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Physico-chemical and bacteriological quality of groundwater in a rural area of Western Niger: a case study of Bonkoukou

Hassane Adamou, Boubacar Ibrahim, Seyni Salack, Rabani Adamou, Safietou Sanfo and Stefan Liersch

ABSTRACT

The precariousness of the rural population in Africa is often symbolized by the lack of potable and safe drinking water. This study investigates the physico-chemical and bacteriological characteristics of 32 water samples with respect to WHO standards. The water samples were collected from wells, boreholes and small drinking water supply systems (DWS) in and around the township of Bonkoukou (Niger). The Water Quality Index (WQI) tool was used to assess the overall water quality with different physico-chemical parameters. Where the pH of the samples was acceptable, the samples showed higher levels of mineralization and deoxygenation. Overall, the samples were slightly hard, chlorinated and sulfated but much alkaline and contained nitrate and nitrite ions 2–16 times higher than the WHO standards. The use of WQI shows that samples in the DWS are safe for drinking. Samples coming from wells are the most polluted (58.50%) compared to those taken from boreholes (53.00%), while the percentage of samples from boreholes, unfit for drinking, is higher (41.00%) than that of the samples taken from wells (25.00%). Moreover, water in this area was characterized by the presence of total germs indicating bacteriological pollution. Hence, for the supply of safe drinking water to the larger number of people in such a rural area, the capacity of actual DWS must be improved and widespread.

Key words | drinking water, groundwater, Niger, rural area, total germs, Water Quality Index

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INTRODUCTION

The main use of drinking water is to compensate for body water loss and to ensure good general physiology and health (Mann & Truswell 2002). According to UNICEF (2004), everyone has the right to have access to safe drinking water. Potable and safe drinking water brings clear health benefits. Water that is unsuitable for nutrition, on the other hand, represents serious health risks. According to WHO (2017), about 30.00% of the world population still has no access to safe drinking water. On the African continent, 320 million people remain excluded from drinking water services (Bazié 2014), where in West Africa, drinking water coverage is below 60.00% (CMAE 2008). In a country like Niger, the rate of access to drinking water in rural areas is theoretically estimated at about 46.00% (MHA 2017). In rural West Africa, groundwater is very often the main source of drinking water. The latter is supplied mostly through wells and increasingly from boreholes (Chippaux *et al.* 2002; Raphael *et al.* 2018), sparsely distributed across rural areas townships and villages. In addition to the low spatial coverage of the groundwater pumping infrastructure,

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rural communities face also the challenges of population growth and the degradation of the existing hydraulic structures due to poor maintenance. The reality, in many rural townships and villages in the rural Niger, is that national companies in charge of drinking water supply do not exist. To compensate this gap, water is supplied in townships and villages, like our study site of Bonkoukou (Western Niger, 140 km northeast of Niamey, the capital city), through wells, boreholes and small drinking water supply systems (DWS). These DWS carry water from a water tower to households through distribution pipes and taps. However, such small DWS cover only a small portion of the rural areas in Niger.

Water availability alone does not safeguard nutrition nor does it guarantee an access to healthy water. In different parts of the world, particularly rural areas, several research studies have been conducted to assess the quality of drinking water (Mulamattathil *et al.* 2015; Khatri *et al.* 2016; Barakat *et al.* 2018; Raphael *et al.* 2018; Malek *et al.* 2019). In West Africa, some studies have been carried out to assess the risk that people face in consuming unhealthy water, especially in rural areas where access to safe drinking water is a great challenge (Chippaux *et al.* 2002; Verheyen *et al.* 2009; Hounsou *et al.* 2010; Degbey *et al.* 2011; Mwabi *et al.* 2011; Dougna *et al.* 2015; Raphael *et al.* 2018). As in many other rural places in the Western Niger, the quality of drinking water in and around the township Bonkoukou has not been assessed. No studies have been conducted so far on the physico-chemical and bacteriological quality of the water consumed by the local population. Hence, it is essential to assess the water quality of the different sources of drinking water in such a rural township in order to determine and characterize its quality with regard to World Health Organization (WHO) standards.

In this paper, the methods used for *in situ* parameter measurements, the analytical methods, the bacteriological analysis and the application of the Water Quality Index (WQI) to determine the chemical and bacteriological quality of the water samples are presented. The chemical and bacteriological characterization provides information on the water quality consumed by the local population and compensates for the lack of such studies in rural areas, particularly in Niger and West Africa in general.

METHODS

Study area and sampling points

In Niger Republic, the Tillabéry region has the densest hydrographic network of the country, where the River Niger is the only river with the permanent flow over 400 km across the western parts of the territory. The surface hydrology is characterized by a strong endorheic system. The geological and hydrogeological explorations conducted by Tirat (1964), Greigert (1966) and other studies revealed the existence of several aquifers. These aquifers represent the region's groundwater resources and have different characteristics. There are continuous and discontinuous, hydraulically connected and non-connected aquifers. Bonkoukou (14°01′ N, 03°13′ E) is the capital city of the rural municipality of Imanan in the department of Filingué in the Tillabéry region in Western Niger (Figure 1). The township is located at 140 km northeast of Niamey (Niamey is the capital city of Niger Republic) with ~20,000 inhabitants spread across more than 40 villages. The economy of these communities is predominantly based on rainfed farming of millet, cowpea, off-season small-scale irrigation of potatoes, livestock breeding (e.g. sheep, cattle, etc.) and inter-village trading through weekly markets. The ground water in Bonkoukou is shallow, supporting thereby small-scale irrigation and enabling the many local people to practise market gardening.

In addition to the township of Bonkoukou, the three surrounding villages (Djami, Beba Tondi and Mokirey) were included in the water sampling process. Some of the water samples were taken from sources constructed to supply drinking water and other samples came from sources designed to supply irrigation water. A total of 32 samples were collected, of which 26 (81.25%) were taken in the town of Bonkoukou and six (18.75%) in the surrounding villages. The water was sampled from a water tower, two taps, 12 wells and 17 boreholes (Figure 1). Water from the boreholes and the water tower (WT) is exclusively used for drinking and other household uses, the wells are mostly used for other activities (laundry, showers, etc.), animal watering and small irrigation.

