Water Supply

Water Supply Vol 25 No 4, 716 doi: 10.2166/ws.2025.043

Assessing drinking water quality in the city of Kenge, Democratic Republic of the Congo

Archal Ngandote[a], Daniel Mudinga[a], John Kayembe[a], Georgette N. Ngweme[b], Séraphin Lusamba[c], Ilunga Kamika[d], Emmanuel K. Atibu [c,*], Fernando Carvalho [e] and John Poté[a,c,f]

[a] Faculté des Sciences, Université Pédagogique Nationale, Kinshasa, Democratic Republic of the Congo
[b] Faculty of Medicine, School of Public Health, University of Kinshasa, Kinshasa, Democratic Republic of the Congo
[c] Department of Chemistry, Faculty of Science, University of Kinshasa, 190 Kinshasa, Democratic Republic of the Congo
[d] Institute for Nanotechnology and Water Sustainability, College of Science, Engineering and Technology, University of South Africa, Florida, 8, Johannesburg 1709, South Africa
[e] Instituto Superior Técnico/Campus Tecnológico e Nuclear, Universidade de Lisboa, Lisboa, Portugal
[f] Department F.-A, Faculty of Science, Forel for Environmental and Aquatic Sciences, and Institute for Environmental Sciences, University of Geneva, 1211 Geneva 4, Switzerland
*Corresponding author. E-mail: emmanuel.atibu@unikin.ac.cd

EKA, 0000-0001-7874-5908; FC, 0000-0002-6639-6138

ABSTRACT

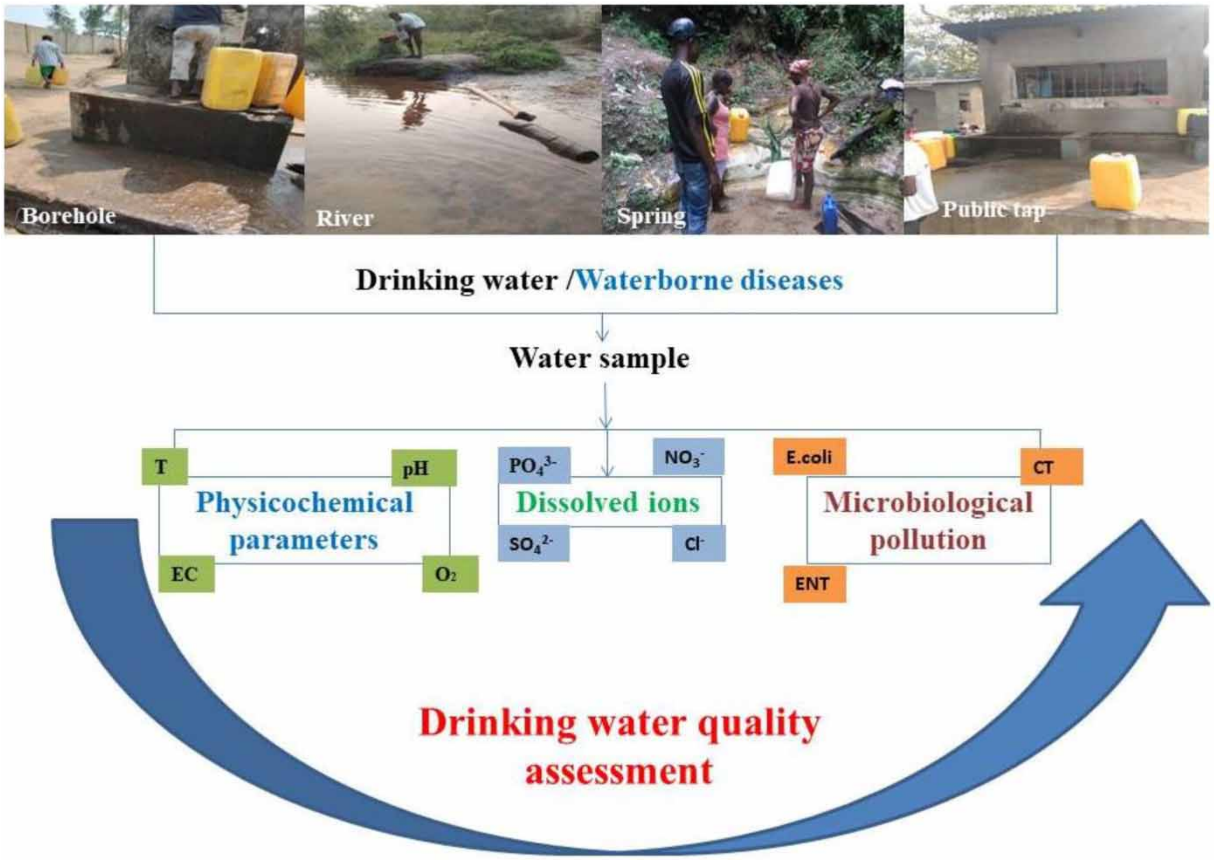
Outbreaks of waterborne diseases, such as typhoid fever, hepatitis, and dysenteric diarrhea, have been consistently increasing over the years and severely impinging public health in Kenge City. The population uses river water and groundwater as drinking water and for other domestic uses. A drinking water quality assessment was conducted in the municipality. Physicochemical and bacteriological analyses of water, including the determination of T, pH, electrical conductivity, O_2, total dissolved solids (TDS), soluble ions, were carried out on 20 water samples collected in the Soussa and Maniéka Rivers, in Kikobo spring, and in two water boreholes, which are the main drinking water supply sources for the municipality. Samples from tap water distributed by the public water company were analyzed also. The results of this assessment revealed that T, pH, O_2, and TDS in water during both the dry and wet seasons generally exceeded the limits set by WHO for drinking water quality. *Escherichia coli* and *Enterococcus* were observed in groundwater samples from boreholes and from the Kikobo spring, while total coliforms were identified in all samples, including those from the public water distribution network. These results explained the increasing trends of waterborne diseases observed in the region.

