

Environmental Microbiological Analyses of Well Water for Domestic Use Located near the Lakes of the City of Yamoussoukro

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Abstract

This study evaluates the physicochemical and microbiological quality of 12 domestic wells near lakes in three neighborhoods of Yamoussoukro in Ivory Coast, with one tap-water sample used as a control. Using *in-situ* measurements and culture-based microbiological tests, the authors report high mesophilic aerobic counts in all wells, fecal coliforms in several wells, and frequent *Salmonella* detection. The paper concludes that the sampled well waters are unsuitable for human consumption without prior treatment.

Keywords

Water, Well, Quality, Microbiological, Health, Yamoussoukro, Ivory Coast

1. Introduction

Water is a fundamental element in the daily life of living beings through its use. Its quality is particularly vital for human health. Diseases in humans are caused through contaminated drinking water, food grown in contaminated soils, seafood harvested from contaminated waters, and bathing and recreating in polluted waters. Infectious diseases due to exposure to human waste include bacterial *Salmo-*

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nella and hookworm, among others [1]. Exposure can also lead to infections and topical conditions, such as rashes and skin infections. Indeed, the consumption of poor-quality water is a source of a range of pathologies such as dysentery, hepatitis, typhoid fever, cholera, and even severe and sometimes fatal diarrhoea [2].

Despite the problems that contaminated water can cause, it is commonly used for drinking, cooking, and personal hygiene. As a result, water quality is a primary public health concern. Drinking water must also comply with rigorous drinking water standards (such as ISO and WHO standards), which guarantee its safety and drinkability [3]. Unfortunately, not all water sources are suitable for human consumption due to the quality issues they may face. Thus, each year, diseases are responsible for 3.4 million deaths worldwide, according to the World Health Organization [4].

West Africa's population is booming. The region had a population of 316 million in 2007, up from 391 million now, and could reach 796 million by 2050. The population is growing faster in cities than in rural areas, partly because of migration. This rapid growth of urban areas is accompanied by planning and infrastructure challenges, including water supply and sanitation. As many cities depend on groundwater for their supplies, there are risks of overexploitation and contamination of this water [5].

Seven cities in West Africa rely primarily on groundwater, either through public water supply networks and/or hand-dug wells: Lagos, Cotonou, Lomé, Abidjan, Bissau, Banjul and Dakar. These cities are based on sedimentary basins containing high-yield aquifers. These sedimentary basins are located along the Atlantic coast and have the same geological age. In the West African sub-region, few studies have been conducted on the quality of well water. In Togo, for example, the study conducted by Bawa *et al.* focused on determining the chlorine demand of well and borehole water in a peri-urban district of the city of Lomé: impact on disinfection [6]. In Côte d'Ivoire, on the other hand, the only study carried out on the quality of well water was the evaluation of the quality of well water for domestic use in four disadvantaged neighbourhoods in Abidjan communes: Koumassi, Marcory, Port-Bouet and Treichville [7]. There is a glaring lack of studies on the microbiological quality of well water in the cities of the interior of Côte d'Ivoire.

In the context of Yamoussoukro, the political capital of Côte d'Ivoire, the study is of paramount importance because of the proximity of the wells to the lakes, which can serve as natural reservoirs but also be a source of pollution. This raises important questions about the potability of well water and its impact on public health. It is therefore essential to carry out a study to examine the microbiological quality of well water in Yamoussoukro. Possible contamination due to the infiltration of water from lakes to groundwater can lead to associated risks. This justifies the following topic of study: "Microbiological analyses of well water near the lakes of Yamoussoukro".

To carry out this work on water quality, the microbiological analysis of the water is carried out in the laboratory according to a methodology, in order to deduce the drinkability of the water through the results by referring to the standards established by the WHO [8] [9].

