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Physicochemical and bacteriological characterisation of domestic drinking water sources in the village of M'pody during the four seasons of 2020 in Côte d'Ivoire

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This study aims to assess the quality of the water in the wells and boreholes at M'pody following an outbreak of diarrhoea in January 2020. The methodology consisted of carrying out four water sampling campaigns of the 72 identified wells and the single borehole over four seasons. Standard physico-chemical parameters were determined using electrochemical and spectrophotometric methods. Microbiological analysis was carried out using membrane filtration and mass incorporation techniques. Results showed that 29.6% of the parameters peaked during the long dry season, 25.9% during the long rainy season, 33.3 and 11.2% during the short dry season and short rainy season, respectively. Water was poorly mineralized, aggressive, and associated with a risk of methaemoglobinaemia in 24.30% of samples. These waters all contained germs indicative of faecal pollution, making them undrinkable. The non-potability of the analysed water was mainly linked to turbidity, pH, total iron levels, and nitrogen derivatives. It would therefore be advisable to treat water from wells in a domestic tank, and a simple chlorine treatment of the water castle would be appropriate before any distribution.

Key word: Drinking water, well, borehole, quality control, health risk.

INTRODUCTION

Water is a vital element full of symbols, culture, and spirituality. It is essential for human, animal and plant life. Having water available in sufficient quantity and quality helps to maintain health (Tamungang et al., 2016). All over the world, the state of water resource has become critical, threatened by sharply rising consumption and an

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increased pollution.

In Africa, studies have highlighted the fragility and vulnerability of groundwater resources due to natural factors such as geology, degree of chemical weathering of various types of rock combined with various human factors including demographic pressure, uncontrolled landfills and sanitation systems. These factors can lead to groundwater pollution (Yapo et al., 2016). Consumption of poor-quality water from traditional wells leads to persistence of waterborne diseases (DE Marsily, 2013; Kabore et al., 2013).

In sub-Saharan Africa, lack of access to safely managed basic water supply and sanitation services for 76 and 78% of the population, respectively, contributes to the deaths of 180,000 children under the age of 5 each year from infectious diarrhoeal diseases (OMS/UNICEF, 2017). This public health problem is the most common and widespread drinking water-related health risk in the region (OMS/UNICEF 2017).

In Côte d'Ivoire, groundwater in rural areas is subject to multiple constraints due to strong demographic growth, the lack of sanitation and the development of agriculture, resulting in the creation of unsuitable septic tanks, discharge of untreated wastewater, uncontrolled dumping, open defecation and abusive use of fertilisers and pesticides which are the main sources of groundwater pollution (Ngouala et al., 2020).

The Anyama commune, like other communes of Abidjan, faces the same pollution problems, including non-existent sanitation services and the presence of traditional non-returnable latrines. This presents chemical and microbiological contamination risks of the groundwater. In 2020, in M'pody, a village located in Anyama sub-division, an outbreak of diarrhoea affected 69 people, including 7 children under the age of 5. However, no human losses were recorded. These cases of diarrhoea were linked to the consumption of water collected from an improved village water system (HVA), which had not been maintained for 3 years. The general aim of the study was to characterise the sources of domestic drinking water in the locality of M'pody during the four seasons.

METHODOLOGY

Presentation of the study area

M'pody belongs to Anyama sub-division in the south of Côte d'Ivoire. Anyama sub-division is located between latitudes 5°10 and 5°35 North and longitudes 3°45 and 5°20 West and covers an area of 114 km^2. It has an estimated population of 389,592 (INS 2014) and has 11 villages, including M'pody. M'pody is located to the north of the Anyama commune at latitude 5°32 North and longitude 3°58 West. It has an area of 67.97 ha and is located 30 km as the crow flies from the coast of the Gulf of Guinea, North-East of Abidjan. Residents of the village of M'pody obtain drinking water from wells and an improved village water supply (HVA) system. Improved village water supply system (HVA) is an intermediate technology between hand pumps and urban water supply systems that aims to provide sustainable access to drinking water to rural populations, using electric pumps to supply water to castles and standpipes. The M'pody population was estimated at around 2.731 in 2014, including 1.136 men and 1.108 women with 487 children under the age of 5 (INS 2014). The climate is equatorial, characterized by alternation of four seasons: long dry season (LDS) from December to March, short dry season (SDS) from August to September, long rainy season (LRS) from April to July, and short rainy season (SRS) from October to November (Assalé 2013); with the peak of the main rainy season in June. Average annual rainfall varies between 1.600 and 2.500 mm (Figure 1).

Equipment

The main measuring equipment consists of a Palintest photometer (UK), a pH meter, a conductivity meter, a turbidity meter for physico-chemical parameters, and a membrane filtration system for bacteriological parameters.

Sampling

Sampling consists of collecting all functional water points. The water points were seventy-two wells with an average depth of 4.27 m and 1 borehole with a depth of 69 m. Samples were taken in 1000 ml polyethylene bottles for physico-chemical parameters and 500 ml for microbiological parameters.

Reagents

All reagents used were of analytical quality. Reagents used to measure chemical parameters were PALINTEST (Great Britain), BIO-RAD Rapid E. coli 2 Agar, BEA (Bile Esculin Azide) agar, and TSN (Tryptone Sulfite Neomycin) agar were used to enumerate markers of faecal contamination.

Sample collection, transportation, and storage

Water samples were taken in accordance with the recommendations of AFNORD FD T90-520 of October 2005 and were stored at a temperature of between +4 and +8°C, then transported to the National Institute of Public Hygiene (INHP)'s water and food laboratory in Abidjan-Treichville using ice accumulators to maintain the cold chain.

