \text{mg}/\ell$. It belongs to the Na-Cl hydrochemical facies. The areas around the lagoon smell offensively of rotten egg. This signifies that the concentration of dissolved hydrogen sulphide, H_2S in the water is greater than 1 mg/ℓ.

There is an approximate ratio of 1:3 of the concentration of the ionic constituents of the Ébrié lagoon to those of the Atlantic Ocean. The concentration of the constituent ions of the water from the surface water bodies—the Ébrié lagoon and the Atlantic Ocean is shown in the graph below (**Figure 3**).

4.2. Groundwater

A total of twenty-eight groundwater samples from already existing domestic wells were analyzed. These wells which tap from the shallow, unconfined quaternary aquifer have distances not exceeding 20 kilometers from the Atlantic coast. The measured physico-chemical parameters of the groundwater samples (**Table 1**). The samples from Anoumabo have lower pH values and were relatively more acidic compared to those from Adjouffou. Majority (86%) of the samples from Anoumabo do not conform to the WHO recommended pH range (6.5 < pH < 8.5) for drinking water. The area has a mean, maximum and minimum pH value of 5.6, 6.6 and 4.5 respectively. The minimum and maximum values were recorded in samples; WM_7 and WM_12 respectively (**Figure 4**).

The groundwater samples from Adjouffou have a mean, maximum and minimum pH of 6.5, 8.1 and 6 respectively. The maximum and minimum pH was recorded in samples WP_10 and WP_4 respectively. About 64% of the samples from this area are acidic and have pH values below the WHO permissible range for drinking water. The acidification of these waters might either be



	pH	Temp	EC	Na	K	Ca	Mg	NH_4	Li	B	Fe	Mn	Sr	HCO_3	F	Cl	NO_3	PO_4	SO_4	Br
Ebrie lagoon	6.9	30.5	14500	2566.44	117.07	148.13	332.88	29.60		1.20	0.02	0.11	1.45	23.18	14.51	4921.98	11.44	6.20	541.21	14.26
Atlantic Ocean	6.24	28.7	44500	8960.67	345.30	369.10	1095.73	0.28	0.25	3.23	0.09	0.05	3.82	32.94	3.45	19243.9	5.49	6.93	2386.41	50.72

Physico-chemical parameters of the surface water bodies

Figure 3. Graph of analytical results of the physico-chemical of the Ebrie lagoon and the Atlantic Ocean. All units are in mg/ℓ **except for the temperature (˚C) and EC** $(\mu S/cm)$**. The blue and red bars represent water sample from the Ebrie lagoon and the Atlantic Ocean respectively.**

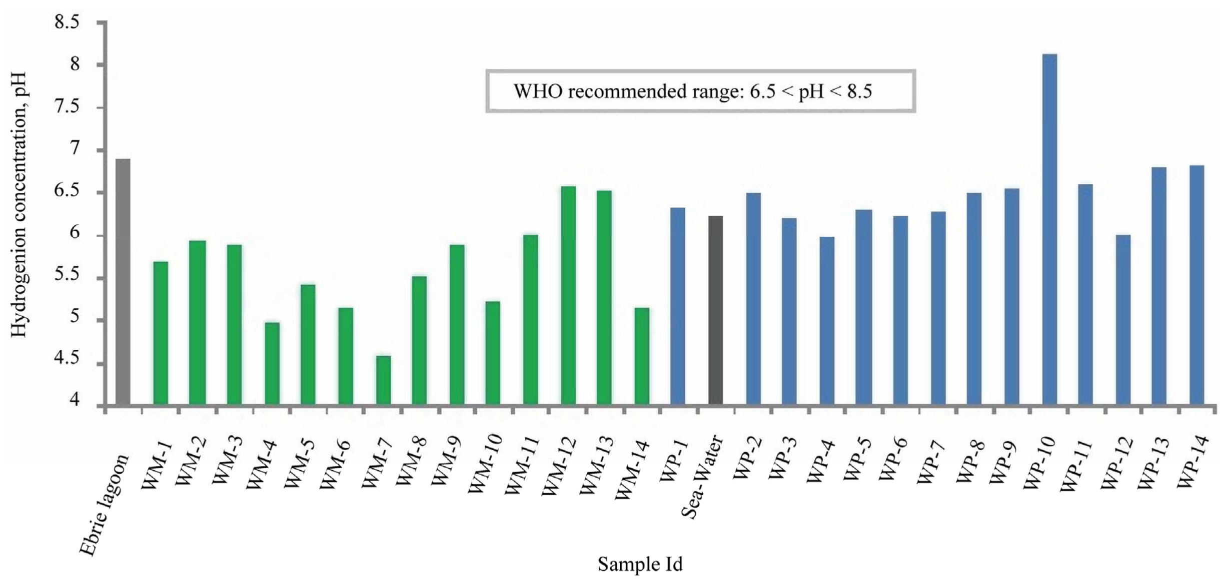


Figure 4. Plot of hydrogen ion concentration, pH of water samples. The green bars represent groundwater samples from Anoumabo while, the blue bars are groundwater samples from Adjouffou.