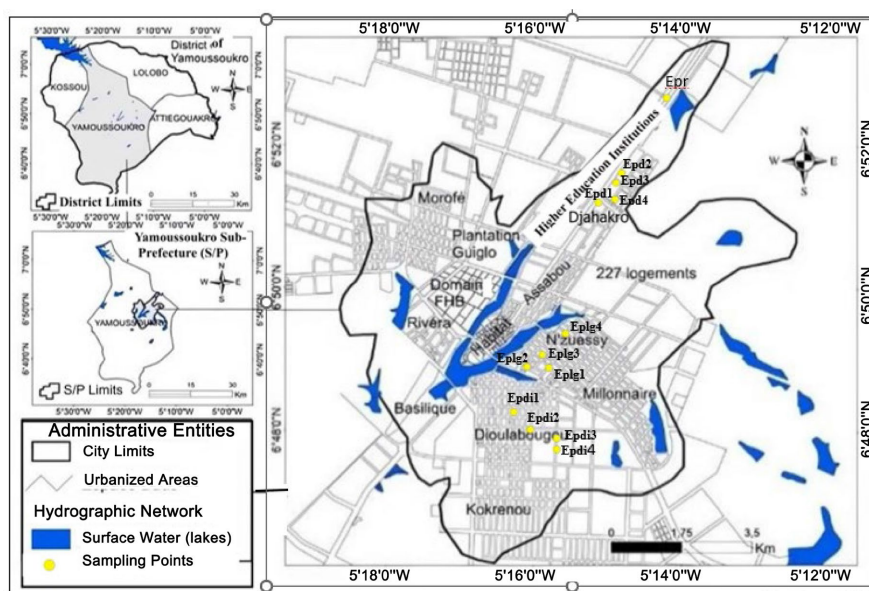
2. Materials and Methods

2.1. Presentation of the Study Area and Equipment

2.1.1. Geographical Location

The Autonomous District of Yamoussoukro is a city located in the center of Côte d'Ivoire. It covers an area of 3500 km² [10]. It has also been the administrative and political capital of Côte d'Ivoire since 1983 and the Chief of the District since January 21, 2002. It is bordered to the north by the department of Tiébissou, to the south by the department of Oumé, to the east by the department of Dimbokro and to the west by the departments of Sinfra and Bouaké, in the Marahoué region [10].

Figure 1 shows the map of the Autonomous District of Yamoussoukro through its different water bodies and sampling points.



Source: Kouassi (2018) [10], adapted from Zedou, 2026.

Figure 1. Presentation of the Autonomous District of Yamoussoukro and the sampling points.

2.1.2. Climate and Hydrography

Yamoussoukro is subject to an equatorial climate with four seasons, namely, a long dry season from mid-November to mid-March, characterized by the presence, in December and January, of the harmattan; a long rainy season from mid-March to mid-July; a short dry season from mid-July to mid-September; and a short rainy season from mid-September to mid-October.

The Autonomous District of Yamoussoukro benefits from a hydrographic network essentially composed of the Marahoué (or Bandama rouge) and the N'Zi, two tributaries of the Bandama [11].

2.2. Hardware

2.2.1. Sampling Sites

The sampling site covers three working-class neighborhoods of Yamoussoukro:

Djahakro, Dioulabougou, and 220 housing units. In these middle-income neighborhoods, the existence of wells for domestic use is proven. Household use of well water is commonplace.

The choice of sources of abstraction was determined taking into account the frequency of use of water points by the populations and the proximity of sources of pollution (lakes). A total of 12 wells were sampled, with 4 wells per neighbourhood, and one tap water sample was used as a control, for a total of 13 water samples to be tested. Well water samples for microbiological analysis were collected in new 1000 mL high-density polyethylene vials, suitable for microbiological sampling. Water is drawn using ropes attached to the sampling containers usually used by households. Each bottle is rinsed three times with the water to be collected, then refilled and hermetically sealed before being taken to the laboratory in a cooler within a period of less than 4 hours, under conditions that do not modify the parameters of the water samples taken.

The sampling sites and their characteristics have been specified in **Table 1**.

2.2.2. Biological Material

The biological material for the study is well water that was taken in August 2024. These samples represent nearly all wells, and preventive measures have been taken to prevent further contamination.

2.2.3. Biological Material Sampling Technique

The distance between the wells and the lakes and/or the canals and streams for the evacuation of runoff water (rainwater and wastewater) varies from 25 m to 1000 m. This distance is determined according to the existing wells and the potential effects it could have on biological material through anthropogenic (e.g., livestock farming) and natural (e.g., flooding) activities.

Each well in the field is sampled three times, at the same times, to constitute the analytical samples (**Figure 2**).



Figure 2. Wells and water samples. (A) Epd3 well; (B) Well water samples (**Table 1**).

After the sampling, the samples were sent to the laboratory as quickly as possible, preserving the initial conditions. Upon receipt, the analyses were carried out twice by sampling in the field, in the laboratory specializing in water treatment.

Table 1 presents the coding and some characteristics of well water taken from the districts of Yamoussoukro.

Table 1. Coding and characteristics of the sampling wells in Yamoussoukro.