Physical and chemical analyses

The physico-chemical parameters were determined by the following methods:

1) The pH is measured with a HACH type digital laboratory pH meter fitted with a combined electrode (Bioblock Scientific) (AFNOR, 1997).
2) Conductivity is measured using a Hach conductivity meter (AOAC, 1990).
3) Turbidity is determined using nephelometry of the Hach nephelometer (AOAC, 1990).
4) Titrimetry has been used to determine organic matter (AFNOR, 1997).
5) Mineral salts and colour were determined colorimetrically using a Palintest 7100 SE photometer equipped with filters and pre-programmed calibration curves. Operational wavelengths varied between 410 and 640 nm. The manufacturer's procedure was used. The mineral salts tested were nitrite, nitrate, fluorides, iron,

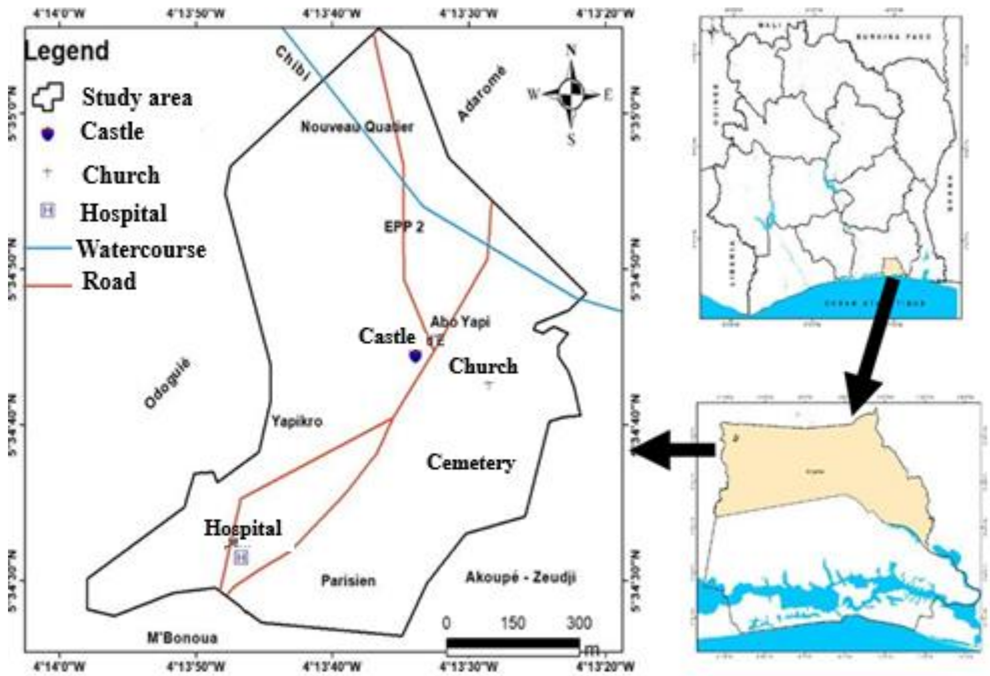

Figure 1. Presentation of the study area. Source. BNETD.

manganese, total alkalimetric titre (TAT), total hydrotimetric degree (THD), ammonium, sodium, magnesium, calcium, sulphate, potassium, bicarbonate, and zinc.

Microbiological analyses

Microbiological analyses were used to identify and count total coliforms (TC), *Escherichia coli* (*E. coli*), *Enterococcus faecalis* (*E. faecalis*), *Pseudomonas* species, and sulphite-reducing anaerobes (SRA). These microorganisms were identified and counted by filtering homogeneous aliquots of 100 ml and 50 cl (sulphite-reducing anaerobes) through a membrane with a pore diameter of 0.45 µm. The membranes were then placed on selective culture media for 24 h at 37°C in a thermostatic oven. The following media were used: BEA (Bile Esculin Azide) agar (selective medium used for the isolation and enumeration of enterococci by the conventional Petri dish counting method) for faecal *Streptococci*, RAPID'E. coli 2 Agar (culture medium for identifying *E. coli*) for total coliforms, TSN agar (Tryptone Sulfite Neomycin) for Clostridium sulfito-reductor, and pseudosel or ketrimide medium for *Pseudomonas*.

Data processing

A descriptive analysis (averages, medians, minimum, maximum, and standard deviation) was carried out. A sample of water is reported non-compliant when at least one of the analysed parameters is non-compliant. Statistical analysis was carried out on the 292 samples over the four seasons, 73 per season, 15 physico-chemical variables, and 5 microbiological variables.

Calculating the risks of corrosion and methaemoglobinaemia

The risk of corrosivity was estimated using the Aggressivity Index (AI) (American Water Works Association, 1977) and the risk of methaemoglobinaemia using the Nitrate-Nitrite Index (OMS 2000):

$$IA = pH + \log_{10}(TAC \times DHT) \quad (1)$$

where AI = Aggression index, TAT = Total alkalimetric titre, THD = Total Hydrotimetric degree. Aggressive water is AI<10, slightly aggressive water is AI ϵ (10-12), and non-aggressive water is AI≥12.

$$MI = \frac{C_{nitrate}}{VG_{nitrate}} + \frac{C_{nitrite}}{VG_{nitrite}}$$

where MI = Methaemoglobinaemia index, C = Concentration, GV = GuideValue. The presence of a risk of methaemoglobinaemia is MI>1, and no risk of methaemoglobinaemia is MI≤1.