Table 1. Results of geochemical of water samples.

Sampling location	Sample Id	Cations						Anions										
		Na^+ (mg/l)	K^+ (mg/l)	Mg^{2+} (mg/l)	Ca^{2+} (mg/l)	NH_4^+ (mg/l)	B^+ (mg/l)	Cl^- (mg/l)	HCO_3^- (mg/l)	F^- (mg/l)	NO_3^- (mg/l)	NO_2^- (mg/l)	SO_4^{2-} (mg/l)	PO_4^{3-} (mg/l)	Br^- (mg/l)	Fe total (mg/l)	Mn total (μg/l)	EB[1]
Anoumabo, Marcory	Ebrie lagoon	2566.44	117.07	148.13	332.88	29.60	1.20	4921.98	23.18	14.52	11.44		541.21	6.2	14.26	24.7	113.9	−0.21
	WM_1	163.63	39.64	5.98	39.3	16.7	0.09	155.13	2.44	16.78	280.38	1.55	45.06	6.93	0.33	70.50	92.40	3.2
	WM_2	21.1	10.14	2.63	35.27	0.15	0.1	22.72	3.05	0.21	20.94		49.91		0.08	83.20	0.00	20.3
	WM_3	48.28	20.69	4.4	44.82	1	0.11	50.92	4.88	0.28	119.74	0.51	66.57	0.75	0.12	222.90	0.30	4.1
	WM_4	40.4	19.84	2.71	30.04	0.38	0.2	53.93	2.2	0.12	61.66		77.47	0.04	0.71	38.60	0.00	−2.3
	WM_5	50.77	21.5	2.92	32.67	2.82	0.16	61.37	3.66	0.73	69.68		111.53	1.94	0.53	40.50	19.20	−5.1
	WM_6	73.3	27.51	3.08	31.7	8.8	0.12	85.2	2.32	0.86	184.1		32.08	0.33	0.1	558.50	18.40	0.7
	WM_7	71.17	21.2	2.65	23.01	1.54	0.15	80.39	6.1	0.01	154.56		35.27	0.12	0.21	492.80	7.40	−4.9
	WM_8	66.61	26.67	4.18	24.49	20.16	0.04	82.02	4.64	0.95	161.75	0.29	50.95	0.37	0.62	86.30	62.90	1.3
	WM_9	99.74	27.23	6.12	44.49	1.75	0.22	100.4	1.46	0.14	143.64	0.54	103.93	0.28	0.74	797.30	50.60	3.1
	WM_10	34.28	12.89	3.18	22.67	0.27	0.1	41.42	3.66	0.69	95.4	0.06	51.12	0.21	0.06	0.00	4.20	−9.2
	WM_11	44.9	20.51	2.67	41.59	0.08	0.15	50.61	17.08	0.3	88.12	0.42	34.41		0.13	282.90	4.10	10.3
	WM_12	105.21	40.19	11.29	126.91	0.02	0.15	98.5	30.5	1	169.81		159.98	0.84	0.42	0.00	2.10	15.5
	WM_13	104.49	40.12	4.32	80.11	0.04	0.08	118.65	19.52	1.82	111.32	4.52	137.36		0.23	0.00	0.00	7.6
	WM_14	74.67	36.5	4.37	39.62	6.44	0.08	95.69	1.46	0.91	233.22		33.38		0.33	76.20	6.50	−2.6
	Average	71.33	26.05	4.32	44.05	4.30	0.13	78.35	7.36	1.77	135.31	1.13	70.64	1.18	0.33	196.41	19.15	
Adjouffou, Port-Bouet	WP_1	49.27	7.64	3.49	34.32	0/35	0.13	85.47	19.52	0.43	13		12.9	1.25	0.23	7.10	0.00	14.6
	Sea water	8960.67	345.30	369.10	1095.73	0.28	3.23	4921.98	32.94	3.56	5.49		2386.41	6.93	73.05	87.10	48.80	−7.5
	WP_2	45.21	7.14	3.72	28.38	0.37	0.09	76.15	6.1	0.17	30.31		24.74		0.27	38.50	0.00	8.7
	WP_3	22.4	5.54	2.11	19.19	0.42	0.06	39.11	7.69	0.08	26.86	0.17	15.13	0.04	0.1	0.00	0.00	6.5
	WP_4	24.19	7.49	1.82	24.63	1.25	0.15	21.43	4.88	0.08	34.23	0.13	24.64	0.02	0.03	58.80	0.00	20.6
	WP_5	53.55	21.39	5.98	55.41	2.45	0.13	65.44	21.72	0.43	141.05		43.49		0.13	55.30	103.20	7.3
	WP_6	58.85	23.32	4.38	40.08	0.63	0.07	67.22	10.98	0.66	116	0.15	43.45		0.33	31.70	19.90	6.3
	WP_7	56.16	16.5	3.67	39.56	0.09	0.14	53.95	9.27	0.23	119.61		25.63	0.02	0.1	0.00	57.10	10.6
	WP_8	21.81	9.32	1.99	34.19	0.99	0.07	20.37	10.98	0.09	39.56	2.25	19.83	0.09	0.03	22.80	0.00	25.0
	WP_9	34.84	13.43	3.09	49.85	1.62	0.11	28.71	25.99	0.18	63.61	0.59	32.14		0.4	132.10	24.90	22.5
	WP_10	50.14	17.46	2.66	68.79	0.68	0.09	49.68	14.64	0.35	83.56	0.91	38.65		0.07	0.00	0.00	24.4
	WP_11	23.48	8.2	2.15	33.96	0.01	0.17	21.94	8.3	0.07	42.88		29.43	0.31	0.05	522.20	30.60	19.8
	WP_12	37.84	10.39	3.51	25.97	0.3	0.08	54.78	5.49	0.14	57.59		22.96	0.14	0.16	19.20	0.00	6.9
	WP_13	17.8	5.56	2.44	28.66	0.27	0.07	25.31	14.64	0.06	4.09		13.08	0.09	0.09	26.60	0.00	32.6
	WP_14	60.23	9.89	7.23	25.08	0.19	0.11	93.25	22.81	0.22	25.58		22.25	1.06	0.23	0.00	0.00	9.6
	Average	38.96	11.97	3.44	36.44	0.71	0.10	47.49	12.58	0?21	60.38	0.70	27.34	0.22	0.15	69.78	18.13	