Key words: City of Kenge, drinking water quality, human heath, microbiological pollution, waterborne diseases

HIGHLIGHTS

- First study in the municipality of Laurent-Désiré Kabila.
- This study correlates the prevalence of the waterborne diseases with the quality of water.
- The sources of drinking water for the municipality include rivers, spring, and water boreholes.
- The physicochemical and bacteriological parameters identified were selected in accordance with WHO guidelines.
- These parameters include *T*, pH, electrical conductivity, O_2, total dissolved solids, soluble ions, *Escherichia coli*, *Enterococcus*, and total coliforms.

GRAPHICAL ABSTRACT



1. INTRODUCTION

Waterborne diseases are prevalent in many parts of the world and pose a major health risk to the human populations. This occurs particularly in developing countries lacking sanitary infrastructures and relying on the use of untreated surface waters as drinking water (WHO 2017; Fazal-ur-Rehman 2018).

According to the World Health Organization (WHO 2011, 2018, 2019), 60% of the world population does not have access to reliable sanitation, 30% does not have access to safe drinking water, and about 2 billion people consume water from sources contaminated with fecal matter. The consumption of water from such sources has been associated with the occurrence of diseases such as diarrhea, cholera, hepatitis A, typhoid fever, and polio (WHO 2011; Nienie *et al.* 2017; Kapembo *et al.* 2022). Worldwide, a prevalence of about 4 billion cases of diarrhea is observed every year, and it is due to a lack of safe drinking water, sanitation, and hygiene. Approximately 1 million diarrhea-related deaths are recorded each year in developing countries, most of which are children under the age of five (Fawell & Nieuwenhuijsen 2003; Mwanamoki *et al.* 2015; Tongesayi & Tongesayi 2015; Kapembo *et al.* 2016, 2022; Nienie *et al.* 2017). The consumption of water is responsible for such an impact on human health, and this is because water sources are contaminated with untreated sewage, wastewater from hospitals, industries, mines, and urban runoff contaminated by waste from anthropogenic activities. Furthermore, surface waters and groundwater are often contaminated with fecal bacteria originating from the practice of open-field defecation and lack of sewage collection and proper treatment (Thevenon *et al.* 2012; Mwanamoki *et al.* 2014; Kilunga *et al.* 2016; Barnett *et al.* 2018; Pakasi 2018; Atibu *et al.* 2022, 2023; Lin *et al.* 2022).

In the Democratic Republic of the Congo (DRC), despite the abundance of freshwater, more than three-quarters of its population, recently estimated at about 70 million, do not have access to safe drinking water, and this is further exacerbated by the rapid population growth (UNEP 2011).

Previous studies conducted in the DR Congo, specifically in Kinshasa and Kikwit cities on epidemiology and drinking water quality, have shown a prevalence of waterborne diseases such as typhoid fever, amebic dysentery, gastroenteritis disorders, and cholera. The water sources investigated in these cities showed high contamination by fecal indicator bacteria (FIB), including *Escherichia coli* (*E. coli*), *Enterococcus* (*ENT*) and total coliforms (TC) (Kapembo *et al.* 2016, 2022; Nienie *et al.* 2017). Many other regions in the DRC may suffer similar contamination of water resources and identical threats to public health, but water research and the monitoring of water quality are lacking throughout the country.

The current study was carried out in the municipality of Laurent-Désiré Kabila, city of Kenge, province of Kwango, in the DRC. This province has faced recurrent outbreaks of waterborne diseases, such as typhoid fever. This study was the first investigation in this region on the prevalence of waterborne diseases and the first assessment of the quality of water from the main supply sources.

2. MATERIALS AND METHODS

2.1. Study area and analytical approach

This study was carried out in the municipality of Laurent Désiré Kabila, located in the city of Kenge, Kwango province, in the DR Congo (Figures 1(a) and 1(b)). Laurent Désiré Kabila is an urban municipality with approximately 31,700 inhabitants and an area of 41,000 km^2. In this municipality, the main economic activity is agriculture, which is mostly based on food crop production and livestock breeding.

The majority of the population uses surface water from the rivers Maniéka and Soussa and groundwater from boreholes as drinking water and water for other domestic uses (cooking and bathing). Several springs are available in the area, and their water is used by a small fraction of the population. The national water treatment and distribution agency, called 'Régie de distribution d'eau' (REGIDESO), also dispenses drinking water at several free-of-charge distribution points (public taps) in the municipality (Figure 2).

The physicochemical and bacteriological parameters to be determined in water sources were selected in accordance with the WHO guidelines for monitoring drinking water quality (WHO 2017). The evaluation of the physicochemical quality of water included the determination of water temperature, pH, electrical conductivity, dissolved oxygen, total dissolved solids, dissolved ions, and the identification and enumeration of microorganisms, including, *E. coli*, *ENT*, and TC in water, as described in the following.