RESULTS

Physico-chemical and bacteriological parameters of well and borehole water during the long dry season (LDS)

The results of the physico-chemical and bacteriological analyses of water samples from wells and borehole water studied during the long dry season are shown in Table 1. Physico-chemically, the well water and borehole water were poorly mineralised with conductivities of 151.02±119.44 and 168.1 µS/cm, respectively. Water from a well has an acidic pH, while the borehole water has a neutral pH. The maximum levels of physico-chemical parameters in the well and borehole water,

Table 1. Results of physico-chemical and bacteriological analyses of well water (n= 72) and borehole water (n=1) during the long dry season (LDS)

Parameter	Borehole	Well				WHO standards (2011)
		Min	Med	Moy±SD	Max	
Turbidity (NTU)	5.91	1.49	7.88	14.12±14.71	96.4	≤4
Conductivity (µS/cm)	168.1	20.32	126	151.02±119.44	643	1000
Colour (TCU)	20	5	30	31.67±16.18	80	≤15
pH	7.17	4.23	5.22	5.31±0.62	6.87	6.5-8.5
Temperature (°C)	24.7	22	28.6	27.47±2.55	30.3	25
Residual chlorine (mg/L)	-	0	0.06	0.51±2.48	16.2	0
Organic matter (mg/L)	6.59	0.72	4.54	4.78±2.83	15.2	≤5
Nitrate (mg/L)	0.3	0.01	15	14.21±7.34	28	≤50
Nitrite (mg/L)	0.02	0.01	0.04	0.13±0.32	1.65	≤0.1
Ammonium (mg/L)	0.24	0.01	0.11	0.363±0.74	4	≤1.5
Total iron (mg/L)	0.55	0.01	0.25	1.113±2.57	13.2	≤0.3
Fluoride (mg/L)	0.18	-	-	-	-	≤1.5
TAT	330	5	50	68.68±54.04	310	-
THD (mg/L)	95	5	10	20.75±33.35	190	500
Magnesium (mg/L)	5	01	01	8.04±12.00	50	≤50
Manganese (mg/L)	0.032	0.001	0.01	0.02±0.01	0.06	≤0.1
Carbonate	250	05	30	41.04±32.50	190	-
Bicarbonate (mg/L)	400	05	65	88.26±76.71	450	-
Total Coliforms (CFU/ml)	10	0	880	1374.56±1593.54	9900	0
E. coli (CFU/ml)	03	0	75	411.75±743.22	3400	0
E. faecalis (CFU/ml)	0	0	0	17.39±51.38	280	0
SRA (CFU/ml)	30	0	0	1.53±3.56	21	0
Pseudomonas spp. (CFU/ml)	0	0	01	51.19±195.72	1500	0

*Turbidity: ≤ 1 UNT for the Ivorian standard

compared with the WHO standard (2011), showed non-compliance in terms of turbidity, organic matter, iron, nitrogen derivatives, and residual chlorine. Bacteriological analyses of well and borehole water showed the presence of Coliforms, Enterococci, SRA, and *Pseudomonas* spp. germs.

Physico-chemical and bacteriological parameters of well and borehole water during the main rainy season (LRS)

The results of the physico-chemical and bacteriological analyses of the well and borehole water studied are shown in Table 2. In terms of physico-chemical parameters, the conductivities of water from the well and from the borehole were similar during the long dry season. The well and borehole waters were all acidic. Non-conformities were observed in the physico-chemical parameters for iron and nitrogen derivatives. Bacteriologically, Coliforms, Enterococci, SRA, and *Pseudomonas* spp. were present in both well and borehole water.

Physico-chemical and bacteriological parameters of well and borehole water during the short dry season (SDS)

The results of the physico-chemical and bacteriological analyses of the well and borehole water studied are shown in Table 3. Physico-chemically, the average conductivity of the well and borehole water was similar to that of the LDS and LRS. These waters were acidic. Physico-chemical parameters incriminated in the non-compliance were iron, nitrogen derivatives, and residual chlorine. From a bacteriological point of view, Coliforms, Enterococci, SRA, and *Pseudomonas* germs were present in both well and borehole water.

Physico-chemical and bacteriological parameters of well and borehole water from the short rainy season (SRS)

The results of the physico-chemical and bacteriological analyses of the water from the well and borehole studied are shown in Table 4. The well and borehole water was

Table 2. Results of physico-chemical and bacteriological analyses of well water (n=72) and borehole water (n=1) during the main rainy season (LRS).

Parameter	Borehole	Well				WHO standards (2011)
		Min	Med	Moy±SD	Max	
Turbidity (NTU)	19.8	1.94	17.05	20.97±17.90	89.5	≤4
Conductivity (µS/cm)	184.7	22	122.9	148.22±96.10	540	1000
Colour (TCU)	20	10	27.5	27.57±14.98	75	≤15
pH	6.92	4.26	5.17	5.23±0.47	6.2	6.5-8.5
Temperature (°C)	26.3	25.7	27.75	27.76±0.59	29.1	25
Residual chlorine (mg/L)	-	0	0	0.00±0.00	0	0
Organic matter (mg/L)	3.65	1.37	5.02	5.30±2.79	17.28	≤5
Nitrate (mg/L)	0.94	0.04	0.64	4.14±8.35	50.9	≤50
Nitrite (mg/L)	0.07	0.01	0.05	0.08±0.15	1.21	≤0.1
Ammonium (mg/L)	0.13	0.01	0.07	0.203±0.33	1.38	≤1.5
Total iron(mg/L)	0.25	0.01	0.23	0.36±0.38	2.05	≤0.3
Fluoride (mg/L)	0.2	-	-	-	-	≤1.5
TAT	85	5	65	78.13±44.20	210	-
THD (mg/L)	45	5	17.5	25.90±24.58	105	500
Magnesium (mg/L)	9	01	8.5	10.06±10.12	65	≤50
Manganese (mg/L)	0.023	0.001	0.012	0.01±0.01	0.06	≤0.1
Carbonate	50	10	40	48.26±25.86	125	-
Bicarbonate (mg/L)	100	25	80	96.32±52.91	255	-
Total Coliforms (CFU/ml)	10	01	850	2484.61±3203.56	13500	0
E. coli (CFU/ml)	03	0	465	1116.74±1422.11	5000	0
E. faecalis (CFU/ml)	0	0	605	1158.18±1249.91	4700	0
SRA (CFU/ml)	30	0	0	0.82±1.5	06	0
Pseudomonas spp. (CFU/ml)	0	0	15	38.60±66.84	350	0

*Turbidity: ≤ 1 NTU for the Ivorian standard.

slightly mineralized, with an average conductivity between 100 and 200 µS/cm, and had an acidic pH. Physico-chemical parameters such as iron, nitrogen derivatives, and residual chlorine were incriminated in the non-compliances. As for bacteriology, well and borehole water showed the presence of Coliform, Enterococcus, SRA, and *Pseudomonas* spp. germs.