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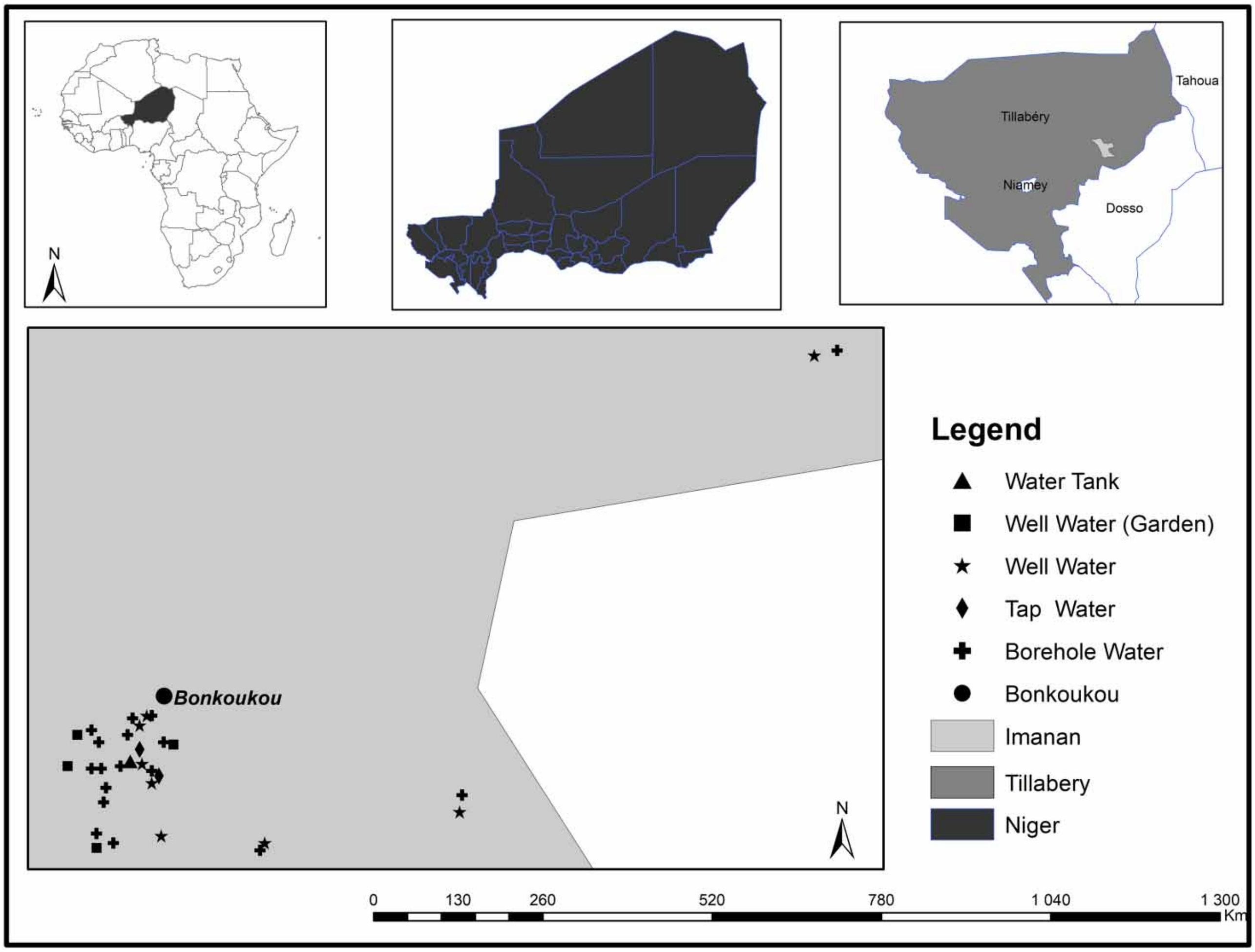

Figure 1 | Location of Bonkoukou and sampled water points.

In situ parameters measurement and laboratory analyses

The water samples were collected in July 2018 following the approach described by Rodier *et al.* (2009). Sterilized 500 mL polypropylene vials were used to conserve the water samples before the chemical and bacteriological analysis. These samples were stored under a temperature of 4 °C to avoid changes in parameters and were quickly analyzed in the laboratory. During the sampling, a 3430 SET F, WTW multi-function multimeter was used to directly measure the physical parameters (temperature (T), hydrogen potential (pH), electrical conductivity (EC), total dissolved solids (TDS) and dissolved oxygen (DO)).

Chemical analysis

The following ions CO_3^{2-}, HCO_3^-, Ca^{2+}, Mg^{2+}, Cl^-, NO_3^-, NO_2^-, Fe^{2+} and SO_4^{2-} were tested and used to determine the chemical quality of the water samples.

The alkalinity (carbonate (CO_3^{2-}) and hydrogencarbonate (HCO_3^-) ions) of the water samples, as well as the concentration of chloride (Cl^-) ions, were determined by titrimetry (APHA 1999; Rodier *et al.* 2009). The alkalinity was determined by using an acid and in the presence of phenolphthalein and a mixture of bromocresol green and methyl red as colored indicators for the determination of carbonate (CO_3^{2-}) and hydrogencarbonate (HCO_3^-) ions, respectively (APHA 1999; Rodier *et al.* 2009). Chloride (Cl^-) ion was determined with silver nitrate in the neutral

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or slightly alkaline medium in the presence of potassium chromate indicating the final titration point (APHA 1999).

The method of Rodier *et al.* (2009) on the complexometric determination of calcium (Ca^{2+}) and magnesium (Mg^{2+}) ions with ethylene diamine tetraacetate (EDTA) in the presence of eriochrome black T (EBT) and Patton and Reeder reagent allowed to assess the water hardness.