Codes of wells	Stations	Depth (m)	Roof Covering	Condition of the well wall	Likely sources of pollution
Epr	INP-HB Centre (tap water)	0	In a pipe	PVC	Protected from contamination
Epd1	Djahakro No. 1	18	Wood	Cemented	Household waste
Epd2	Djahakro No. 2	12	Slab	Cemented	Stagnant water and stream
Epd3	Djahakro No. 3	09	Slab	Cemented	Stagnant water
Epd4	Djahakro No. 4	21	Wood	Cemented	Proximity to the toilets
Epd11	Dioulabougou No. 1	18	Coverage	Cemented	No water infiltration
Epd12	Dioulabougou No. 2	16	Slab	Cemented	Streams
Epd13	Dioulabougou No. 3	23	Without coverage	Cemented	Proximity to the toilets
Epd14	Dioulabougou No. 4	21	Wood	Cemented	Household waste
Eplg1	220 housing units No. 1	10	Slab	Cemented	Water and stream infiltration
Eplg2	220 housing units No. 2	16	Without coverage	Uncemented	Proximity to the toilets
Eplg3	220 housing units No. 3	8	Wood	Cemented	Proximity to the toilets
Eplg4	220 housing units No. 4	13	Slab	Cemented	Household waste and stagnant water

2.2.4. Technical Equipment

1) Apparatus and consumables

The equipment used can be grouped into two groups.

The first are those used for the measurement of *in-situ* parameters: a Soven GO Duo Pro pH meter for pH measurement, a HACH 2100Q turbidity meter for turbidity, and a WTW Cond 3110 conductivity meter for conductimetry.

As far as microbiological analyses are concerned, the equipment used consisted of conventional laboratory equipment such as Petri dishes (Gosselin), vials for the preparation of culture media, an oven (Mamert, Germany), an autoclave (Mamert, Germany) for the sterilization of culture media, a magnifying glass for the enumeration of germs, and other essential microbiological equipment. Distilled water was also used in both cases. A KCl buffer solution was used for the calibration of the pH meter.

2) Culture media

Various culture media were used during this study and are:

- PCA (Plate Count agar) medium, Bio-Rad, France, used for the enumeration of mesophilic aerobic germs (MAGs).
- VRBL (Violet Red Bile Lactose Agar) medium, for the enumeration of *Escherichia coli*.
- EPT (Buffered Peptone Water), RVS (Rappaport Vassiliadis Soy), and *Salmonella* Shigella (SS Agar) medium, for testing for the presence or absence of *Salmonella*.
- Slanetz and Bartley Medium, for the enumeration of fecal *Streptococci*.

2.3. Methods

2.3.1. Methodology for Measuring *In-Situ* Parameter

The measurement of the *in-situ* parameters was focused on temperature, hydrogen potential (pH), turbidity, and conductivity; these are essential parameters to be determined in any type of water analysis, as they condition the other physico-chemical and biological parameters.

- **Hydrogen Potential (pH) Measurement**

For the estimation of acidity or alkalinity, the pH of the waters was determined according to the AOAC (1995) method [12]. The pH was determined using an electronic pH meter by dipping the electrode into the water sample and the pH value was read directly on the pH meter display. Before the pH was measured, the calibration of the device was ensured by the use of a KCl buffer solution.

- **Turbidity measurement**

The turbidity of the water samples was measured by transferring 10 mL of the water sample into a tube in the turbidity meter.

- **Conductivity and temperature measurement**

Conductivity and temperature were simultaneously measured using a conductivity meter with a built-in temperature probe, according to ISO 7888 of the year 1985, as shown in Table 2 [13].

Table 2. Standards and methods for the parameters measured.

Measured parameters	Standards or Analytical Methods
Acidity or alkalinity	AOAC Methods [12]
Turbidity	Methods of Turbidity Meter Reading
pH	Methods of pH meter reading
Conductivity	ISO 7888 [13]

2.3.2. Microbiological Testing and Seeding Techniques

1) Microbiological Testing

The search for total mesophilic aerobic flora, *Escherichia coli*, and faecal *Streptococci* was carried out using the solid media enumeration method with the mass seeding technique. The method consists of depositing 1 mL of the inoculum (sample) into the petri dish (empty) before pouring approximately 15 mL of the super-cooled solid medium into each petri dish containing the inoculum (ISO 4833-1 (2013)) [14].