Temporal trends in physico-chemical and bacteriological parameters of M'pody drinking water over the four seasons

Changes over time in the levels of physico-chemical elements

Electrical conductivity: The electrical conductivity of water from both the borehole and well followed a similar sawtooth pattern, exhibiting two peaks during the long dry season and the short dry season (Figure 2B). The minimum conductivity values recorded for the borehole and well water were 168.1 and 148.22 µS/cm, respectively. The minimum for the borehole occurred during the long dry season, while the minimum for the well water was observed during the long rainy season. The maximum conductivity values were 223 µS/cm for the borehole and 178.88 µS/cm for the well, both of which were recorded during the short dry season.

Turbidity: The turbidity curves for borehole water showed an increasing and decreasing trend with a peak in the main dry season, while those for well water showed a sawtooth pattern with two peaks in the main dry season and in the short rainy season (Figure 2A). Turbidity values in the wells ranged from a minimum of 14.12 NTU in the very dry season to a maximum of 20.97 NTU in the very wet season. Turbidity values at the borehole ranged from 0.51 to 19.8 NTU during the short and long rainy seasons, respectively.

pH: The pH of the borehole and well water decreased over the four seasons (Figure 2C). In the case of borehole water, the lowest pH value was recorded during the short rainy season (6.13), while the highest value was recorded during the long dry season (7.17). As for the wells, the lowest pH was 4.86 and was obtained during the short rainy season, while the highest value of 5.31 was recorded during the long dry season.

Table 3. Results of physico-chemical and bacteriological analyses of well water (n=72) and borehole water (n=1) during the short dry season (SDS).

Parameter	Borehole	Well				WHO standards (2011)
		Min	Med	Moy±SD	Max	
Turbidity (NTU)	0.51	3.39	13	19.43±17.30	86.4	≤4
Conductivity (µS/cm)	208.5	23.9	128.9	153.26±137.50	964	1000
Colour (TCU	40	10	15	24.03±14.73	70	≤15
pH	6.13	3.72	4.84	4.86±0.53	6.19	6.5-8.5
Temperature (°C)	29.5	26.8	28.2	28.16±0.50	29.2	25°C
Residual chlorine (mg/L)	-	0	0.23	0.36±0.40	1.62	0
Organic matter (mg/L)	7.3	0.63	2.97	3.13±1.54	6.3	≤5
Nitrate (mg/L)	6.8	0.5	17.45	20.70±17.74	137.7	≤50
Nitrite (mg/L)	0.13	0.01	0.02	0.07±0.15	0.87	≤0.1
Ammonium (mg/L)	0.1	0.01	0.26	0.573±1.06	8.6	≤1.5
Total iron (mg/L)	2.68	0.07	0.23	0.38±0.38	2.73	≤0.3
Fluoride (mg/L)	0.3	-	-	-	-	≤1.5
TAT	120	5	65	78.28±43.79	210	
THD (mg/L)	50	5	22.5	29.10±26.03	135	500
Magnesium (mg/L)	5	01	05	6.56±5.32	25	≤50
Manganese (mg/L)	0.024	0.001	0.011	0.02±0.01	0.06	≤0.1
Carbonate	30	10	40	49.31±24.54	120	-
Bicarbonate (mg/L)	65	25	85	87.15±38.81	210	-
TotalColiforms (CFU/ml)	0	0	1155	2429.11±8377.04	72000	0
E. coli (CFU/ml)	0	0	290	649.10±764.43	2820	0
E. faecalis (CFU/ml)	0	0	280	614.39±780.43	2970	0
SRA (CFU/ml)	0	0	0	0.51±1.67	10	0
Pseudomonas spp. (CFU/ml)	0	0	0	2.31±11.30	70	0

*Turbidity: ≤ 1 UNT for the Ivorian standard.

Nitrate ion concentration: The nitrate concentration curves for well water showed two peaks during the long dry season and the short rainy season, respectively, while those for borehole water showed a peak during the short rainy season (Figure 2D). In the wells, the nitrate concentration fluctuated between a minimum of 4.14 mg/L in the main rainy season and a maximum of 20.70 mg/L in the short rainy season. Nitrate levels in borehole water varied from 0.023 (short dry season) to 6.8 mg/L (short rainy season).

Nitrite ion concentration: Nitrite concentrations in well water showed a decreasing trend, rising again during the short rainy season (Figure 2E). In the borehole water, the curves showed an increasing trend with a peak during the short rainy season. Nitrite levels varied between a minimum of 0.02 mg/L in the long dry season and a maximum of 0.13 mg/L in the short rainy season in the borehole water. For well water, nitrite concentrations varied from 0.05 mg/L in the short rainy season to 0.13 mg/L in the long dry season.

Ammonium ion concentration: The curve of ammonium concentrations in the borehole water showed an increasing trend with a peak in the short rainy season, while the well water showed a peak in the short dry season (Figure 2F). In the borehole water, ammonium values ranged from 0.1 mg/L in the short dry season to 2.9 mg/L in the long dry season. In well water, ammonium concentrations ranged from 0.20 mg/L in the long rainy season to 0.57 mg/L in the short rainy season.

Iron ion concentration: The curves for iron ion concentrations in the borehole water showed a sawtooth pattern with two peaks in the long and short dry seasons, respectively, while the well water showed a decreasing pattern and stabilised with a peak in the long dry season (Figure 2G). Iron levels in borehole water varied from 0.25 mg/L in the long dry season to 2.9 mg/L in the short dry season. In well water, iron concentrations ranged from a low of 0.35 mg/L in the short dry season to a high of 1.11 mg/L in the long dry season.