EB[1] = Electronic neutrality has units in %; [2]It was calculated using the Aquachem software-ions contributing more than 10% to the overall water chemistry were used in determining the water type.

due to the direct infiltration of acid rain or from the ionization of the metallic well casings.

The samples from Anoumabo were slightly mineralized with electrical conductivity, EC ranging between 388 (min.) and 1494 μS/cm (max.) for samples, WM_2 and WM_12 respectively. The area has a mean EC of 783 μS/cm. On the other hand, the samples from Adjouffou have a mean EC of 494 μS/cm, and a minimum and maximum EC value of 298 μS/cm and 779 μS/cm for wells, WP_3 and WP_5 respectively. The EC values of the samples from Anoumabo were relatively higher than those from Adjouffou.

The redox potential, Eh shows that oxidizing as well as reducing conditions are prevalent within the wells (**Table 1**). Reducing conditions was recorded only in wells, WM_12, WM_13 (Anoumabo) and WP_2, WP_8, WP_9, WP_11, WP_13, WP_14 (Adjouffou).

4.2.1. Geochemical Analyses

Water Classification

The profile of the major cations and anions are presented in the Schoeller semi-logarithmic plot (**Figure 5**).

There are four main categories of water type distinguishable in the studied wells of Anoumabo. These are the sodium-dominated, the calcium-dominated, the chlorine-dominated and the sulphate-dominated water types (**Figure 6**). Although, nitrate was the dominant anion in some of these groundwater samples, it was not included in the facies determination, because, it is normally listed as a minor anionic constituent of water.

There is a dominance of Na-Cl hydrochemical facies in the area. Samples, WM_1, WM_6, WM_7, WM_8, WM_10, WM_13 and WM_14, belong to this category. Other hydrochemical facies in the area are Na-SO_4 (samples, WM_4 and WM_5); Ca-SO_4 (samples, WM_2 and WM_12); Ca-Cl (samples, WM_3, WM_9 and WM_11).

In the commune of Adjouffou, the two distinguishable hydrochemical facies are Na-Cl (samples WP_1, WP_2, WP_3, WP_6, WP_7, WP_12 and WP_14) and Ca-Cl (WP_4, WP_5, WP_8, WP_9, WP_10, WP_11, and WP_13).