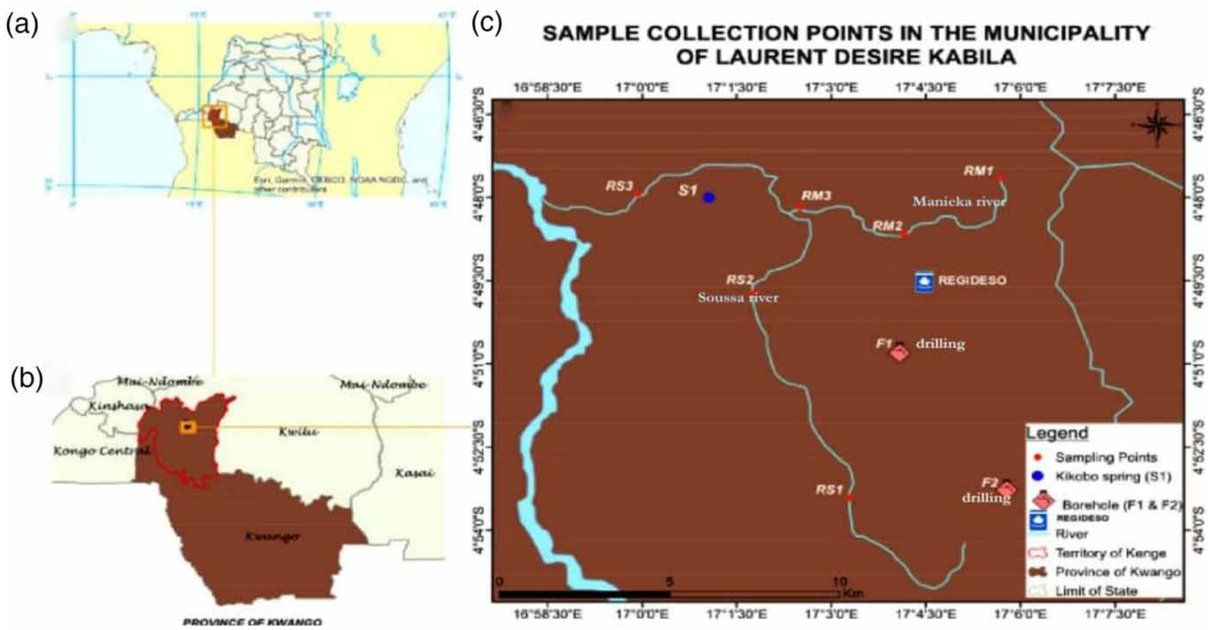


Figure 1 | (a) Kwango province in the DR Congo, (b) Kenge City in Kwango province, and (c) water sampling points in the Laurent Désiré Kabila municipality.

Figure 2 | Image showing sampling points. (a) Mangangu borehole, (b) Barrière borehole, (c) Kikobo spring, (d) Soussa River, (e) Maniéka River, and (f) public tap from REGIDESO (Photos by A. Ngandote).

2.2. Evaluation of waterborne diseases in the Laurent Désiré Kabila municipality

For the assessment of the prevalence of waterborne diseases in the study area, secondary data were used. These data were obtained from the central office of the Kenge health zone and are based on the annual attendance reports of the sick population in four health facilities from 2016 to 2020. The health facilities were the Kenge General Hospital of Reference, the Centre de Santé «Barrière», the Centre de Santé «Référence», and the Centre de Santé «Jumeaux».

2.3. Water sampling for analyses

A total of 10 sampling points, all used by the population for water provision, were selected for the collection of water samples. The global positioning system (GPS) locations of the sampling points are shown in Table 1.

Table 1 | Geographic coordinates (GPS) of the water sampling points

Sampling site	Sampling point	Longitude	Latitude
Soussa River	RS1	17°07′04″	4°91′17″
	RS2	17°02′92″	4°82′85″
	RS3	17°99′98″	4°79′75″
Maniéka River	RM1	17°09′52″	4°79′38″
	RM2	17°06′95″	4°81′01″
	RM3	17°04′10″	4°80′19″
Kikobo spring	S1	17°09′08″	4°83′38″
Mangangu borehole	F1	17°06′87″	4°84′60″
Barrière borehole	F2	17°09′65″	4°88′76″
REGIDESO	REGIDESO	17°02′337″	4°49′337″

These sampling points encompassed two rivers (Maniéka and Soussa, with three sampling points each), two boreholes (Barrière and Mangangu, respectively, with 15 and 30 m depth), a spring source (Kikobo), and a public tap from the REGIDESO public water distribution network. The water sampling was carried out during the dry season (August) and repeated in the rainy season (November) in 2022.

At each sampling point, the water physical-chemical parameters were determined *in situ* with a portable probe. Triplicate samples of about 500 mL each were collected directly into 1 L sterile polyethylene bottles for dissolved ions analysis. In the rivers, water samples were taken at about 1 m from shore and 20–30 cm deep, with caution to avoid suspending the bottom sediments. All samples for dissolved ion analysis were stored in a 4 °C cooler and transported to the laboratory for analysis. Additional samples for microbiological analysis were collected, in triplicate, directly into sterile plastic bottles and stored in a 4 °C cooler. These samples were immediately transported to the Microbiology Laboratory of the University of Kinshasa, and the analyses were carried out within 24 h.

The water samples were labeled as follows: (1) RM1, RM2, and RM3 for the Maniéka River; (2) RS1, RS2, and RS3 for the Soussa River; (3) F1 and F2 for Mangangu and Barriere boreholes, respectively; (4) SK for the Kikobo spring source; and (5) for the tap water provided by REGIDESO to the population (Table 1).

2.4. Determination of physical-chemical parameters of water and bacteriological analysis

Physicochemical parameters of water, including temperature (T), hydrogen potential (pH), dissolved oxygen (O_2), electrical conductivity (EC), and total dissolved solids (TDS) were determined *in situ* using a 340i multiparameter probe (WTW, Weilheim, Germany), calibrated by the manufacturer.