Temporal variation in bacteriological parameters of drinking water

E. coli densities

E. coli density curve for borehole water was constant,

Table 4. Results of physico-chemical and bacteriological analyses of well water (n=72) and borehole water (n=1) during the short rainy season (SRS).

Parameters	Borehole	Well				WHO standards (2011)
		Min	Med	Moy±	Max	
Turbidity (NTU)	10.9	1.95	11.25	15.84±13.54	64.45	≤4
Conductivity (µS/cm)	223	21.87	125.8	178.88±227.41	1283	1000
Colour (TCU)	25	10	25	28.89±15.23	95	≤15
pH	6.99	4.16	5.06	5.13±0.53	6.86	6.5-8.5
Temperature (°C)	29	26.6	27.9	27.81±0.56	29.7	25
Residual chlorine (mg/L)	-	0	0.14	0.36±0.68	4.92	0
Organic matter (mg/L)	8.28	2.38	4.81	5.63±3.05	17.8	≤5
Nitrate (mg/L)	0.02	0.4	6.45	17.35±18.88	73.8	≤50
Nitrite (mg/L)	0.08	0.01	0.01	0.05±0.15	1.04	≤0.1
Ammonium (mg/L)	2.9	0.01	0.08	0.293±0.58	3.9	≤1.5
Total iron (mg/L)	2.9	0.01	0.2	0.353±0.46	2.8	≤0.3
Fluoride (mg/L)	0.15					≤1.5
TAT	270	5	55	71.18±65.63	480	
THD (mg/L)	60	5	15	23.13±20.32	85	500
Magnesium (mg/L)	6	01	06	7.25±6.85	45	≤50
Manganese (mg/L)	0.025	0.001	0.012	0.011±0.01	0.05	≤0.1
Carbonate	40	15	40	50.63±34.00	165	
Bicarbonate (mg/L)	90	25	75	91.11±49.99	255	
Total Coliforms (CFU/ml)	0	0	955	2672.64±4483.48	27000	0
E. coli (CFU/ml)	0	0	390	1612.11±3630.40	2000	0
E. faecalis (CFU/ml)	0	0	290	1454.35±3821.09	15000	0
SRA (CFU/ml)	0	0	0	0.53±1.57	10	0
Pseudomonas spp. (CFU/ml)	0	0	0	3.72±15.09	84	**0**

*Turbidity: ≤ 1 UNT for the Ivorian standard.

whereas well water showed a peak during the short dry season. In the borehole water, *E. coli* densities varied from 0 CFU/ml in the short dry and rainy season to 4 CFU/ml in the long rainy season. In well water, *E. coli* densities ranged from 411.75 CFU/ml in the long dry season to 1612.11 CFU/ml in the short dry season (Figure 2H).

Densities of E. faecalis

The well water curves showed a pattern with a peak in the short dry season, while the borehole water remained constant over the four seasons, with a peak in the long rainy season. In the borehole water, *E. faecalis* loads ranged from 0 CFU/ml in the long dry season, the short dry season, and the short rainy season to 60 CFU/ml in the long rainy season. In well water, *E. faecalis* densities ranged from 17.39 CFU/ml in the long dry season to 1454.35 CFU/ml in the short dry season (Figure 2I).

Multivariate analysis

The Pearson correlation matrix was used in this study because normality was verified (n≥31). Examination of the correlation matrix (Figure 3) reveals the presence of variables that are well correlated with each other. These are pH with iron parameters (0.88); TAT with THD (0.67) and bicarbonate (0.68); DHT with sulphate (0.5) and bicarbonate (0.57); total coliforms with *E. coli* (0.5); and *E. coli* with *E. faecalis* (0.64).

Analysis of non-conformities and health risk assessment

The aim was to determine non-conformities at the sample level and for each parameter measured.

Non-conformity of samples

Table 5 shows the quality of the water used for consumption in the village of M'pody. Out of the 292 water samples analysed, none complied with the WHO recommendation.