Nitrate (NO_3^-), nitrite (NO_2^-) and iron (Fe^{2+}) ions were determined by UV–Visible spectrophotometry (APHA 1999; Skoog *et al.* 2015). The measurement of nitrate ions was a simple determination with concentrated sulfuric acid at 216 nm wavelength. Nitrite ions were determined by the formation of a purple-red azo dye by coupling with diazotized sulfanilamide and N-(1-naphthyl)-ethylenediamine dihydrochloride (NED) at a wavelength of 543 nm. The determination of iron ions was based on the formation of an orange complex with orthophenantroline monohydrate, hydroxylamine hydrochloride and sodium acetate trihydrate at a wavelength of 512 nm.

The determination of sulfate ions (SO_4^{2-}) was carried out by conductometric titration on the basis of the precipitation reaction of sulfate ions with barium ions and was monitored by conductimetry (APHA 1999; Garcia & Schultz 2016).

These analytical methods are sensitive, simple, cheap and easily applicable. They also give very good results. UV–Visible spectrophotometric methods are characterized by excellent detection ranges from 0.25 to 20,000 $\mu g\ L^{-1}$ with a recovery rate almost equal to 100%.

Bacteriological analysis

Bacteriological quality is one of the important parameters of water potability. It is measured by the presence of a pollution indicator of organisms, in particular, total germs and fecal coliforms (*Escherichia coli*). Total germs represent the density of the bacterial population in drinking water. This measure allows a global assessment of the pernicious nature of water, without determining the sources of contamination (Levallois 2003). *E. coli* is one of the most determined bacteria that indicates fecal contamination (Edberg *et al.* 2000). Total germs and *E. coli* are used as indicators to measure pollution level and water quality.

Samples from the wells, open structures, are practically used for irrigation and watering animals and are therefore very susceptible to pollution. The risk of contamination of these samples seems to be greater than that of boreholes and the small DWS, which are better protected from pollution. Thus, the bacteriological analysis is relevant for the 13 samples from boreholes and the DWS in order to characterize the bacteriological quality of water in the village of Bonkoukou. Out of the 32 water samples, 13 were analyzed for bacteria. Emphasis was placed on the most commonly used water samples (water samples from the boreholes) for drinking water. These chosen samples provided an exhaustive picture of the bacteriological water quality in the Bonkoukou area.

The membrane filtration technique of Rodier *et al.* (2009) was used during this work for bacteriological analysis. This analysis was limited to the determination of total germs and *E. coli*. This technique consisted of passing 1 and 100 mL of water samples for total germs and *E. coli*, respectively, through a cellulosic membrane with pores of uniform diameter equal to 0.45 µm. After filtration, this membrane was placed in a petri dish containing a standard culture medium TTC (triphenyl chloride tetrazolium) and Tergitol TTC, respectively, for total germs and *E. coli*. At the end of the operation, the petri dishes were placed in the incubators set at 37 °C for total germs and 44 °C for *E. coli*. The results were collected 24 hours after incubation (Hounsou *et al.* 2010; CEAEQ 2016).

The results are analyzed by considering the bacteriological standards for the detection and enumeration of fecal bacteria in water of the WHO and the International Organization for Standardization (ISO). With regard to these standards, in any water (directly intended for drinking, treated and entering the distribution system), any *E. coli* or thermotolerant coliform bacteria must not be detectable in a volume of 100 mL (WHO 2017).

WQI analysis

In this study, water quality (physico-chemical and bacteriological) and its degree of pollution were assessed in relation to the standards defined and recommended by the World Health Organization (WHO 2017). In addition, the WQI was used in the assessment as the practical tool for synthesizing physico-chemical water quality parameters (CCME 2001). The WQI is commonly used for the detection

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and assessment of water pollution and can be defined as the reflection of the composite influence of different quality parameters on overall water quality. The use of WQI makes more comprehensible the meaning of the analyzed parameters. The calculation of the WQI was based on the method described by Batabyal & Chakraborty (2015). A correlation (r) analysis was conducted to quantify the relationship between these different datasets (physico-chemical parameters and WQI).

The WQI expresses chemical pollution which is strongly related to chemical ions and parameters like pH and EC. The calculation of the WQI included 11 important parameters (pH, EC, DO, HCO_3^-, Ca^{2+}, Mg^{2+}, Cl^-, NO_3^-, NO_2^-, Fe^{2+}, SO_4^{2-}), as well as their WHO standards (WHO 2017). The temperature is not taken into account in the calculation of WQI because the presence of ions is not related to the temperature. The WQI formula does not take into account the contribution of CO_3^{2-}. EC and TDS both express the conductivity of a water sample. The two parameters are almost identical. Due to the fact that no standard is defined for TDS, EC is used in this study to represent the conductivity. The WQI was calculated using the following formula:

$$\mathrm{WQI} = \frac{\sum q_n W_n}{\sum W_n}$$

$$q_n = \frac{V_n - V_{\mathrm{id}}}{S_n - V_{\mathrm{id}}} * 100$$

$$W_n = \frac{k}{S_n}$$

$$k = \frac{1}{\sum \frac{1}{S_{n=1,2\ldots n}}}$$

where

q_n: quality of nth water quality parameter

W_n: Unit weight of nth water quality parameter

S_n: permisible value of nth water quality parameter

V_n: Estimated value of nth water quality parameter at a given sample location

V_{id}: ideal value for nth parameter in pure water (0 for all other parameters except the pH and dissolved oxygen, respectively, 7 and 14.6 mg L^{-1})

k: Constant of proportionality.

Once the WQI value has been calculated, the corresponding quality was determined by using the following scale: excellent (<50), good (50–100), poor (100–200), very poor (200–300) and unfit for drinking (>300).

RESULTS

In situ parameters

The overall physico-chemical parameters of all water samples analyzed in and around Bonkoukou are shown in Table 1.