The concentrations of dissolved ions phosphate (PO_4^{3-}), sulfate (SO_4^{2-}), nitrate (NO_3^-), calcium (Ca^{2+}), magnesium (Mg^{2+}), and chloride (Cl^-) were determined by ion chromatography (Dionex ICS-3000, Canada) according to the method described by Graham *et al.* (2014). Specific chromatographic columns (Thermo Fisher Scientific) were used for cations and anions.

As an analytical quality control procedure, a water-certified reference material (CRM) (Ontario-99, Water Research Institute, Canada) was used to verify the instrument's accuracy. The CRM results were within the 95% acceptable range of values issued on the CRM certificate (Mavakala *et al.* 2016; Kapembo *et al.* 2022).

The bacteria, including *E. coli*, *ENT*, and TC, were quantified in water samples using the membrane filtration method (Nienie *et al.* 2017; Kapembo *et al.* 2022). In brief, water samples were passed through a 0.45 μm filter (47 mm diameter, Millipore, Bedford, USA) and placed on different selective culture media (Biolife, Italia) supplemented with the antifungal compound Nystatin (100 $\mu g\, mL^{-1}$ final concentration), using the following incubation conditions: *E. coli*: Tryptone Soy Agar (TSA) medium, incubated at 37 °C for 4 h and transferred to Tryptone Bile X-Gluc Agar medium at 44 °C for 24 h; *ENT*: Slanetz Bartley Agar medium, incubated at 44 °C for 48 h and transferred into Bile Aesculin Agar medium at 44 °C for 4 h; TC: Endo Agar, incubated at 35 °C for 24 h. The results were expressed as colony-forming units per 100 mL of water (CFU.100 mL^{-1}).

The reproducibility of the whole bacteriological experimental procedure was tested by means of triplicate analysis of selected samples. The results of triplicate analyses displayed a mean coefficient of variation of 8% for *E. coli* and TC and 9% for *ENT*, which is considered acceptable (APHA 2005).

2.5. Data analysis

All measurements and analyses were conducted in triplicate for each sample. SigmaStat 11.0 (Systat Software, Inc., USA) and XLSTAT software from Addinsoft (2020) (Statistical and data analysis solution. New York, United States, https://www.xlstat.com) were used to perform statistical data treatment.

3. RESULTS AND DISCUSSION

3.1. Epidemiologic survey of waterborne diseases

Table 2 displays the frequency of waterborne diseases recorded in four primary health centers of the study area over a 5-year period, from 2016 to 2020. The population does not frequently visit hospitals due to budgetary constraints, except in severe cases. As a result, the information gathered is not fully representative of the public health conditions, and it is an underestimation of illness cases, but it is the only information available.

Table 2 | Prevalence of waterborne diseases during the period from 2016 to 2020 in the Laurent Désiré Kabila municipality (data source: Kenge Health Zone office)

	Year	Kenge General Hospital of Reference	'Barrière' Health Center	'Référence' Health Center	'Jumeaux' Health Center
Typhoid fever	2016	660	350	370	400
	2017	800	370	560	800
	2018	2,000	500	650	1,200
	2019	2,500	912	800	1,800
	2020	4,000	1,700	1,600	3,000
Hepatitis	2016	1,000	550	600	466
	2017	1,130	600	700	556
	2018	1,200	750	912	800
	2019	2,500	1,000	1,200	875
	2020	3,500	2,000	1,900	1,200
Amoebae	2016	300	150	155	450
	2017	450	155	300	550
	2018	750	300	500	570
	2019	900	350	700	590
	2020	1,000	500	1,000	610
Diarrhea	2016	1,826	980	1,055	620
	2017	2,500	1,050	1,200	900
	2018	3,000	1,250	1,800	1,300
	2019	4,000	1,800	2,500	1,850
	2020	4,600	2,500	3,000	1,900

Overall, the number of cases of waterborne illnesses increased steadily over the years, and it was multiplied by a factor of 3–7.5 in the 5-year period, constituting an alarming situation. The ramp-up of the number of cases is an indication that the contamination of water sources expanded dramatically over the years.

In general, the main cause of the increase in the number of cases of waterborne diseases is the lack of access to safe drinking water (Podewils *et al.* 2004; Ugboko *et al.* 2020). Previous studies in Democratic Republic of the Congo (DRC) demonstrated a prevalence of waterborne diseases, including diarrhea, gastroenteric disorders, typhoid fever, amebic dysentery, and cholera, particularly in the localities of Mont-ngafula, Selembao, and Kimbaseke, all located in the Kinshasa metropolitan area (Kapembo *et al.* 2019, 2022).

3.2. Physical-chemical parameters of water

This study was performed to take into account the potential seasonal variation of water parameters round the year. The values of physicochemical parameters measured on water samples (T, pH, EC, O_2, and TDS) in both dry and wet seasons are presented in Table 3. Therein, these parameter values are compared with the water quality guidelines issued by the WHO for drinking water (WHO 2017).

Regarding the water temperature, it was observed that only the samples RM3 (26.1 °C), S1 (25.6 °C) and F1 (25.2 °C) deviated during the dry season from the range of temperature values recommended by WHO (12–25 °C) while for the wet season, most samples showed values above 25 °C, except the samples RM2 (24.2 °C) and F2 (24.7 °C). The water sample of «REGIDESO», collected for comparison, displayed a temperature value of 25.6 °C (wet season) and 24.6 °C (dry season). These results are comparable with those published for tropical conditions by Nienie *et al.* (2017) (ranging from 24.5 to 25.6 °C in the wet season and from 24.7 to 29.2 °C in the dry season) and Kapembo *et al.* (2022) (ranging from 25.8 to 28.8 °C in the wet season and from 23.9 to 26.9 °C in the dry season).