Non-conformity of parameter levels

All the water from the borehole was non-drinkable (Table

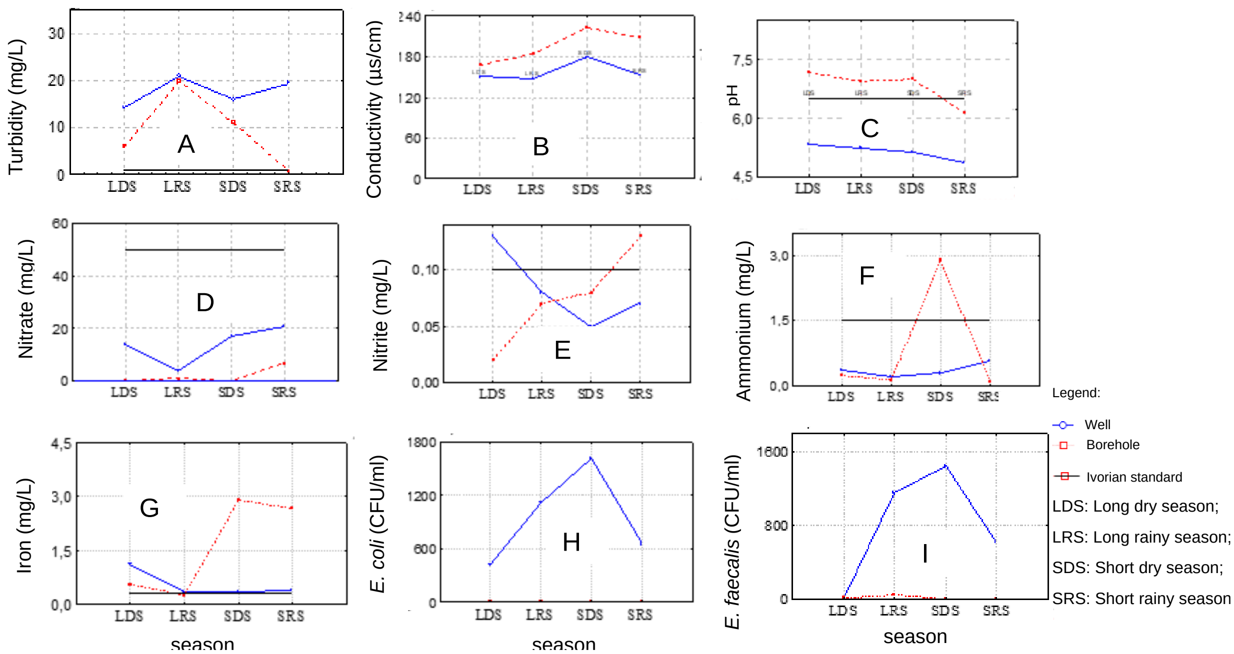

Figure 2. Seasonal trends in physico-chemical and bacteriological parameters in various drinking water sources. Well, borehole, Ivorian standard, LDS: Long dry season, LRS: Long rainy season; SDS: Short dry season; SRS: Short rainy season.

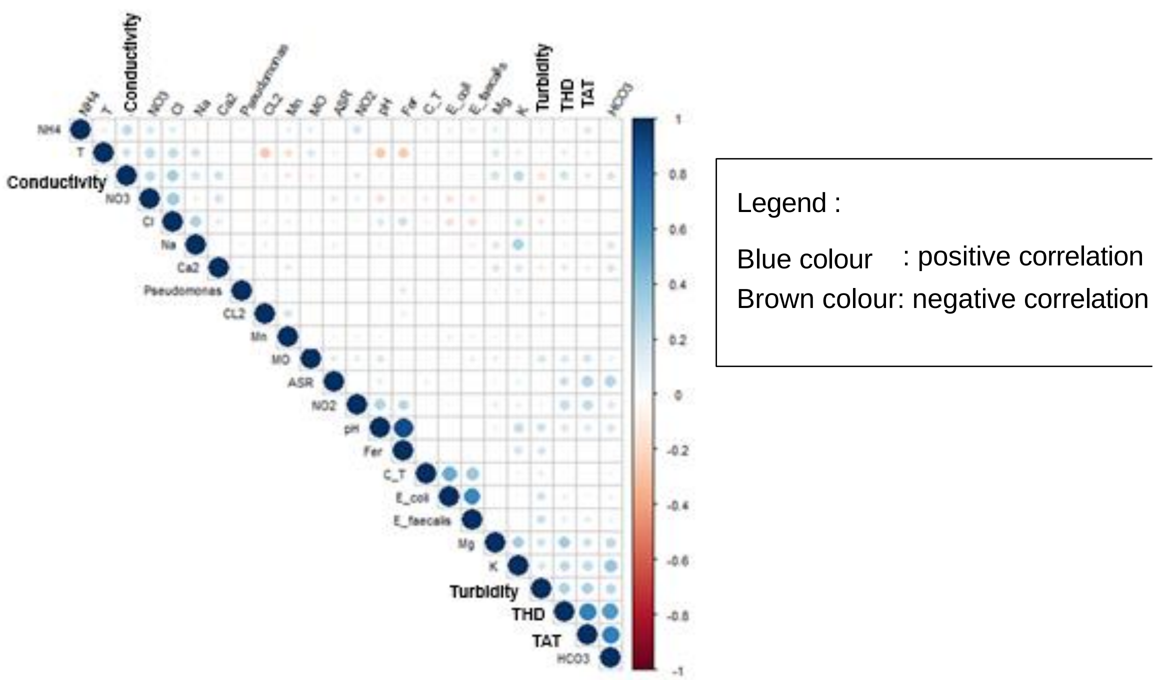

Figure 3. Correlation between the values of physico-chemical and bacteriological parameters of the three water sources.

6) and therefore presented a risk to consumers. The physico-chemical parameters responsible for the numerous non-conformities were pH, turbidity, residual chlorine, total iron, nitrate, nitrite, ammonium, potassium, and organic matter. Bacteriological non-compliances concerned most of the bacteria identified (TC, *E. coli*, *E.*

Table 5. Overall quality of samples.

Samples	Borehole samples	Well samples
Compliant	0 (0%)	0 (0%)
Non-compliant	4 (100%)	288 (100%)
Total	4	288

Table 6. Non-compliant physicochemical and bacteriological parameters.

Parameters	Borehole (n=4) (%)	Well (n=288) (%)
Turbidity (NTU)	NC (75)	NC (85.06)
pH	NC (25)	NC (98.26)
Residual chlorine (mg/L)	-	NC (67.80)
Nitrates (mg/L)	-	NC (2.43)
Nitrite (mg/L)	NC (25)	NC (11.45)
Ammonium (mg/L)	NC (25)	NC (2.77)
Total iron (mg/L)	NC (75)	NC (40.27)
Organic matter (mg/L)	NC (75)	NC (39.58)
Potassium (mg/L)	-	NC (12.50)
TC (CFU /100 ml)	NC (50)	NC (96.18)
E. coli (CFU/100 ml)	NC (50)	NC (87.50)
E. faecalis (CFU/100 ml)	NC (25)	NC (80.56)
SRA (CFU /20 ml)	NC (25)	NC (23.26)
Pseudomonas spp. (CFU/100 ml)	-	NC (24.65)
Samples	NC (100)	NC (100)

TC: Total coliforms; SRA: sulphite-reducing Anaerobic bacteria; NC: Non-compliant.

faecalis, *Pseudomonas* spp., and SRA) with high microbial loads.