For the search for *Salmonella*, the surface seeding method was used following the first two phases, namely pre-enrichment and enrichment according to the NF EN ISO 6579-1-2017 standard [15]. The surface seeding technique consists of depositing 0.1 mL of inoculum (sample) in a petri dish containing the solidified medium.

Each well water stock solution was diluted to 10^{-2} , 10^{-1} for mass seeding. The petri dishes were then incubated at an appropriate temperature and for a given amount of time for each germ sought.

2) Germ Testing

a) Testing for Fecal Coliforms (*E. coli*)

Fecal coliforms (=thermotolerant coliforms) are from the group of Gram-negative, non-spore-forming, lactose-fermenting bacteria with gas production at 44°C - 45°C. They are a group that includes the species *Escherichia coli* (*E. coli*) but also *Klebsiella*, *Citrobacter*, and *Enterobacter* at high temperatures. The term is therefore broader than *E. coli* alone.

• Determination of *Escherichia coli* (*E. coli*)

Precise bacterial species and is the only coliform strictly of fecal origin. *Escherichia coli* is a facultative, anaerobic, gram-negative enterobacterium. It does not multiply in the environment. Its presence in water is a specific indicator of recent fecal contamination and may therefore indicate the presence of pathogenic microorganisms. It is the reference marker of fecal contamination of human or animal origin. It produces indole from tryptophan, which distinguishes it from other fecal coliforms.

Its determination is made according to the ISO 9308-1:2014 standard (drinking water) [16]. The determination protocol is as follows:

- Membrane filtration protocol (seeding)

We proceed by:

- Filter 100 mL of water through a 0.45 µm membrane
- Place the membrane on Chromocult selective medium.
- Incubation at 44°C ± 0.5°C for 24 ± 2 h
- Reading: fluorescent blue (Chromocult) or pink-red colonies
- Confirmation by indole test or oxidase test if necessary

- Protocol by culture (MPN/MPP)

For this protocol, we proceed as follows:

- Tubing of peptone whey broth (presumption)
- Incubation at 37°C for 24 - 48 h → off-gassing = positive
- Transplanting on tryptone broth → indole test at 44°C (*E. coli* confirmation)
- Expression in MPN/100 mL according to the Mac Grady table

b) Search for fecal *Streptococci*

Fecal *streptococci* are Gram-positive, catalase-negative, Lancefield's group D shells. That is to say, they are composed essentially of: *Enterococcus faecalis*, *E. faecium*, *E. durans*, *E. hirae*, capable of growing in the presence of sodium azide and at 44°C. They are gut bacteria. They have the antigenic substance (teichoic acid). They mainly include *Streptococcus bovis* and *Streptococcus equinus* and are an indicator of fecal pollution of animal origin because all of them are found in feces.

*Determination of *Streptococci*

Its determination is made according to the ISO 7899-2:2000 standard (membrane filtration) [17].

- The membrane filtration protocol is used by:

- Filter 100 mL on a 0.45 µm membrane.

- Drop on Slanetz & Bartley medium
- Incubation at $36^{\circ}\text{C} \pm 2^{\circ}\text{C}$ for 44 ± 4 h
- Red, brown, or pink colonies = positive presumptive
- Transfer to Bile Esculin Azide (BEA) agar at 44°C for 2 h (darkening = confirmation)
- Fecal streptococcus counts

The enumeration of *streptococci* with the mass seeding method using the Slanetz and Bartley agar medium. The count concerned all the colonies that turned red, pink, and purple.

c) Search for Faecal Enterococci

Fecal enterococci are a subgroup of fecal *streptococci* (*Enterococcus faecalis*, *E. faecium*, *E. durans*, *E. hirae*). They are resistant to 60°C for 30 min, able to grow at pH 9.6 and in the presence of 6.5% NaCl. These are the markers recommended by the European directive for bathing and drinking water.

- Determination of Enterococci
- The determination protocol of the ISO 7899-2:2000 [17]/Directive 98/83/EC standard allows them to be determined. It consists of membrane filtration by:
- Filter 100 mL using a $0.45\ \mu\text{m}$ membrane.
- Place on m-Enterococcus agar or Slanetz & Bartley medium,
- Incubation at $36^{\circ}\text{C} \pm 2^{\circ}\text{C}$ for 44 h
- Confirmation on Bile Esculin Azide at 44°C (2 h),
- Use of Chromocult Enterococci chromogenic medium (pink/red colonies).
- Enterococci count

Counts of suspected enterococci are often performed with suspected thermo-tolerant coliform and coliform counts.

d) Testing for *Salmonella*

The *Salmonella* bacterium originates in the digestive tract of many vertebrate animals (birds, mammals, reptiles). It is mainly transmitted to humans through the ingestion of contaminated food or direct contact with infected animals.