The pH values of the water samples from Bonkoukou ranged from 6.17 to 7.85. The WHO recommends that the pH of drinking water should be in the range 6.50–8.50. Almost all samples had pH values within this range, except for 15.63% of the samples, where pH values were below 6.50. The temperature of the different water samples varied between 29.80 and 32.80 °C and were therefore all above the WHO standard of 25 °C. DO levels in the samples ranged from 1.35 to 6.10 mg L^{-1}. Twenty-seven samples or 85.00% had DO contents below the WHO guideline value of 5.00 mg L^{-1} (from which 88.24% originated from boreholes and 91.67% from wells).

EC values ranged from 99.30 to 15,750.00 µS cm^{-1}. Water from the WT and those from the two taps (T1 and T2) were weakly mineralized with EC ranging from 99.30 to 117.50 µS cm^{-1}. Of the total water samples, 19 had EC values greater than 400.00 µS cm^{-1}, which is the WHO threshold value allowed for drinking water. Therefore, 59.38% of the analyzed water samples exceed this EC threshold. Out of these 19 samples, nine had EC values between 400.00 and 1,000.00 µS cm^{-1}, which is up to more than twice as high as the WHO standard. The other 10 samples showed EC values exceeding 1,000.00 µS cm^{-1} and had EC values of more than 5–40 times higher than the WHO threshold. Twelve out of these 19 water samples were from boreholes and seven from wells. This means that 70.59 and 58.30% of the water samples from boreholes and wells, respectively, had EC values higher than the standard. Especially the water in the samples from well W2 and boreholes D5 and D6 were heavily charged and were therefore of very poor quality.

No health-based guideline values have been proposed for TDS by the WHO. However, the flavor of drinking

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Table 1 | Physico-chemical parameters of waters in Bonkoukou and surrounding villages

Samples	pH	T (°C)	EC (μS cm^{-1})	TDS (mg L^{-1})	DO (mg L^{-1})	[CO_3^{2-}] (mg L^{-1})	[HCO_3^-] (mg L^{-1})	[Ca^{2+}] (mg L^{-1})	[Mg^{2+}] (mg L^{-1})	[Cl^-] (mg L^{-1})	[NO_3^-] (mg L^{-1})	[NO_2^-] (mg L^{-1})	[Fe^{2+}] (mg L^{-1})	[SO_4^{2-}] (mg L^{-1})
Water tower (WT)	6.96	31.00	117.50	117.00	6.10	0.00	73.20	8.00	9.60	14.20	0.00	0.02	0.00	0.00
T. Goumar (T1)	7.70	32.60	99.30	99.00	3.98	0.00	97.60	6.00	8.40	19.88	0.30	0.01	0.00	0.00
T. Sahara (T2)	6.33	32.20	100.70	101.00	5.91	0.00	73.20	4.00	12.00	9.94	0.59	0.01	0.00	0.00
B. Soly (B1)	7.84	30.90	2,700.00	2,700.00	3.72	0.00	268.40	120.00	57.60	241.40	576.85	1.36	0.00	226.62
B. Ada (B2)	7.30	32.80	3,460.00	3,460.00	3.22	0.00	451.40	68.00	28.80	653.20	176.30	1.21	0.00	144.00
B. Issa (B3)	6.67	32.40	3,020.00	3,020.00	3.18	0.00	244.00	104.00	50.40	465.76	385.14	0.77	0.00	96.00
B. Oumarou (B4)	6.58	32.40	2,810.00	2,820.00	3.16	0.00	256.20	104.00	40.80	397.60	370.58	0.68	0.00	96.00
B. Tamma (B5)	7.16	32.50	15,750.00	15,780.00	3.79	0.00	549.00	934.00	510.00	1,349.00	3,416.86	10.29	0.00	1,344.00
B. Ayouba (B6)	6.22	32.40	15,560.00	15,590.00	4.57	0.00	402.60	856.00	489.60	1,675.60	3,450.78	0.45	0.00	1,152.00
B. Djintodo (B7)	6.60	32.40	597.00	598.00	2.33	0.00	73.20	40.00	14.40	59.64	107.34	0.11	0.00	48.00
B. Issa1 (B8)	6.76	32.20	477.00	477.00	5.99	0.00	183.00	32.00	7.20	48.28	94.23	0.02	0.00	45.29
B. Na Abala (B9)	6.28	32.60	521.00	522.00	3.17	0.00	61.00	24.00	14.40	56.80	74.79	0.09	0.00	33.60
B. Abdou (B10)	6.65	32.00	392.00	398.00	3.14	0.00	109.80	12.00	9.60	42.60	29.99	0.01	0.00	432.00
B. CSI (B11)	6.29	32.30	1,058.00	1,060.00	3.44	0.00	146.40	46.00	22.80	45.44	170.73	0.53	0.00	92.13
B. Ecogar (B12)	6.69	31.80	644.00	646.00	3.37	0.00	134.20	36.00	2.40	66.74	63.53	0.02	0.00	67.20
B. Bonkano (B13)	7.07	31.50	396.00	396.00	4.41	0.00	122.00	16.00	4.80	26.98	51.53	0.01	0.00	13.01
B. Mosquée (B14)	6.57	32.10	238.00	238.00	5.07	0.00	48.20	16.00	8.40	24.14	50.80	0.02	0.00	28.17
B. Djami (B15)	6.94	31.30	501.00	501.00	3.30	0.00	122.00	32.00	9.60	34.08	85.10	0.31	0.00	0.00
B. Beba Tondi (B16)	6.74	32.00	386.00	386.00	3.68	0.00	73.20	24.00	9.60	31.24	104.94	0.01	0.00	0.00
B. Mokirey (B17)	7.62	32.90	227.00	228.00	2.78	0.00	85.40	8.00	2.40	17.75	44.29	0.04	0.00	0.00
W. Face (W1)	6.98	31.80	896.00	900.00	2.41	0.00	158.60	40.00	12.00	85.20	117.96	0.06	0.00	100.80
W. Abdoulaye (W2)	7.70	30.10	11,760.00	11,770.00	3.53	0.00	561.20	636.00	331.20	972.70	3,202.36	0.82	0.00	720.58
WG. Maire (W3)	7.69	30.20	444.00	444.00	5.23	0.00	195.20	16.00	6.00	31.24	37.14	0.23	0.00	38.40
W. Abdou (W4)	6.83	30.30	2,260.00	2,270.00	2.40	0.00	280.60	84.00	36.00	319.50	224.10	7.44	0.00	109.61
W. Issia (W5)	7.64	30.00	3,440.00	3,460.00	2.06	0.00	427.00	36.00	62.40	670.24	192.83	0.46	0.00	203.60
WG. Aguiwane (W6)	6.17	30.90	561.00	562.00	4.02	0.00	231.80	12.00	9.60	39.76	66.99	0.17	0.04	0.00
WG. Wadata (W7)	7.06	30.20	280.00	280.00	1.35	0.00	122.00	24.00	4.80	25.56	24.12	0,07	0.00	0.00
WG. Balley Koira (W8)	7.10	29.80	333.00	333.00	3.43	0.00	109.80	32.00	8.40	22.72	45.75	0.13	0.00	86.40
WG. Irack (W9)	7.07	30.10	342.00	342.00	4.58	0.00	85.40	24.00	7.20	19.88	64.38	0.04	0.00	24.00
W. Djami (W10)	7.14	30.30	223.00	223.00	4.71	0.00	97.60	24.00	1.20	17.04	46.86	0.12	0.00	0.00
W. Beba Tondi (W11)	6.88	30.20	445.00	444.00	3.94	0.00	48.80	40.00	8.40	28.40	128.37	0.22	0.00	0.00
W. Mokirey (W12)	7.29	31.10	247.00	248.00	2.68	0.00	97.60	16.00	2.40	22.72	31.74	0.14	0.00	0.00
Standard (WHO 2017)	6.50–8.50	25.00	400.00	–	>5.00	0.00	120.00[a]	100.00	30.00	200.00	50.00	0.10	0.30	250.00