4.2.2. Cations

The measured cations and their resulting concentrations are briefly discussed below:

Sodium and Potassium

The sodium content of the samples from both localities was below the WHO permissible limit $(250\ \text{mg}/\ell)$ for drinking water. The samples from Anoumabo have a mean sodium concentration of $71.3\ \text{mg}/\ell$, and a maximum and minimum of $163.6\ \text{mg}/\ell$ and $21.1\ \text{mg}/\ell$ in wells, WM_1 and WM_2 respectively. The samples from Adjouffou have a mean sodium concentration of 38.9 mg/ℓ, with a maximum of $60.2\ \text{mg}/\ell$ and minimum of $17.8\ \text{mg}/\ell$ in samples, WP_13 and WP_14 respectively. The potassium concentration of the tested sample of both localities is very low with values ranging between 5.5 and $40.1\ \text{mg}/\ell$.

Calcium and Magnesium

The tested samples from Anoumabo have mean calcium and magnesium concentrations of the water samples are $44\ \text{mg}/\ell$ and $4.3\ \text{mg}/\ell$ respectively. This is a slightly higher concentration than those from Adjouffou which have average calcium and magnesium concentrations of $36\ \text{mg}/\ell$ and $3.4\ \text{mg}/\ell$ respectively.

These recorded concentrations are lower than the recommended WHO drinking water standard of $400\ \text{mg}/\ell$ and $120\ \text{mg}/\ell$ for calcium and magnesium ions re-

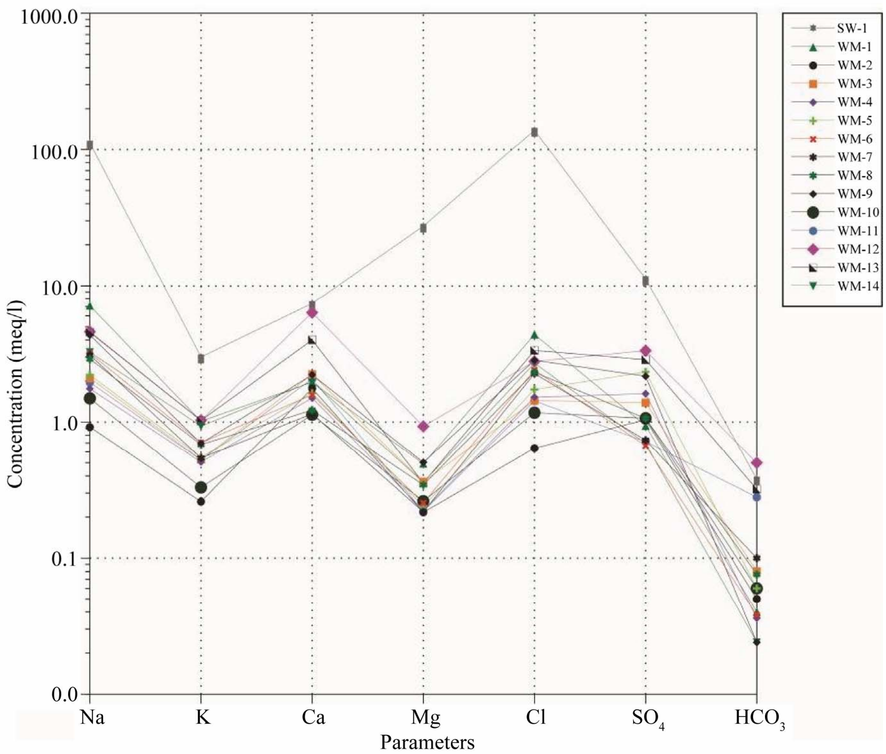


Figure 5. Schoeller plot for Anoumabo. SW_1 is the Ébrié lagoon.