The search for this germ was carried out by the classical microbiology technique according to the ISO 19250:2010 standard [18]. It took place in five stages.

Step 1—Pre-enrichment

First, a pre-enrichment was carried out as follows:

- Sample volume: 1 to 10 liters membrane filtered or 1 L directly
- Medium: Buffered Peptone Water (BPW) or Whey Broth
- Temperature: $37^{\circ}\text{C} \pm 1^{\circ}\text{C}$
- Duration: 16 - 20 h

Step 2—Selective Enrichment (Double)

Enrichment was done by depositing 1 mL of each inoculum initially pre-enriched in tubes containing RVS medium (Rappaport Vassiliadis Soy) before incubating the whole at $41.5^{\circ}\text{C} \pm 0.5^{\circ}\text{C}$ for 24 ± 3 hours (Table 3).

Step 3—Selective Media Isolation

Isolation was done on selective media, as follows:

- Mediums: XLD (Xylose Lysine Deoxycholate) + a second medium (Hektoen,

MLCB, or Rambach)

- Temperature: $37^{\circ}\text{C} \pm 1^{\circ}\text{C}$
- Duration: 24 ± 3 hours
- Typical appearance on XLD: black colonies with a black center (H₂S), pink-red halo.

Table 3. Selective enrichment temperature as a function of medium and duration.

Midfield	Temperature	Duration
Rappaport-Vassiliadis Soybean Broth (RVS)	$41.5^{\circ}\text{C} \pm 0.5^{\circ}\text{C}$	24 ± 3 hours
Muller-Kauffmann Tetrathionate-Novobiocin Broth (MKTn)	$37^{\circ}\text{C} \pm 1^{\circ}\text{C}$	24 ± 3 h

Step 4—Biochemical Confirmation

Biochemical confirmation was made following the tests:

- Tests: TSI, urea-indole, LDC, mobility, citrate.
- *Salmonella* profile: glucose +/gas, lactose –, H₂S+, urease –

Step 5—Serological confirmation

Serological confirmation according to:

- Serotyping with antisera O and H (polyvalent then monovalent)
- Expression: presence/absence in the volume under test.

2.3.3. Germ Count Calculations

Two petri dishes were inoculated by dilution; valid counts were between 30 and 300 colonies for GAM and between 15 and 150 for faecal *streptococci* and *E. coli*. The calculations of the sprout count were carried out according to the NF EN ISO-7218: (2014) [19] standard which determines the number N of colonies according to Formula (1).

$$N = \frac{\sum C}{V(n_1 + 0.1n_2)d} \quad (1)$$

- N: number of microorganisms in CFU/mL
- n_1 : number of boxes counted at the lowest dilution retained.
- n_2 : number of cans counted at the second dilution used,
- d : is the lowest dilution considered,
- V: is the volume of the inoculum
- $\sum C$: is the sum of all the colonies counted on all the Petri dishes considered.

3. Results

In this part, the results of the analyses will be highlighted. We will first present the results of the *in-situ parameters* and then those of the microbiological analyses. The samples are identified as follows: Epd to designate those of Djahakro; Epdi to designate those of Dialabougou; Eplg to designate those of 220 dwellings and finally Epr for the designation of the tap water sample, used as a reference (control: Epdr) (Table 4).

3.1. In-Situ Parameter Measurement Results

The *in-situ* parameters measured were: turbidity, hydrogen potential (pH), conductivity, and temperature.

- **Turbidity measurements**

Table 4 shows that the turbidity of the samples from Djahakro varies from 2.71 to 47.8 NTU, those from Dioulabougou range from 2.44 to 14 NTU, and those from the 220 dwellings range from 1.27 to 14.25 NTU, while the tap water has a value of 2.5 NTU.

Table 4. Physicochemical parameters measured at sampling points.