B, borehole; W, well (G: garden); T, tap; WT, water tower.
[a]American standard.

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water with a TDS content of less than about 600.00 mg L^{-1} is generally considered as good, it becomes significantly and gradually undrinkable when this content exceeds 1,000.00 mg L^{-1} (WHO 2017). The TDS contents of the different water samples varied from 99.00 to 15,780.00 mg L^{-1}. Based on the TDS specifications, 65.62% of the total water samples were of good quality and 34.38% of poor quality. Among the poor quality water samples, seven were boreholes and four wells. These structures were located exclusively in the city of Bonkoukou. 42.30% of the water samples (50.00% of the boreholes and 44.50% of the wells) were evaluated as undrinkable.

Chemical quality assessment

The WHO does not have a guideline value for the alkalinity of drinking water, but the United States Environmental Protection Agency (US EPA) sets a directive of 120.00 mg L^{-1} not to be exceeded for HCO_3^- (US EPA 2002). Concentrations of HCO_3^- ranged from 48.20 to 561.20 mg L^{-1} in the analyzed samples. Out of the 32 water samples, 56.25% had concentrations of HCO_3^- above the US EPA standard. The number of samples with HCO_3^- concentrations between 1 and 2 times the standard is the same as that between 2 and 5 times. There were as many analyzed water samples whose HCO_3^- concentrations were more than 1–2 times the standard as those of concentrations 2–5 times the standard. Among these water samples, 11 were from boreholes and seven from wells.

The hardness of water is relatively related to the contents of calcium and magnesium metal cations. The concentrations of Ca^{2+} and Mg^{2+} were in the ranges of 4.00–934.00 mg L^{-1} and 1.20–510.00 mg L^{-1}, respectively. Six of the 32 samples had concentrations of Ca^{2+} ranging from 104.00 to 943.00 mg L^{-1}, which is above the WHO standard for concentrations of Ca^{2+} of 100.00 mg L^{-1}. In addition to these six samples, two other samples were characterized by the contents of Mg^{2+} above the WHO standard of 30.00 mg L^{-1}. These non-standard contents ranged from 36.00 to 510.00 mg L^{-1}. The majority (75.00%) of the water samples was within the hardness standard. Nevertheless, the water in some samples was very hard. Indeed, the contents of Ca^{2+} and Mg^{2+} were 6–10 and 11–16 times higher than the WHO standards.

The concentrations of Cl^- obtained from the analyzed samples varied from 9.90 to 1,675.60 mg L^{-1}. In 72.00% of the samples, the Cl^- concentrations were below the WHO standard of 200.00 mg L^{-1}. The concentrations of the samples that were out of the norm were in the range between 241.40 and 1,675.60 mg L^{-1}, ranging from 2–8 times higher than the standard.

The standards authorized by the WHO in drinking water for nitrate and nitrite ions are 50.00 and 0.10 mg L^{-1}, respectively. Concentrations of NO_3^- varied from 0 to 3,450.78 mg L^{-1} and concentrations of NO_2^- ranged from 0.01 to 10.29 mg L^{-1}. The samples from the WT and the two taps presented no or very low NO_3^- concentrations. Of the 32 samples, 22 (15 boreholes and seven wells) had values above the WHO standard for NO_3^-. Therefore, 68.75% of the analyzed samples have too high NO_3^- concentrations ranging from 50.80 to 3,450.78 mg L^{-1}. Eight of these 22 samples were from 1 to 2 times, eight from 2 to 5 times, two from 5 to 10 times, one up to 12 times and three samples from 60 to 70 times higher than the WHO standard. This means that 88.24% of the 17 analyzed boreholes and 58.34% of the 12 analyzed wells were polluted with high NO_3^- concentrations, respectively. In 18 (56.25%) out of 32 samples, the NO_3^- concentrations were above normal. The non-standard concentrations ranged from 0.11 to 10.29 mg L^{-1}. Of these 18 samples, five had contents between 1 and 2 times, five between 2 and 5 times, four between 5 and 10 times, two between 10 and 20 times, and two between 70 and 100 times higher NO_2^- concentrations than the suggested standard. This means that 52.9% of the boreholes and 75.00% of the wells were polluted with NO_2^-. Of all samples analyzed, 43.75% (nine boreholes and five wells) showed concurrent elevated NO_3^- and NO_2^- concentrations where the WHO standard was exceeded by at least twice the standard value.