Risks of corrosion and methaemoglobinaemia

Calculations of the risks of corrosion and methaemoglobinaemia showed that all the borehole and well waters were corrosive (Table 7) and presented risks of methaemoglobinaemia of 25 and 24.3%, respectively, for the borehole and well waters (Table 8).

DISCUSSION

Physico-chemical characterisation of water sources

Drinking water in the locality of M'pody had very low mineralisation for borehole water and well water, respectively. Similar conductivity values were obtained by Kouamé et al. (2021), who carried out studies on the physico-chemical characteristics of borehole water for domestic use in the town of Daloa (west-central Côte d'Ivoire).

In terms of pH, the well water had an average pH of 5.13. while the well water had a pH of 6.96. In fact, several authors (Ligban et al., 2009; Ahoussi et al., 2013; Adjiri et al., 2018; Ehoussou et al., 2019; Traoré et al., 2022) have shown in their various works that well water in this region comes from shallow aquifers. The acidity of drinking water poses no health problems for consumers. The taste of water, its corrosiveness and solubility, and speciation of metal ions are all influenced by pH. At low pH, water may taste sour, while at high pH, water tastes bitter or soapy (DWA 1998). Water with a low pH level may cause corrosion in galvanized or copper pipes (DWA 1998). Total heavy metal content in water could increase at low pH, which is a matter of public concern (Virkutyte and Sillanpää, 2006). There are no health consequences attributed to the pH of water, except at extreme values. The direct health effects of low and high pH levels include acid and alkali burns, respectively. These extreme pH levels may also cause irritation of the mucous membranes (DWA 1998). According to these authors, the acidification of these waters is due to the disappearance of easily alterable primary minerals and the non-dissociation of organic acid and carbonic acid, which act as buffers to limit the acidity of the water. The acidity of water is one of the essential characteristics of water in Côte d'Ivoire in general and in the greater Abidjan region in particular. In fact, pH is influenced by the biological and geological processes occurring in a body of water, and by

Table 7. Corrosion criteria.

Risk of corrosion	AI	Borehole samples (%)	Well samples (%)
High	≤10	100	100
Low	10-12	0	0
Absence	≥12	0	0

AI: Aggressiveness index

Table 8. Risk of methaemoglobinaemia.

Risk of methaemoglobinaemia	MI	Borehole samples (%)	Well samples (%)
Presence	>1	25	24.30
Absence	≤1	75	75.70

MI: Methaemoglobinaemia Index.

the nature of the terrain through which it flows (Soro et al., 2021). The temperature of the well and borehole water was above 20°C. The temperature varied between 22 and 30°C over the four seasons. These values were similar to those obtained by Kanohin et al. (2017) for groundwater in Bingerville, a commune located about 50 km from M'pody. A groundwater temperature in excess of 25°C may correspond to ambient atmospheric temperatures and could indicate the openness of the aquifer system and therefore its vulnerability to pollution. However, a temperature above 20°C favours the development of micro-organisms (Rodier et al., 2016).

Mineral measurements in the water samples taken showed very low concentrations of fluoride, calcium, magnesium, sulphate, chloride, phosphate, sodium, and zinc over the four seasons, with no impact on water quality. Similar results were reported by the studies of Mahamane and Guel (2015) in Burkina Faso and Pambou et al. (2022) in Gabon on major ions (Na^{2+}, K^{+}, Ca^{2+}, Mg^{2+}, SO_4^{2-}, Cl^{-}) in groundwater. Levels of trace elements such as iron showed high peaks in wells during the dry season. The high concentrations of iron observed in the groundwater are due to the geological nature of the area. The geology of the study area consists mainly of amphiboles. These are ferromagnesian rocks, the alteration of which will lead to an accumulation of iron in the soils, giving way to ferralitic soils. The ferralitic nature of the area's soils was reported by Djade et al. (2020). The heavy leaching of these soils by rainfall leads to infiltration and accumulation of this element in groundwater. Similar concentrations of iron were reported by Ahoussi et al. (2013) in well water in the sub-prefecture of Biankouma, located in the mountainous west of Côte d'Ivoire. The elevated iron levels in the groundwater were comparable to those reported by Lanciné et al. (2008) in the Tiassalé region of southern Côte d'Ivoire, approximately 50 km from the village of M'pody. The high iron content has led to a problem with the acceptability of the water to local people. This element gave the water an unpleasant metallic taste. According to Goné et al. (2005), the high levels of Fe^{2+} and Mn^{2+} suggested that the environment was low in dissolved O_2.

The nitrate content of the well water (13.67±13.58 mg/L) was higher than the nitrate content of the borehole water (5.38±5.48 mg/L). Nitrates were the final stage in the oxidation of nitrogen and represented the most highly oxidised form of nitrogen in water. However, the main source of nitrates in well water was attributed to human activities. In fact, their content in well water is linked to agrarian activities (use of fertilisers), domestic wastewater, and animal manure (Yuan et al., 2017). The presence of nitrates in water is thought to be due to agricultural activities using chemical fertilisers. Another likely source is the decomposition of plant organic matter (Soro et al., 2019). In addition, the massive use of fertilisers and heavy rainwater drainage has contaminated groundwater by increasing nitrate levels (Ahoussi et al., 2013; Aka et al., 2013). This vertical infiltration of nitrates was accelerated or delayed by the geological nature of the unsaturated zone. Well water was vulnerable to organic pollutants from domestic activities, latrines, refuse dumps, and infiltration of wastewater (Traore et al., 2016).