All samples displayed acid pH values for both seasons, ranging from 4.49 to 5.10 in the dry season, and from 4.49 to 5.25 in the wet season. The «REGIDESO» water samples also showed an acidic pH of 4.43 (dry season) and 5.77 (wet season). These values were below the WHO-recommended pH range of 6.5–9.5. Similar findings were also made by Kapembo *et al.* (2022), who reported pH values ranging from 4.6 to 7.8 in the wet season and from 5.2 to 6.9 in the dry season in the Kinshasa metropolitan area. As explained in our previous studies performed in similar environments (e.g., Kapembo *et al.* 2016; Nienie *et al.* 2017), several parameters, including acid rain in the studied location, natural rock formations, landfills, organic matter

Table 3 | Physicochemical parameter values of water samples collected in the dry and wet seasons

Site	Sample	*T* (°C)		pH		EC (μS. cm^{-1})		O_2 (mg L^{-1})		TDS (mg L^{-1})	
		Dry	Wet	Dry	Wet	Dry	Wet	Dry	Wet	Dry	Wet
	RS1	22.9	**27.4**	**4.95**	**5.25**	265	187	4.7	4.9	**62.4**	**60.4**
Soussa	RS2	23.9	**26.1**	**4.81**	**5.12**	280	220	4.6	4.8	**66.7**	**65.6**
River	RS3	23.9	**26.5**	**4.95**	**5.03**	215	201	5	**3.1**	**68.1**	**70.8**
	RM1	24.9	**26.3**	**4.55**	**4.88**	250	211	**3.1**	**3.3**	**70.7**	**72.7**
Maniéka	RM2	24.2	24.2	**4.49**	**4.9**	268	268	**3.1**	**2.13**	**56.67**	**58.67**
River	RM3	**26.1**	**26.2**	**4.49**	**4.49**	287	289	**3.2**	**2.1**	**64.2**	**65.2**
Kikobo spring	S1	**25.6**	**25.7**	**5.1**	**5.1**	296	271	**9.1**	**9.8**	**0.71**	0
Mangangu borehole	F1	**25.2**	**25.3**	**5**	**5.17**	294	283	**9.6**	**9.83**	**0.45**	**0.55**
Barrière borehole	F2	24.3	24.7	**4.68**	**4.81**	279	241	**7.6**	**7.95**	**0.12**	**0.15**
	REGIDESO	24.6	**25.6**	**4.43**	**5.77**	465	**180**	**7.8**	**7.95**	**0.27**	**0.3**
	WHO[a]	12–25		6.5–9.5		200–800		4–6		0	

[a]Recommended values set by the WHO Guidelines for Drinking-water Quality (WHO 2017).
Note. In bold, values in no conformity with the WHO water quality guidelines.

decomposition, the presence of animal farms, and chemical runoff from agricultural fields, can explain the causes of poor water physicochemical parameters, especially low pH.

The EC of water varied in the range of 215–296 μS cm^{-1} in the dry season and in the range of 201–281 μS cm^{-1} in the wet season. These values were within the range of the WHO drinking water quality standards (200–800 μS cm^{-1}). The «REGIDESO» sample displayed a value of 465 μS cm^{-1} (dry season) and 180 μS cm^{-1} (wet season).

The dissolved oxygen (O_2) generally displayed values between 4 and 6 mg L^{-1}, the range of values recommended by the WHO. However, several water samples displayed values outside the recommended range.

For the TDS parameter, only one water sample, Kibibobo Spring (S1), displayed the value of 0 mg L^{-1}, in agreement with the recommended value of WHO. All other samples showed values above 0 mg L^{-1}, ranging from 0.12 to 70.70 mg L^{-1} (dry season) and from 0.15 to 72.70 mg L^{-1} (wet season). Mangangu borehole and Barrière borehole water samples, and both Soussa and Maniéka Rivers displayed very high TDS values, namely those for Maniéka River, which also displayed low O_2 content in dry and wet seasons, suggesting the presence of high amounts of organic matter and stagnant water.

The concentrations of dissolved ions PO_4^{3-}, NO_3^-, Cl^-, SO_4^{2-}, Ca^{2+} and Mg^{2+} in water samples are shown in Table 4. In general, during the dry and wet seasons, the ion concentrations in water samples met the values recommended by the WHO guidelines for drinking water quality (WHO 2017). There were some exceptions, especially for PO_4^{3-} which varied from 4.23 to 45.7 mg L^{-1} during the dry season and from 4.25 to 35.8 mg L^{-1} during the wet season, and for Mg^{2+} in sample RM3 (with 54.2 mg L^{-1}) during the dry season.

The water samples from the Soussa and Maniéka Rivers displayed high concentrations of dissolved ions when compared with the Kikobo spring and Mangangu and Barrière boreholes during the dry and wet seasons. The high concentrations of phosphate ions in water likely were, at least in part, a result of organic matter decomposition in surface waters, but their presence in groundwater from boreholes seems to indicate also a geological source of phosphate ions.

In general, the dissolved ion concentration values were higher in the dry season than in the wet season, which is due to the dilution effect of the more abundant water flows occurring in the wet season.