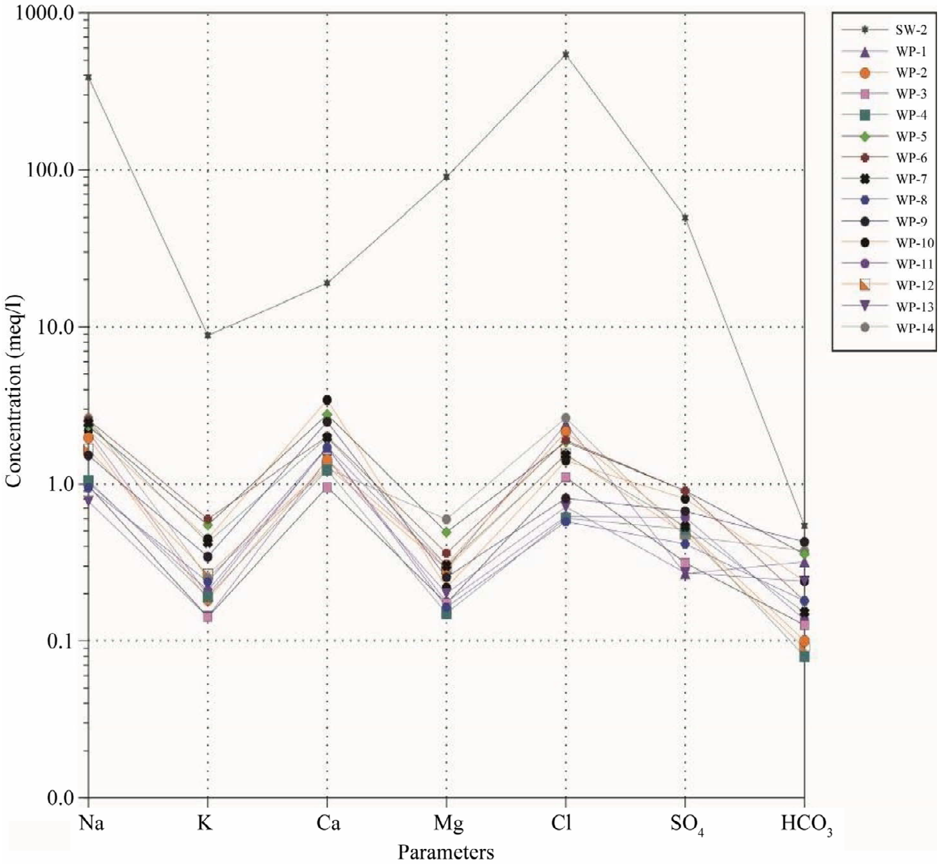


Figure 6. Schoeller plot of for Adjouffou. Sample SW_2 is the Atlantic Ocean.

spectively.

The Total Hardness

Calcium and magnesium are the major bivalent ions contributing to hardness of water. Although, the total hardness of water does not necessarily affect its hydrochemical quality, it is however detrimental to the washing process. The samples were categorized into five distinct classes of water hardness. These are very soft, soft, slightly hard, moderately hard and hard in order of increasing degree of water hardness. The samples from Anoumabo with relatively higher concentrations of calcium and magnesium ions fell into the category of very soft to hard, while, the samples from Adjouffou fell into the category of very soft to slightly hard (**Table 2**).

4.2.3. Anions

The analyzed anions and their resulting concentrations are briefly discussed below:

Carbonates and Chloride

Bicarbonate ion is the dominant carbonate species in the tested water samples as they have pH values ranging between 4.4 and 8.3; values at which bicarbonate dominates. The bicarbonate concentration was estimated from the measured total alkalinity content, TAC. The samples from Anoumabo were weakly mineralized and have low alkalinity with values ranging between 1.5 and 19.5 mg/ℓ and a mean value of $7.4\ mg/\ell$. The samples from Adjouffou have relatively higher alkalinity values ranging between $4.9\ mg/\ell$ and $26\ mg/\ell$ with a calculated mean of $12.6\ mg/\ell$.

The calculated carbon dioxide concentration of the samples was plotted against the bicarbonate concentrations of the samples in order to ascertain the presence of free aggressive CO_2 (**Figure 7**). Samples from the Ébrié lagoon and groundwater samples, WM_13 and WP_10 from Anoumabo and Adjouffou respectively show the presence of free aggressive CO_2. Three samples: WM_12 (Anoumabo); WP_9 and WP_14 (Adjouffou) have no free CO_2. The rest of the samples were in a state of carbonic acid—carbonate equilibrum.

Typical chloride concentration in groundwater ranges between 6 and $15\ mg/\ell$. Groundwater samples from Anoumabo and Adjouffou have mean chloride concentrations of $78.4\ mg/\ell$ and $47.5\ mg/\ell$ respectively, exceeding the natural concentration. Although, these samples have chloride concentrations above the natural background values, they do not exceed the recommended WHO limit of $250\ mg/\ell$ for drinking water. Possible external chloride sources include human feces from leaky sewage tanks and salt water intrusion.

Table 2. Table showing total hardness of samples.