Microbiological characterisation of water sources

The results of the analysis showed the presence of faecal contamination bacteria in the well and borehole water at M'pody. This study showed that the well and borehole water was highly contaminated with faecal germs such as faecal coliforms (*E. coli*), total coliforms, and intestinal enterococci, which generally occur when people draw water from the wells (Mwanza et al., 2019). Faecal coliforms are considered to be among the most commonly and frequently used indicators of faecal contamination of water in human health risk assessment (Merhabi et al., 2019). Faecal coliforms, enterococci, and *E. coli* are of animal or human origin. The presence of faecal coliforms in the water indicates recent faecal contamination, which means that there is a likely risk of pathogens being present in these waters. Like almost all villages in Côte d'Ivoire, M'pody has no adequate sanitation system. Some of the houses have no latrines, which means that people generally have to relieve themselves in the open air. On the other hand, most houses with latrines have wells nearby, usually less than 15 m away.

In addition, the acidity of the region's water could encourage the proliferation of total coliforms. According to Douagui et al, (2012), water analysis revealed a positive correlation between the abundance of total coliforms and the acidity of the pH (average of 5.8). These results are confirmed by those published by Dakouri Desmos (2021), who reports the high presence of total coliforms, *Clostridium* species, and faecal streptococci in drinking water.

Non-compliance with physico-chemical and bacteriological parameters

The results of the borehole and well water samples analysed revealed that 25% of the water points in this locality presented major risks of methaemoglobinaemia. Pregnant women and infants should be forbidden to drink such water to prevent methaemoglobinaemia. Infant methaemoglobinaemia is the only health effect that has been unequivocally associated with excessive exposure to nitrate through drinking water. Methaemoglobinaemia results from the reduction of nitrate to nitrite by microorganisms in the digestive system, followed by the oxidation by nitrites of the ferrous iron (Fe^{2+}) in haemoglobin to ferric iron (Fe^{3+}), which produces methaemoglobin. Unlike haemoglobin, methaemoglobin is unable to bind oxygen, which reduces the transport of oxygen from the lungs to the tissues (Dégbey et al., 2010). These results are similar to those reported by Dégbey et al. (2008), who worked on well water quality in the Abomey-Calavi commune in Benin.

Well and borehole water was aggressive and corrosive, with aggressivity indices (AI) of less than 10. The acidic and aggressive nature of the groundwater was consistent with studies conducted by Ligban et al. (2017) in the Daloa region of West-Central Côte d'Ivoire and by Kouassi et al. (2017) on fractured aquifers in Côte d'Ivoire. The acidity of drinking water poses no health problems for consumers. However, acidic water stored in containers can become enriched with heavy metals as a result of corrosion of metallic and cement-based materials (Eblin et al., 2014) and therefore pose a threat to consumer health.

In terms of turbidity, 85.06% of well water and 75% of borehole water were non-compliant. This turbidity is thought to be caused by the presence of suspended matter (clay, silt, fibrous, or organic particles, and microorganisms) (Yapo et al., 2010). Water with high turbidity could therefore harbour micro-organisms (Pritchard et al., 2007).

Most households with wells use chlorination to treat their well water, while no chlorine treatment was carried out on the water from the village water tower. Residual chlorine was found in 67.80% of wells. Although it is acceptable to treat well water contaminated by microbes, it is not advisable to pour chlorine into a well, as there is a risk of not being able to control the quantity of chlorine required. If large quantities of organic matter are present, the action of chlorine on this matter can lead to the formation of chlorine derivatives such as trihalomethanes, which are carcinogenic. This practice is in line with the proposal by Tampo et al. (2014), who proposed chlorination adapted to the composition of well and borehole water to make it drinkable in order to reduce the risk of waterborne diseases.

Bacteriological analysis showed that 98.63% of well water and 50% of borehole water contained very high levels of coliforms. As for *E. faecalis* levels, the non-compliances were 80.56 and 25% respectively in well and borehole water. These bacteria of faecal origin in well and borehole water are dangerous to health (Temgoua et al., 2009; WHO, 2017). Consumption of these waters exposes the population of this locality to numerous waterborne diseases, such as typhoid, dysentery, and diarrhoea, as these waters contain high levels of coliforms and *E. faecalis* (WHO, 2017). Sulphite-reducing spore-forming anaerobic loads were significant in 25% of the borehole water and 23.26% of the well water. The group of sulphite-reducing anaerobes includes the genus Clostridium, in particular the species *Clostridium perfringens,* a microorganism of faecal origin whose spores are very resistant in the environment (Sorensen et al., 1989; Davies et al., 1995). These bacteria are therefore the most appropriate indicators of the most resistant pathogens in water, such as enteric viruses, parasitic protozoa, and helminth eggs (Payment and Franco, 1993). According to some authors, sulphite-reducing anaerobes are responsible for gastroenteritis in children and the elderly (Payment et al., 2003).

Pseudomonas spp. was found in 24.65% of wells. This bacterium particularly infects young children, immunocompromised people, and the elderly in whom it can cause severe diarrhea, eye infection, osteomyelitis, otitis, and folliculitis, the latter often following a bath (Geldreich and LeChevallier, 1999).

Conclusion

At the end of this study, the physico-chemical and bacteriological characteristics of the water from all 72 wells and the single borehole were determined for the four seasons in the locality of M'pody. Of the 15 physico-chemical parameters measured, the levels of turbidity, pH, and a number of other parameters, such as iron, nitrogen derivatives, nitrites, and ammonium in the well water and the turbidity of the borehole water, were found to be non-compliant. The presence of residual chlorine, normally absent in a well, also indicates non-compliance.

In terms of bacteriological parameters, well and borehole water is contaminated by bacteria indicative of faecal pollution. There are a large number of undeveloped water points, and the high germ densities in this water pose major short-term health risks for consumers. The high load of coliforms and sulphite-reducing anaerobes in the borehole water could have contributed to the diarrhoea epidemic that occurred in this village.

To minimise any health risks, people should be advised to adopt hygiene measures, in particular by treating water from wells and stored in a home reservoir. For the borehole, simple chlorine treatment of the water in the reservoir would be appropriate before distribution to the population.

CONFLICT OF INTERESTS

The authors have not declared any conflict of interests.

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