3.3. Microbiological quality of water

Figure 3 shows the results of the microbiological monitoring for *E. coli*, *ENT*, and TC recorded during the dry and wet seasons. Only the water samples RM3 (in wet season), RS1 (in the wet season), F1, F2, S1 (in the dry season) and REGIDESO (dry season) met the WHO guideline for drinking water quality regarding contamination by *E. coli*. Regarding the contamination by *ENT,* only three samples (F1, F2, and REGIDESO (dry season) displayed 0 CFU.100 mL^{-1}, in agreement with the WHO standard, and no sample met the WHO standard for TC contamination. The *E. coli* average values (CFU.100 mL^{-1}) ranged from 2 to 35 during the dry season and from 1 to 60 during the wet season. The *ENT* average values (CFU.100 mL^{-1})

Table 4 | Concentrations of dissolved ions in water samples (mg L^{-1}) collected in dry and wet seasons

Site	Sampling site Season	PO_4^{3-} Dry	PO_4^{3-} Wet	NO_3^- Dry	NO_3^- Wet	Cl^- Dry	Cl^- Wet	SO_4^{2-} Dry	SO_4^{2-} Wet	Ca^{2+} Dry	Ca^{2+} Wet	Mg^{2+} Dry	Mg^{2+} Wet
Soussa River	RS1	**25.4**	**21.9**	16.2	15.3	3.8	3.52	6.7	6.8	118.3	102.5	46.1	41.4
	RS2	**17.3**	**13.2**	17.5	14.3	4.21	3.48	6.1	7	109.6	66.64	34.5	31
	RS3	**45.7**	**35.8**	16.3	15.1	3.64	2.14	5.3	5.8	72.16	65.25	32.7	28.5
Maniéka River	RM1	**12.5**	**10.5**	12.3	10.5	3.8	3.12	6.7	6.8	132.7	128.6	24.4	21.1
	RM2	**26.8**	**14.2**	17.4	15.3	4.8	3.73	3.4	3.5	115.2	116.7	32.4	26.8
	RM3	**31.3**	**18.3**	15.4	13.7	3.8	3.57	5.8	5.9	121.3	111.4	**54.2**	44.4
Kikobo spring	S1	**6.74**	**4.25**	9.18	7.4	3.8	3.86	1.1	1.1	26.78	21.61	20	16.3
Mangangu borehole	F1	**4.23**	**4.5**	4.06	3.14	9.56	7.46	3.5	3.6	17.25	4.41	13.7	11.5
Barrière borehole	F2	**8.47**	**6.47**	4.75	4.7	12.4	10.4	7.6	7.7	19.11	6.82	25.2	22.2
REGIDESO		**9.13**	**8.65**	4.15	4.1	13.4	12.4	4.4	4.5	32.49	33.4	18	6.03
WHO[a]		≤0.5	≤0.5	50	50	250	250	500	500	270	270	50	50

[a]Limit recommended by WHO Guidelines for Drinking-water Quality (WHO 2017).
Note. In bold, values not in agreement with the water quality guidelines recommended by the WHO.

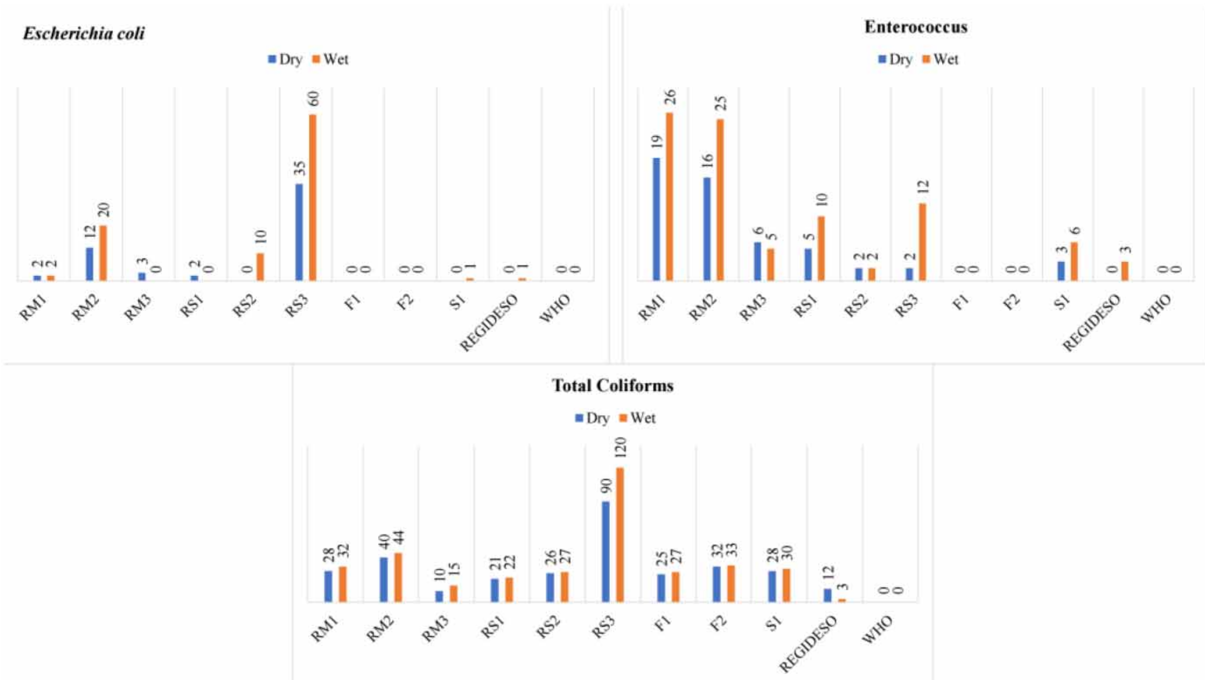


Figure 3 | Seasonal (dry and wet seasons) variation in FIB (CFU.100 mL^{-1}) quantified in the water samples. In the graphic, the WHO column represents the value recommended by WHO for drinking water quality (WHO 2017).

ranged from 2 to 19 during the dry season and from 2 to 26 during the wet season. Regarding the TC, the CFU.100 mL^{-1} values determined in water samples ranged from 10 to 90 during the dry season and from 3 to 120 during the wet season.