Settings	Sampling points													
	Units	EPR	Epd1	Epd2	Epd3	Epd4	Epd1	Epd2	Epd3	Epd4	Eplg1	Eplg2	Eplg3	Eplg4
Turbidity	NTU	2.5	15	22.7	2.71	47.8	3.65	2.6	2.44	14	14.25	11.1	2.25	1.27
pH	-	6.8	6.34	6.42	6.58	6.88	5.31	6.45	6.64	6.75	6.8	6.51	7.11	6.5
Conductivity	μS/Cm	700	450	720	1218	1362	1216	793	1009	725	727	790	2260	1155
Temperature	°C	24.8	28	22.8	29.1	28.8	28.25	29.4	27.7	29.1	29.1	27.9	27.9	28.2

- **Conductivity measurement**

The conductivity varies from 450 to 1362 μS/cm for the Djahakro samples (Epd), from 725 to 1216 μS/cm at the level of Dioulabougou (Epd1) and from 727 to 2260 μS/cm at the level of 220 dwellings (Eplg) (**Table 4**).

- **Temperature measurements**

Table 4 shows that the temperature of the samples varies from 22.8°C to 29.1°C for Djahakro, but those from Dioulabougou and 220 dwellings are 27°C to 29.4°C below the maximum allowable value of 40°C.

- **pH Measurements**

In addition, **Table 3** shows that the pH obtained for all samples is in the range of 5.31 to 7.11, compared with the recommended standard of 6.5 to 8.5 (**Table 5**).

Table 5. Statistical treatment of measured parameters against WHO standards.

Settings	WHO limit values	Units	Minimum Values	Maximum Values	Mean ± Standard Deviation
Turbidity	≤25	NTU	1.27	47.80	10.94 ± 13.03
pH	6.5 ≤ pH ≤ 8.5	-	5.31	7.11	6.55 ± 0.43
Conductivity	≤1000	μS/cm	450	2260	1009.62 ± 460.41
Temperature	≤25	°C	22.8	29.40	27.77 ± 1.89

3.2. Microbiological Analysis Results

Analyses are carried out on bacteriological parameters. Bacteriological analysis makes it possible to highlight fecal pollution of the water. Pathogenic organisms are very numerous and varied and cannot be the subject of specific research. In addition, their identification is very difficult, if not impossible in the case of vi-

ruses, because their lifespan can be very short. For these various reasons, it is necessary to look for germs that are always present in large numbers in the feces of men and warm-blooded animals, and that are more easily maintained in the external environment. These are: total germs, fecal coliforms, fecal *streptococci*, and *salmonella*.

The results contained in **Table 6** show an absence of faecal *streptococci* in all the samples analyzed, a presence of total germs in all samples with a range of 6.43×10^3 to 18.70×10^3 CFU/mL for the Djahakro samples, from 6.65×10^3 to 25×10^3 CFU/mL for those of Dioulabougou and 176 to 289 CFU/mL in the samples of 220 compartments. Tap water has a zero value of 0 CFU/mL.

For the enumeration of faecal coliforms, there is a total absence in the samples from Dioulabougou (Epd1), sample 2 from Djahakro (Epd2) gives a value of 23 CFU/mL. It was also found in 75% of the samples from 220 dwellings (Eplg) with a higher number at the level of sample 1 (47 CFU/mL).

Regarding the test for the presence or absence of *salmonella*, a presence was observed in 76% of all samples, with an exception for tap water, samples 2 and 4 from Dioulabougou (Epd1).

The values given in **Table 5** are CFU/mL for FAMT, fecal coliforms, and fecal *Streptococci*.

Table 6. Microbiological test results (CFU/mL).

Codes	FAMT	Fecal coliforms	Fecal <i>streptococci</i>	<i>Salmonella</i>	Distance from wells to lakes or runoff channels (m)
EPR	0	NE	NE	Absence	-
Epd1	1870. 103	NE	NE	Attendance	70
Epd2	6.43. 103	23	NE	Attendance	60
Epd3	1680. 103	NE	NE	Attendance	52
Epd4	1735. 103	NE	NE	Attendance	150
Epd11	1832. 103	NE	NE	Attendance	800
Epd12	4.50. 103	NE	NE	Absence	30
Epd13	25. 103	NE	NE	Attendance	50
Epd14	6.65. 103	NE	NE	Absence	900
Eplg1	176	47	NE	Attendance	400
Eplg2	287	17	NE	Attendance	300
Eplg3	212	NE	NE	Attendance	600
Eplg4	289	45	NE	Attendance	400
WHO Standard	≤100	0	0	0	25 ≤ D ≤ 1000

FAMT: total mesophilic aerobic flora. NE: None (no germs identified) D: Methodological regulatory distance allowed.

Regarding the distance (D) between the sampling wells and the pollution sources, microbiological impacts have been observed. A comparative study with surround-

ing towns and villages without lakes could confirm or refute this. The results (NE) of the germs analyzed are those that were not detected by our method used.