Sampling location Anoumabo, Marcory Adjouffou, Port-Bouet					
Sample Id	Hardness*	Classification	Sample Id	Hardness*	Classification
W_M1	6.9	Soft	W_P1	5.6	Soft
W_M2	5.5	Soft	W_P2	4.8	Soft
W_M3	7.3	Soft	W_P3	3.2	Very soft
W_M4	4.8	Soft	W_P4	3.9	Very soft
W_M5	5.2	Soft	W_P5	9.1	Slightly hard
W_M6	5.1	Soft	W_P6	6.6	Soft
W_M7	3.8	Very soft	W_P7	6.4	Soft
W_M8	4.4	Soft	W_P8	5.2	Soft
W_M9	7.6	Soft	W_P9	7.7	Soft
W_M10	3.9	Very soft	W_P10	10.2	Soft
W_M11	6.4	Soft	W_P11	5.2	Soft
W_M12	20.3	Hard	W_P12	4.4	Soft
W_M13	12.2	Moderately hard	W_P13	4.6	Soft
W_M14	6.5	Soft	W_P14	5.2	Soft

*hardness as German hardness (dH).

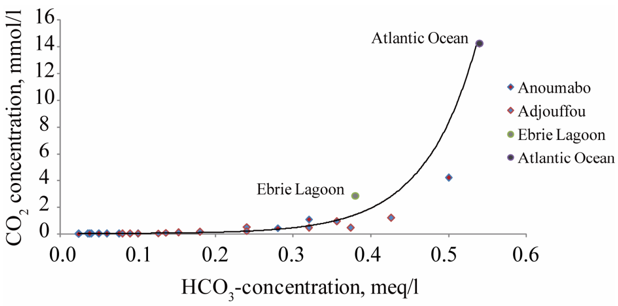


Figure 7. Graph of CO_2-HCO_3 equilibrum curve.

Sulphate and Fluoride

The sulphate concentration of tested samples from Anoumabo (mean: $70.46\ mg/\ell$) is relatively than those of Adjouffou (mean: $26.31\ mg/\ell$). The resulting sulphate concentrations of samples from both localities do however conform to the WHO permissible value of $250\ mg/\ell$ for drinking water.

The WHO permissible limit for fluoride $(1.5\ mg/\ell)$ in drinking water was exceeded by samples WM_1 $(16.78\ mg/\ell)$ and WM_13 $(1.82\ mg/\ell)$ both from Anoumabo. The rest of the tested samples have concentrations below the WHO permissible limit. Excessive high fluoride concentration in water is harmful to the overall dental health and can lead to fluorosis and tooth decay in younger children.

4.2.4. Nutrients in Groundwater

Nitrogen-Nitrate Concentration

The distribution of nitrate in groundwater is shown by the **Figure 8**. Nitrate usually enters groundwater either from biologic or anthropogenic sources of nitrogen. It is not derived primarily from water-rock interaction. Majority of the tested groundwater samples from both study area displayed alerting levels of nitrogen compounds (nitrate-NO_3, nitrite-NO_2 and ammonium-NH_4). Recent studies on nitrate contamination of groundwater resources in Abidjan revealed that the major pollution threats are sewers and the lack of a developed system for collection and treatment of waste and wastewater [3,4]. This has led to the high nitrate concentrations (commonly 100 - 300 mg/ℓ, max. $500\ mg/\ell$ as NO_3) in water supply boreholes (1994-2004) with cholera cases between 2001 and 2003 being attributed to contaminated groundwater [8].

When compared against the WHO permissible limit for drinking water $(N\text{-}NO_3 \geq 50\ mg/\ell)$, only one sample (WM_2) from Anoumabo was within safe drinking water limits. Groundwater samples (WP_1, WP_2, WP_3, WP_4, WP_8, WP_13, WP_14) from Adjouffou have concentrations within the WHO permissible limit for drinking water.

The level of nitrate contamination of water wells in Anoumabo is relatively higher than those in Adjouffou. This is due basically to lack of proper housing planning, location of water wells close to sewage tanks and the overall unhygienic sanitation conditions prevalent within the community. Where there is high nitrate content, there is inevitably bacterial contamination. Possible diffused, non-point nitrate sources are decomposing organic matter, leaching of chemical fertilizers, leaching of animal manure and discharges from septic and sewage tanks. The coarse surface soil texture and shallow well depths are also contributing factors.