For the three FIB groups, the highest concentrations occurred during the wet season, which points out that, following rains, the surface runoff and overflow of pit latrines are the likely vehicles for bacterial contamination of water supply sources. This is in agreement with results from previous reports from developing countries in tropical regions (Kapembo *et al.* 2016, 2019, 2022; Nienie *et al.* 2017).

The water from the two boreholes (F1 and F2), the spring source (S1), and the water from REGIDESO, supposedly treated, displayed better conditions for *E. coli* and *ENT* than surface waters from rivers. However, all of them were contaminated with TC.

The high values of microbial concentrations observed at the RS3 site were confirmed to be caused by runoff from households and during the rainy season, more specifically, by latrine water discharges occurring upstream of the sampling site. In general, the Laurent-Désiré Kabila municipality lacks infrastructures for residential waste collection and sanitation facilities, such as the sewers network, which are at the root of this widespread microbial contamination of water bodies.

3.4. Statistical correlation

Spearman correlation tests between the physicochemical and bacteriological parameters evaluated in this study were performed for both dry and wet seasons (Table 5A and B).

Positive and significant correlations were observed between T and Cl^- ($R^2 = 0.516$), EC and Cl^- ($R^2 = 0.748$), O_2 and Cl^- ($R^2 = 0.785$) for the dry season, suggesting that Cl^- transport is positively influenced by those parameters.

Negative correlations were found between parameters such as *T* and Ca^{2+} ($R^2 = -0.665$), *T* and *ENT* ($R^2 = -0.797$), EC and Ca^{2+} ($R^2 = -0.536$), Mg^{2+} ($R^2 = -0.605$), NO_3^- ($R^2 = -0.603$), TDS ($R^2 = -0.579$); O_2 and Ca^{2+} ($R^2 = -0.85$), Mg^{2+} ($R^2 = -0.671$), PO_4^{3-} ($R^2 = -0.746$), NO_3^- ($R^2 = -0.94$), and TDS ($R^2 = -0.924$) in the wet season, suggesting a negative influence of *T*, EC, and O_2 in the transport of those soluble ions and bacteria.

Positive correlations were also observed between Ca^{2+} and Mg^{2+} ($R^2 = 0.72$), PO_4^{3-} ($R^2 = 0.542$), NO_3^- ($R^2 = 0.851$), *ENT* ($R^2 = 0.708$), TDS ($R^2 = 0.941$); Mg^{2+} and PO_4^{3-} ($R^2 = 0.696$), NO_3^- ($R^2 = 0.747$), TDS ($R^2 = 0.777$); PO_4^{3-} and NO_3^- ($R^2 = 0.761$), CT ($R^2 = 0.616$), TDS ($R^2 = 0.775$) and *E. coli* ($R^2 = 0.806$); NO_3^- and TDS ($R^2 = 0.928$); *ENT* and TDS

Table 5 | Spearman correlation of physicochemical and bacteriological parameters during the (A) dry season and (B) wet season

A	T	pH	EC	O_2	Ca^{2+}	Mg^{2+}	PO_4^{3-}	NO_3^-	SO_4^{2-}	Cl^-	ENT	CT	TDS
Ca^{2+}	**−0.665**	−0.102	**−0.536**	**−0.85**									
Mg^{2+}	−0.269	−0.128	**−0.605**	**−0.671**	**0.72**								
PO_4^{3-}	0.106	−0.336	−0.362	**−0.746**	**0.542**	**0.696**							
NO_3^-	−0.403	−0.332	**−0.603**	**−0.94**	**0.851**	**0.747**	**0.761**						
SO_4^{2-}	−0.075	0.068	−0.203	−0.269	0.394	0.436	0.22	0.176					
Cl^-	**0.516**	0.139	**0.748**	**0.785**	**−0.714**	**−0.561**	**−0.561**	**−0.848**	0.08				
ENT	**−0.797**	0.263	−0.338	−0.406	**0.708**	0.176	0.165	0.459	0.069	−0.492			
CT	0.387	−0.237	−0.107	−0.32	−0.033	−0.055	**0.616**	0.309	−0.022	−0.274	0		
TDS	−0.43	−0.178	**−0.579**	**−0.924**	**0.941**	**0.777**	**0.775**	**0.928**	0.388	**−0.761**	**0.582**	0.25	
E. coli	0.362	−0.314	−0.092	−0.446	0.115	0.153	**0.806**	0.433	−0.059	−0.351	0.056	**0.935**	0.405
B	**T**	**pH**	**EC**	**O_2**	**Ca^{2+}**	**Mg^{2+}**	**PO_4^{3-}**	**NO_3^-**	**SO_4^{2-}**	**Cl^-**	**ENT**	**CT**	**TDS**
Ca^{2+}	**0.677**	−0.096	−0.56	−0.748									
Mg^{2+}	0.393	−0.526	−0.031	−0.752	**0.64**								
PO_4^{3-}	0.383	−0.589	0.144	−0.784	0.461	**0.598**							
NO_3^-	0.362	−0.567	−0.071	−0.938	**0.791**	**0.814**	**0.745**						
SO_4^{2-}	0.272	0.01	0.064	−0.367	0.298	0.473	0.338	0.275					
Cl^-	−0.449	**0.765**	−0.063	**0.756**	−0.644	−0.639	−0.542	**−0.814**	0.007				
ENT	**0.695**	−0.118	−0.358	−0.398	**0.771**	0.197	0.276	**0.538**	−0.006	−0.577			
CT	0.222	−0.633	**0.541**	−0.361	0.035	0.079	**0.733**	0.365	0.05	−0.391	0.288		
TDS	**0.57**	−0.422	−0.208	−0.924	**0.898**	**0.818**	**0.724**	**0.947**	0.423	−0.769	**0.598**	0.284	
E. coli	0.138	−0.586	0.451	−0.49	0.125	0.129	**0.789**	0.478	0.014	−0.414	0.292	**0.966**	0.378