The standard indicated by WHO in drinking water for Fe^{2+} is 0.30 mg L^{-1}. The concentrations of Fe^{2+} in all the analyzed water samples were nil except for a single sample that certified 0.04 mg L^{-1} a content far below this standard.

The concentrations of SO_4^{2-} found in the analyzed samples ranged from 0.00 to 1,344.00 mg L^{-1}. Out of all samples, 12.50% had contents higher than the WHO's proposed quality reference for SO_4^{2-} for drinking water, set at

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250.00 mg L^{-1}. The concentrations of the samples were almost 2–6 times higher than the standard. The water from the WT, the taps and those sampled in the hamlets were exempt of any SO_4^{2-}. The other water resources used by these populations had variable contents of SO_4^{2-}, but all were below the WHO standard.

Bacteriological quality assessment

The results of the bacteriological analysis (Table 2) show that, with the exception of one borehole with a total germ count (50 CFU mL^{-1}) less than the 100 CFU mL^{-1} WHO standard, all water samples were characterized by a number of total germ colonies above the WHO guideline. Although total germs were detected in the samples, a contamination with *E. coli* could not be proven. However, this result did not completely reject the possibility of contamination of samples by fecal matters. Further investigation will be required in future studies to assess drinking water contamination by animal excreta.

Correlation between chemical parameters

The results of the correlation coefficients between the variables are summarized in Table 3. The coefficients in bold indicate a very good correlation.

There was an almost total linear independence ($r = -0.36$–0.27) between the pH and the other parameters. The same report was observed with the DO and T. Nevertheless, the EC showed a perfect dependence on TDS ($r = 1$). These two almost identical parameters can replace each other. The variation in EC as a function of Ca^{2+}, Mg^{2+}, Cl^-, NO_3^- and SO_4^{2-} showed an excellent correlation ($r = 0.96$–99). The bond between EC and HCO_3^- was very good ($r = 0.83$). The correlation between EC and NO_2^- was also significant ($r = 0.55$). On the other hand, the concentration of Fe^{2+} was independent of EC. The parameters EC, HCO_3^-, Ca^{2+}, Mg^{2+}, Cl^-, NO_3^- and SO_4^{2-} were interdependent. The degree of this dependence was more amplified in this order HCO_3^-, Cl^-, SO_4^{2-}, NO_3^-, Ca^{2+}, Mg^{2+}, EC. These parameters were mutually related, to a lesser extent ($r = 0.50$–0.56) to NO_2^- and WQI. Noteworthy, NO_2^- and WQI have the strongest correlation ($r = 1$).

WQI of the different waters

The WQI values of the different analyzed water samples are recorded in Table 4. WQI values ranged from 5.88 to 7,510.16. These values were particularly affected by NO_2^-, SO_4^{2-}, Ca^{2+}, Mg^{2+}, Cl^- and NO_3^-. The WQI values of the water samples indicated that 37.50% of all analyzed samples were excellent, 15.63% were good, 12.50% were poor, 3.12% were very poor and 31.25% were unfit for human consumption. Among the boreholes, excellent and good water quality was represented by 52.94% compared to 47.06% of poor, bad and unfit for human consumption. Concerning well water, 41.66% were of excellent, good and average quality and 58.34% of poor, bad and unfit for human consumption.

DISCUSSION

Physico-chemical quality of Bonkoukou's water

The pH is one of the most important parameters of water quality. It influences physical and chemical water characteristics (HC 2016). The pH promotes the solubility of certain substances that are harmful to water quality. The waters sampled from Bonkoukou are slightly acidic and basic. The main adverse direct effect caused by extreme pH values ($5 \geq$ pH, pH ≥ 11) is an increase in skin and eye irritation (HC 2016). The pH of any sampled water was not in this configuration. The pH values of the samples were largely in the range recommended for drinking water. Similar

Table 2 | Bacteriological parameters

Samples	WT	T1	T2	B6	B8	B9	B11	B12	B14	B15	B16	B17	W12	WHO guideline value
Total germs	>100	>100	>100	>100	>100	50	>100	>100	>100	>100	>100	>100	>100	<100 CFU mL^{-1}
E. coli	0	0	0	0	0	0	0	0	0	0	0	0	0	0 CFU/100 mL

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Table 3 | Correlation matrix between the different parameters

Parameters	pH	T	EC	TDS	DO	HCO_3^-	Ca^{2+}	Mg^{2+}	Cl^-	NO_3^-	NO_2^-	Fe^{2+}	SO_4^{2-}	WQI
pH	1													
T	−0.36	1												
EC	0.05	0.12	1											
TDS	0.05	0.12	**1**	1										
DO	−0.15	0.04	−0.01	−0.01	1									
HCO_3^-	0.27	−0.03	**0.83**	**0.83**	−0.16	1								
Ca^{2+}	0.01	0.12	**0.98**	**0.98**	0.04	**0.74**	1							
Mg^{2+}	0.01	0.13	**0.99**	**0.99**	0.05	**0.75**	**0.99**	1						
Cl^-	0.04	0.14	**0.96**	**0.96**	−0.07	**0.86**	**0.91**	**0.93**	1					
NO_3^-	0.05	0.08	**0.98**	**0.98**	0.04	**0.75**	**0.99**	**0.98**	**0.91**	1				
NO_2^-	0.08	0.03	0.55	0.55	−0.14	0.54	0.56	0.55	0.50	0.49	1			
Fe^{2+}	−0.30	−0.10	−0.07	−0.07	0.05	0.06	−0.08	−0.07	−0.09	−0.07	−0.05	1		
SO_4^{2-}	0.01	0.15	**0.95**	**0.96**	0.00	**0.73**	**0.96**	**0.97**	**0.90**	**0.94**	0.57	−0.09	1	
WQI	0.08	0.03	0.55	0.55	−0.14	0.54	0.56	0.55	0.50	0.49	1	−0.05	0.58	1

pH values were obtained in previous research in the Niamey region of Niger, M'nasra in Morocco and the central region of Togo (Chippaux *et al.* 2002; Bricha *et al.* 2007; Dougna *et al.* 2015).