The distance from wells to stormwater and wastewater runoff lakes or channels varies from 30 m to 900 m (Table 7). This distance depends on the availability of existing wells at the household level and on the manifestation of flooding and infiltration effects, which are the basis of possible contamination.

Table 7. Distance from wells to lakes or runoff channels.

Settings	Methodological limit values	Units	Minimum Values	Maximum Values	Mean $\pm$ Standard Deviation
Distance	$25 \leq D \leq 1000$	m	30	900	317.66 ± 308.39

For an average distance of 317.66 ± 308.39 m, faecal coliforms are present. These are the wells: Epd2, Eplg1, Eplg2 and Eplg4. This could be the cause of the infections recorded elsewhere.

4. Discussion

4.1. Discussion on *In-Situ* Parameter Measurement

The analysis shows that 25% of the well water in Dioulabougou (Epd4), 50% in 220 homes (Eplg1 and Eplg2) and 75% in Djahakro (Epd1, Epd2 and Epd3) are cloudy because their turbidity far exceeds the WHO standard (≤ 5 NTU), with a very high value (150 NTU) in Sample 1 of Djahakro, which can be explained by the shallow depth of the well. These results show that the majority of the well water in Djahakro that is located near the lakes is very turbid; this may be due to the presence of suspended solids (sediments, microorganisms, etc.) caused by an infiltration of the lake water into the groundwater that feeds the wells, especially since there are agricultural activities (vegetable crops) near the lake [20]. The average high turbidity of 50% of the Yamoussoukro wells is below those obtained by Seki *et al.* on the wells of 67.42% of the city of Aboisso, in Côte d'Ivoire [21].

The 50% of the wells in each locality studied do not comply with the required standard on conductivity (≤ 1000 $\mu\text{S}/\text{cm}$), with a very high value (2260 $\mu\text{S}/\text{cm}$) at the level of sample 3 of 220 dwellings. This could indicate the excessive presence of dissolved salts (such as chlorides, sulphates, sodium, calcium, etc.) that would be caused by exchanges of wells with lakes (domestic wastewater receptacles in the city). Work was also carried out by Bawa *et al.* in the city of Lomé in Togo where they found chlorine demand values varying between 0.6 and 3.5 mg/L [6]. The high temperatures measured in the wells ($26^\circ\text{C} \pm 3^\circ\text{C}$ on average) are identical to those measured by Nwala *et al.* [8]. Also, the slightly acidic pH of these wells is consistent with the results of Bawa *et al.* [6]. This acidity is thought to come from the biological decomposition of organic compounds buried in the soil, or the geology of the environment is related to their slightly acidic pH (average pH of 6 ± 1). This is because heat can influence the biological breakdown of soil compounds, thus influencing pH. These high temperatures may be due to the sampling period or the shallow depth of some wells exposed to direct sunlight. Hand-dug wells are

particularly vulnerable to a variety of sources of contamination, as they exploit shallow aquifers that are very close to the surface. It is common to find fecal bacteria, nitrates or other anthropogenic contaminants. This is demonstrated by Yves *et al.* in the process of acidification of well water in the city of Abidjan, Côte d'Ivoire [22]. Flooding in the rainy season aggravates the dispersion of contaminants in the subsoil and subsequent contamination of wells. The flooded areas are generally occupied by working-class neighbourhoods, such as the three sites studied. This phenomenon is identical to the work of Ossey *et al.* in four disadvantaged neighbourhoods of Abidjan communes (Koumassi, Marcory, Port-Bouët and Treichville) nitrate values between 0 and 286 mg/L and ammonium up to 39.6 mg/L [23] [24].

4.2. Discussion of Microbiological Analysis Results

The results of the analysis of well water near the lakes show the presence of total germs in all samples. This indicates general bacterial contamination in the water. The values recorded are relatively high, ranging from 6,433,103 to 25,103 CFU/mL, except for tap water. These values are well above the norm (≤ 100 CFU/mL). This high content of total mesophilic aerobic flora in the samples indicates the existence of a significant bioburden. This can be due to organic contamination from a variety of sources, such as sewage, animal waste, or the decomposition of plant matter. Contaminants can be found in well water through the seepage of surface water (lakes) that is exposed to contaminated stormwater. This runoff water is often contaminated by anthropogenic activities and animal and human excrement, especially for fragile groundwater that is ineffective in filtration. The contamination of this water by total germs could also be due to the poor protection of the wells (open wells, in the majority of cases). Lack of knowledge of basic hygiene rules and the surrounding pollution (livestock breeding, existence of septic tanks and latrines) of the population could lead to contamination. Especially for the samples of Djahakro and Dioulabougou, taken in the conditions of lack of sufficient sanitation network for the evacuation of water, would be at the origin of these germs found. The zero value of 0 CFU/mL for tap water (Epdr) compared to well samples shows an effective treatment of drinking water before its distribution by the Water Distribution Company in Côte d'Ivoire (Table 6).