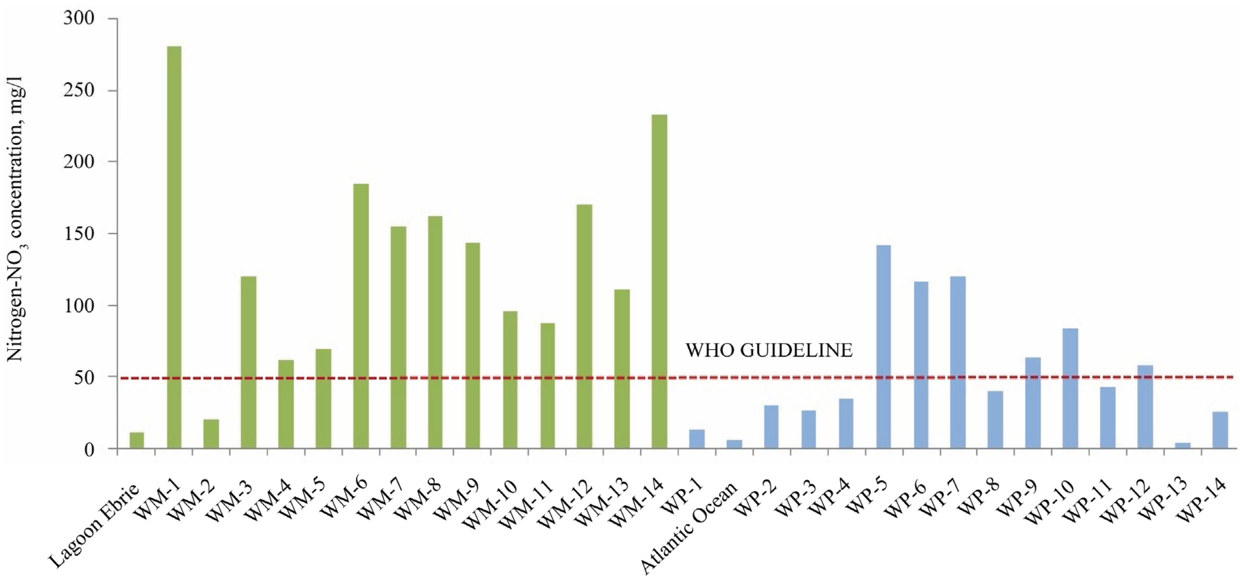


Figure 8. Graph showing the nitrate concentrations of the samples.

Measures must be put in place to upgrade the sanitary conditions within these slums and seasonal groundwater quality monitoring as it can result in grave health consequences, mainly on little babies below six months resulting in methemoglobinema or "blue baby syndrome" which threatens oxygen building capacity of the blood. It is therefore advisable that these waters should not be used for babies under six months old without adequate treatment measures.

Nitrites and Ammonia

The groundwater samples from Anoumabo have an average nitrite concentration of $1.14\ \text{mg}/\ell$. 29% of the samples have nitrite levels exceeding the WHO limit of $0.55\ \text{mg}/\ell$. The groundwater samples from Adjouffou have an average nitrite concentration of $0.75\ \text{mg}/\ell$ and 21% of water samples in this area exceeded the WHO permissible limit for drinking water. Nitrite when present in water is toxic even at very little concentrations.

Ammonia is a form of nitrogen present in reducing groundwater. 50% of the samples from Anoumabo have levels of ammonia exceeding the WHO limit (1.5 mg/ℓ), while 14% exceeded this recommended limit in the Adjouffou community. Ammonia is in itself not toxic, but, it can be oxidized under favorable environmental conditions to nitrates and nitrites, having greater toxicity.

4.2.5. Minor Constituents

All the tested samples from both study location exceed the WHO limit for bromide $(0.01\ \text{mg}/\ell)$ in drinking water. There was mean bromide concentration of 0.34 mg/ℓ and $0.16\ \text{mg}/\ell$ of samples from Anoumabo and Adjouffou respectively. Bromide above the WHO recommended concentration hampers the water treatment processes by triggering chemical reactions producing potentially harmful by-products. It has also been reported to increase the risk of cancer when taken over a long period of time.

4.2.6. Heavy Metals

Samples were initially tested qualitatively for the presence of heavy metals (iron, Fe; magnesium, Mn; strontium, Sr; zinc, Zn; cadmium, Cd; uranium, U; lead, Pb; nickel, Ni and chromium, Cr) with the flame atomic adsorption spectrometer at a detection limit of $1\ \text{mg}/\ell$. Significant peaks were observable only for elements Fe, Mn, Sr and Zn after the initial quick run. Subsequently, the instrument was calibrated using calibrants of each of the observed species with known stoichiometry. Quantification was done using calibration curves. The WHO standard for iron in drinking water $(0.3\ \text{mg}/\ell)$ was exceeded by 14% of the samples from Anoumabo and by 7% of the samples from Adjouffou. The Mn, Sr and Zn concentrations of the samples fell within the WHO [11] permissible limit for drinking water.