Although the temperatures of the water samples are higher than recommended by the WHO, they can be considered to be normal in the respective environment (Alhou *et al.* 2009). The observed water temperatures are adequate for good filtration and also allow for effective turbidity removal. On the other hand, microbiological characteristics (growth and survival of microorganisms) are affected by these high temperatures, thus stimulating the proliferation of harmful organisms that can make the water unhealthy (Volk & Joret 1994; Makoutode *et al.* 1999).

With five out of six (83.34%) of the analyzed water samples having non-standard DO contents, this study area is characterized by high deoxygenation. The high DO concentrations are the result of physical, chemical and biological factors (WHO 2017). The depletion of DO has promoted the microbial reduction of NO_3^- to NO_2^- in these analyzed samples.

More than half of the water samples have an excessive mineral charge. This charge is expressed by EC or TDS. Ions found in very high concentrations in the water samples, lying outside the WHO guideline values, originate from agricultural land and waste water. The geology of the area may also be the origin of the presence of these ions. Taste alteration is the main impact of conductivity on the quality of the water samples (CEAEQ 2015). The strong correlations between EC and Ca^{2+}, Mg^{2+}, Cl^-, NO_3^-, SO_4^{2-}, HCO_3^- indicate that the mineralization of the samples is strongly verified by these ions. This result is also proven by Dougna *et al.* (2015).

In terms of CO_3^{2-}, the alkalinity of all water samples is good, but it was differently appreciated compared to HCO_3^-. The presence of HCO_3^- in more than half of the analyzed water samples shows a strong capacity of the water to neutralize acids, but it is not available for drinking in the daily life due to its high alkalinity (FEPS 2010).

An abnormal hardness was observed in one-quarter of the analyzed water samples, which falls in the category of 'great concern'. The water samples W2, B5, B6 are not fit for human consumption. The natural sources of this hardness are mainly sedimentary rocks, soil infiltration and stream. In general, hard water originates from areas where the arable layer is thick and the rocks are calcareous.

Some samples in Bonkoukou and the surrounding villages, in particular, water samples from the boreholes, which are most often used for drinking, contained alarming concentrations of Cl^-. With concentrations above the standard, associated with the predominance of calcium and magnesium cations, chloride gives a bad taste to water

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Table 4 | Water Quality Index (WQI) values of samples

Samples	**WT**	**T1**	**T2**	**B1**	**B2**	**B3**	**B4**	**B5**	**B6**	**B7**	**B8**	**B9**	**B10**	**B11**	**B12**	**B13**	**B14**	**B15**	**B16**	**B17**
WQI	9.86	9.70	7.73	993.47	887.14	564.16	496.26	7,510.16	341.80	77.08	12.85	68.46	10.31	383.68	18.53	8.52	13.58	225.38	5.88	29.94
Status	E	E	E	UD	UD	UD	UD	UD	UD	G	E	G	E	UD	E	E	E	VP	E	E
Samples	**W1**	**W2**	**W3**	**W4**	**W5**	**W6**	**W7**	**W8**	**W9**	**W10**	**W11**	**W12**								
WQI	45.42	613.41	170.76	5,419.50	342.00	126.16	56.22	97.90	27.65	88.55	161.62	105.28								
Status	E	UD	P	UD	UD	P	G	G	E	G	P	P								

E, excellent; G, good; P, poor; VP, very poor; UD, unfit for drinking.

(HC 2008a). The existence of Cl^- in these water samples can be attributed to irrigation water. The same observation was observed by Chippaux *et al.* (2002) in most of the analyzed water samples from wells in their study.

NO_2^- are less present than NO_3^-. They are a result of the degradation of organic matter. In particular, nitrites come from the reduction of nitrate. NO_3^- has considerably degraded the quality of drinking water. The abnormal concentrations of NO_3^- and NO_2^- in almost half of the analyzed samples can be explained by the excessive use of nitrogen fertilizers used in the irrigation perimeters in this area and by the drainage of waste water and human or animal excreta. Bonkoukou is an agricultural area and its sanitation system communicates directly to the groundwater. The excessive presence of nitrite and nitrate in the drinking water presents a health risk, because of its toxicity. The water consumption constitutes a great danger for the population, especially for the juvenile population. The consumption of contaminated water exposes the population most often to methemoglobinemia (HC 2013). High nitrate concentrations are reported in some groundwater studies (Chippaux *et al.* 2002; Bricha *et al.* 2007; Dougna *et al.* 2015). The good correlation of NO_3^- with HCO_3^-, Cl^-, SO_4^{2-}, Ca^{2+}, Mg^{2+} proves that these ions come from the same origin. In addition to the anthropogenic origin of NO_3^-, it would be important to consider and assess the contribution of minerals.

Fe^{2+} was almost non-existent in these analyzed water samples, which can be explained by the slightly acidic pH values, which largely prevent the existence of Fe^{2+} (HC 2008b).

An eighth (12.50%) of the analyzed water samples in Bonkoukou and surrounding villages are characterized by SO_4^{2-} concentrations above the WHO drinking water standard. Concentrations of SO_4^{2-} in the analyzed samples originate from certain minerals. The forms of these minerals found in the samples were calcium sulfate and magnesium sulfate. The water samples W2, B5 and B6 with very high contents of Mg^{2+}, Ca^{2+} and SO_4^{2-} were characterized by a very unpleasant taste.