As far as faecal coliforms are concerned, there is an absence in the Dioulabougou samples, but their presence in 75% of the samples from 220 dwellings means the almost certain existence of faecal contamination of water according to Rodier *et al.* [3]. These same results of coliform contamination were obtained by Yapo *et al.* in well water intended for watering market gardeners in the town of Korhogo, in northern Côte d'Ivoire [25].

However, the results show an absence of faecal *streptococci*, which may suggest that there is no old faecal contamination in the samples, according to the work of Nwala *et al.* [8]. The WHO states that the presence of *Escherichia coli* (*E. coli*) provides indisputable proof of recent faecal pollution [4]. This suggests that these faecal coliform (*E. coli*) positive waters have been confronted with recent faecal

contamination. Based on our surveys at the sites of the monitored wells, this contamination is caused by domestic discharges and septic systems in the vicinity of the wells, and by the infiltration of contaminated surface water into poorly protected wells.

The presence of *Salmonella* in 76% of well water samples is a concern. *Salmonella* is an indicator of fecal contamination, which can come from several sources, including sewage infiltration, animal or human waste, or stormwater runoff that carries these contaminants to wells. This contamination represents a significant risk to public health because the *Salmonella* germ is responsible for serious food-borne infections that can cause gastroenteritis and systemic diseases. However, the absence of *Salmonella* in some samples 2 and 4 from Dioulabougou may be related to the fact that well water taken at these levels is located further away from sources of contamination, such as latrines, domestic farms, or landfills. The average distance of the wells from the sources of contamination in our work is 317.66 ± 308.39 (Table 6). The absence of *Salmonella* may also indicate more rigorous water management, including basic treatment or more effective natural underground filtration at some sites.

5. Conclusions

Our study, which analyzed the microbiological parameters of well water near the lakes of Yamoussoukro, revealed that all the analyzed wells suffered from widespread microbial contamination, characterized by high levels of mesophilic aerobic bacteria. The presence of fecal coliforms (*E. coli*) and *Salmonella* in more than half of the samples indicates fecal contamination in the wells analyzed in Djahakro, Dioulabougou, and 220 dwellings located near the lakes. This microbial contamination could be due to the proximity of the wells to the lakes or runoff channels, resulting from the infiltration of lake water contaminated by human activities or flooding, animal waste, and other sources. These infections are also thought to be caused by domestic wastewater, the proximity of wells to septic tanks, and the fact that most wells were open (especially those in Djahakro and Dioulabougou). The presence of *Salmonella* in well water is very concerning. Ingesting contaminated water can lead to serious infections, especially in children, the elderly, or immunocompromised individuals. Furthermore, certain strains of *Escherichia coli* (*E. coli*) can cause severe infections with symptoms such as bloody diarrhea and kidney complications (hemolytic uremic syndrome). Therefore, consuming water contaminated with *E. coli* represents a major health risk.

To address these issues, measures aimed at improving well protection against surface seepage must be encouraged, particularly by installing well curbs, relocating sources of pollution (latrines, dumps), and ensuring adequate drainage around wells.

Government officials should also consider raising awareness among local populations about the importance of hygiene and water protection, which could also help reduce contamination. Similarly, the use of home water treatment systems

(chlorination, filters) should be promoted for populations dependent on well water to reduce the risk of infection.

These findings highlight the need for increased attention to the management and protection of water sources in urban and rural areas surrounding Yamoussoukro. Effective and efficient well water management, in particular, is a key factor in resolving this public health problem.

Authors' Contributions

All authors made substantial contributions to the design of the article.

Dongo Koffi René, corresponding author, participated in the conceptualization and all of the activities of the article.

Kouame Kouakou Benoit, participated in the methodology, analysis, and writing of the article.

Briton Bi Gosse Henri participated in the analysis, writing, and investigation.

Zedou Abalé Molière participated in the investigation and mapping.

Conflicts of Interest

The authors declare no conflicts of interest.

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