4.2.7. TCE (Trichloroethene) and PCE (Tetrachloroethene)

Samples were tested for the presence of TCE (trichoroethene) and PCE (tetrachloroethene) using the gas chromatograph-mass spectrometer. There were no significant peaks for the tested samples. This signifies the waters are free from TCE and PCE contamination.

4.3. Microbiological Analyses

The tested bacteriological parameters, *Total* and *Fecal coliforms* and *Fecal streptococci* of all the samples were above the WHO permissible limit (**Table 3**).

According to WHO drinking water guidelines [11], these bacterial organisms must not be detectable in any 100 ml sample. There was alerting levels of microbial pollution of the groundwater in both areas. The high *Fecal streptococci* content of the some of the samples confirm the presence of fresh fecal contamination. They are therefore, far from been potable and unfit for consumption.

Samples (WM_11, WM_1, WP_1 and WP_7) have values of *Fecal coliforms* and *Fecal streptococci* less than 1 count/100ml. These are wells reportedly been disinfected periodically with chlorine solutions by the well owners. Although, free from fecal contamination, these wells are contaminated by *Total coliforms*. The rest of the samples show varying degrees of fecal contamination. The ratio of *Fecal coliforms* to *Fecal streptococci* can be used to investigate different sources of fecal contamination. Ratios between 2 and 4 or higher are indicative of human contamination while, ratios less than 2 are indicative of animal contamination. Although, no longer recommended due to ambiguities in the microbial identification process, this ratio is still useful in the monitoring of very recent fecal pollution.

Human feces was the identified pollution source in samples; WM_2, WM_7 and WP_2 having *Fecal coliforms* to *Fecal streptococci* ratios of 2.5, 7.1 and 2.7 respectively. All the other samples have ratios lower than 2, indicating animal sources of fecal pollution. These fecal pollution sources can be directly linked to the rearing of animals and the construction of public latrines and bathrooms very close to the recharge sources of these wells. Both human and animal wastes are as such emptied directly into the lagoon and subsequent serve as microbial pollution sources of contamination for the underlying groundwater aquifer being recharged by this lagoon. Animal wastes from these public bathrooms and toilets into the Ébrié lagoon are possibly sources of the high microbial contamination of this water body.

5. Conclusion

The analytical results of the water from these domestic wells showed very low pH, abnormally elevated concentrations of nitrates amongst other organic and non-organic contaminants. They are also not free from microbial contamination. Therefore, without doubt, the water contained within these hand dug wells is unsafe for both human and animal consumption. The identified point and diffuse sources of groundwater contamination within the area are leaky cesspools, sewage tanks, animal-rearing activities and domestic and industrial effluents. Although, drilling new wells to the deeper layers of the confined Continental Terminal, CT aquifer would have been the most feasible solution, this is at the moment unrealistic due to the cost involved. However, simple preventive measures of contamination prevention should be adopted at household levels by these well-owners. Measures such as provision of shades/covers for the open wells to mini-

Table 3. Result of microbial analyses.

Sampling location Anoumabo, Marcory	Indicator bacteria*		Adjouffou, Port-Bouet	Indicator bacteria*	
Sample Id	*Fecal coliforms*	*Fecal streptococci*	Sample Id	*Fecal coliforms*	*Fecal streptococci*
Ebrie lagoon	3300	2100	WP_1	<1	<1
WM_1	18	<1	Atlantic Ocean	<1	<1
WM_2	121	48	WP_2	375	510
WM_3	112	90	WP_3	172	165
WM_4	141	120	WP_4	480	180
WM_5	193	222	WP_5	8	<1
WM_6	51	102	WP_6	520	290
WM_7	85	12	WP_7	<1	<1
WM_8	1370	1020	WP_8	131	188
WM_9	420	214	WP_9	550	820
WM_10	487	503	WP_10	122	750
WM_11	<1	<1	WP_11	124	184
WM_12	20	20	WP_12	1560	600
WM_13	<1	<1	WP_13	148	164
WM_14	70	112	WP_14	1260	1060

*units as counts/100ml.

mize atmospheric pollution, sealing up areas around the wells to prevent direct infiltration of possible contaminants, location of wells at reasonable distances from sewage tanks and cesspools could help in mitigating groundwater contamination. The people should be sensitized about the health risk associated with the use of such contaminated waters. Majority of the occupants of these slums are illiterates. Reports show that there are already cases of diarrhea, cholera, typhoid fever, blue baby syndrome amongst others prevalent in the area. The causes of these illnesses were attributed to spiritual attacks by greater percentage of the inhabitants when interviewed.

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