Water pollution assessment using WQI

The assessment of water pollution using the WQI method conducted in this study is the first of its kind in Niger. From the correlation between WQI and the

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physico-chemical parameters of water quality, it is obvious that nitrate, nitrite, sulfate and chloride ions, alkalinity, hardness and EC were the most important factors in the calculation of WQI in this study.

The water samples WT, T1 and T2 of the small DWS are of excellent quality. Water samples from the wells are the most polluted (58.34%) compared to those taken from the boreholes (52.94%). The population's preference to consume water from boreholes rather than from wells is therefore justified. Pollution of water samples from the wells is explained by the fact that animals are watered at wells that are always open, leaving their excrement in the vicinity of these wells. The percentage (41.18%) of water samples from the boreholes (B1, B2, B3, B4, B5, B6, B11) unsuitable for consumption is higher than the one (25.00%) from the wells (W2, W4, W5). It is therefore recommended to strictly prohibit the consumption from these sources.

Water quality is preserved when its quality is excellent or good. A threat of deterioration is not observed for water of excellent quality and it is minor when the quality is good (CCME 2001). Water of excellent quality is exclusively used for drinking and water of good quality is used for domestic purposes. These two categories of water quality are also used for irrigation. Water of poor and very poor quality is almost always threatened or subject to further degradation (CCME 2001). Water of poor quality should only be used for irrigation. This use of water of very poor quality should be restricted. Water unfit for consumption must be properly treated before use.

This is in perfect agreement with the analysis of physico-chemical parameters in relation to the potability of water defined by WHO (2017).

Understanding the bacteriological quality water samples

The results of the bacteriological analysis showed that all the analyzed water samples contained high concentrations of total germs, but *E. coli* was not detected in any sample. The proximity of the ground water in this area to the soil surface makes it highly vulnerable to potential bacteriological pollution. The presence of total germs in the analyzed water samples does not directly indicate fecal contamination. However, the total germs provide information on the potential vulnerability of these waters to surface pollution. Indeed, the infiltration of surface water into the shallow groundwater aquifer is the origin of the degradation in terms of bacteriologial quality. Infiltration increases the risk of contamination by the dispersion of animal excreta, the use of manure, open defecation, the flow of wastewater from toilets and the discharge of untreated domestic and agricultural waste. The above-mentioned conditions show that the sources of drinking water, widely used by the population, are exposed to a very high risk of bacteriological contamination.

Otherwise, no *E. coli* was detected in the bacteriological analysis in this study. Razzolini *et al.* (2011) state that the absence of these pathogens could be due to the fact that the high content of total germs can have a competitive or even inhibitory effect on the growth of *E. coli* germs or that the technique adopted was not reliable enough to reveal this germ.

High temperatures, such as those observed in the analyzed samples, constitute conditions favored by microorganisms supporting survival and proliferation of bacteria (Volk & Joret 1994; Makoutode *et al.* 1999). Contamination is also assumed to have their origin in pumping installation failures (Chippaux *et al.* 2002).

Although some samples, particularly those of small DWS (WT, T1 and T2), are characterized by excellent physical and chemical quality, the bacteriological analysis reveals the danger of the high presence of bacteria. Similar results have been obtained in Niger by Chippaux *et al.* (2002), Benin by Verheyen *et al.* (2009), Hounsou *et al.* (2010), Degbey *et al.* (2011) and Egypt by Al-Afify *et al.* (2018). The presence of these pathogens in the drinking water can lead to many diseases of varying severity, like benign gastroenteritis, dysentery, hepatitis, typhoid fever, severe and sometimes fatal diarrhea (Degbey *et al.* 2011).

To reduce the microbial load of these samples, treatments such as filtration or boiling can be used individually or in combination. In addition, to improve the bacteriological quality, disinfection by using a disinfectant, such as hypochlorite, is recommended.

CONCLUSION AND RECOMMENDATIONS

The water samples collected in Bonkoukou and surrounding villages were analyzed in the laboratory. The results

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obtained from the bacteriological analysis show that samples are largely characterized by total germ colonies above the WHO standard, except for water samples from boreholes, which had a total germ count below the WHO standard of 100 CFU mL^{-1}.

The WQI values of the analyzed water samples indicate that 37.50% are excellent, 15.63% are good, 12.50% are poor, 3.12% are very poor and 31.25% are unfit for human consumption. For water samples from boreholes, excellent and good water quality represent only 52.94% compared to 47.06% of poor, bad and unfit for human consumption. Concerning water samples from wells, 41.66% are excellent, good and average quality, and 58.34% are poor, bad and unfit for human consumption. Pollution of water samples in wells is explained by the fact that animals are drinking at open wells and leave their feces and urine in the vicinity of the wells. However, the samples taken from the small drinking water supply system (DWS) are of excellent physico-chemical quality but of poor bacteriological quality.

The physico-chemical and bacteriological quality of these rural groundwaters are severely affected by market gardening activities and the lack of household waste and wastewater management systems. The current consumption of these groundwaters exposes the local communities to an enormous health risk. Thus, it is imperative to prohibit the consumption of water with physico-chemical and bacteriological concentrations that are higher than the WHO standards, such as water from wells in the study area.

In order to prevent this pollution, the best way is to raise public awareness of hygiene measures and to avoid excess application of fertilizers in agriculture. Therefore, a large-scale distribution of water from the small drinking water supply system and the application of chemical disinfectants are alternative solutions for improving access to safe drinking water in rural areas, such as Bonkoukou and the surrounding villages.

In a wider context, this study also shows that, in addition to the well-known problem of access to water in dry and semi-arid regions in general, poor and deteriorating water quality can be a major problem and further endangers access to safe water.

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CONFLICT OF INTEREST

The authors declare no competing interests regarding the publication of this paper.

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