Note. Physicochemical parameters including: pH, temperature (*T*), EC, dissolved oxygen (O_2) and soluble ions (Ca^{2+}, Mg^{2+}, PO_4^{3+}, NO_3^-, SO_4^{2-}, Cl^-,) and bacteria (*E. coli*, *ENT*, and TC). Positive and significant coefficients ($p < 0.05$) are in bold.

($R^2 = 0.582$) and CT and *E. coli* ($R^2 = 0.935$) for the dry season, indicating that, in general, the soluble ions and the bacteria were associated and originated from the same sources.

The negative correlation between Cl^- and Ca^{2+} ($R^2 = -0.714$), Mg^{2+} ($R^2 = -0.561$); PO_4^{3-} ($R^2 = -0.561$), NO_3^- ($R^2 = -0.848$) and TDS ($R^2 = -0.761$) in the dry season suggested different origins and different cycling pathways of Cl^- compared to the other dissolved ions. The same trend was observed for the wet season (Table 5B).

4. CONCLUSIONS

This study is the first assessment of the physical-chemical and bacteriological parameters in surface waters from the Soussa and Maniéka Rivers, spring water (Kikobo spring) and groundwater from boreholes (Mangangu and Barrière) in the Laurent-Désiré Kabila municipality of Kenge City, DRC. These water sources provide more than 80% of the water used for domestic purposes, including drinking water for the population. The tap water from the public water distribution network, REGIDESO, was also analyzed.

Results revealed that the water from investigated sources was not suitable as drinking water particularly because of fecal bacteria contamination (*E. coli*, *ENT*, and TC). The high and widespread bacterial contamination of these water sources is thus the reason for the outbreaks of waterborne diseases observed in the region.

The water samples collected from surface rivers, spring, and boreholes also showed a high content of dissolved PO_4^{3-} ion, exceeding the concentration limit recommended by the WHO for drinking water quality. For the parameters pH and TDS, the values determined in water samples were also not in conformity with the WHO recommendations. These findings showed that this water, besides contamination by fecal bacteria, is also of poor chemical quality.

Very worrisome was the finding that tap water provided by the water company to the population at public distribution points (taps) is also of non-sufficient quality according to the international water quality guidelines set by WHO. Therefore, the water treatment of the public water company must be improved.

To diminish the impact of waterborne diseases, some urgent measures are needed, such as the supply of safe drinking water to substitute the contaminated water sources in use by the population. Furthermore, in the long run, it is needed to abate contamination of the water sources. However, the quality of traditional water sources may only improve if policies are approved to implement the construction of improved sanitary infrastructures and to spread awareness of good hygienic practices.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

REFERENCES

Addinsoft (2020) *XLSTAT Statistical and Data Analysis Solution*. New York, NY, USA. Available at: https://www.xlstat.com (Accessed: 11 July 2020).

APHA (American Public Health Association), American Water Works Association & Water Environment Federation (2005) *Standard Methods for the Examination of Water and Wastewater*, 21st edn, Washington, DC, USA: APHA-AWWA-WEF.

Atibu, E. K., Arpagaus, P., Mulaji, C. K., Mpiana, P. T., Poté, J., Loizeau, J.-L. & Carvalho, F. P. (2022) High environmental radioactivity in artisanal and small-scale gold mining in eastern democratic republic of the Congo, *Minerals*, **12**, 1278. https://doi.org/10.3390/min12101278.

Atibu, E. K., Kamika, I., Mudogo, C. N., Lusamba, S. N., Mulaji, C. K., Carvalho, F. & Poté, J. (2023) Quantification of heavy metals and mercury-resistant bacteria in artisanal and small-scale gold mining sites, Maniema region, Democratic Republic of the Congo, *Int. J. Environ. Res.*, **17**, 34. https://doi.org/10.1007/s41742-023-00524-y.

Barnett, M. J., Jackson-Smith, D. & Haeffner, M. (2018) Influence of recreational activity on water quality perceptions and concerns in Utah: a replicated analysis, *J. Outdoor Recreation Tourism*, **22**, 26–36. https://doi.org/10.1016/j.jort.2017.12.003.

Fawell, J. & Nieuwenhuijsen, M. J. (2003) Contaminants in drinking water, *Br. Med. Bull.*, **68**, 199–208. doi:10.1093/bmb/ldg027.

Fazal-ur-Rehman, M. (2018) Polluted waterborne diseases: symptoms, causes, treatment and prevention. A review, *J. Med. Chem. Sci.* **2** (1), 21–26. doi:10.26655/jmchemsci.2019.6.4.

Graham, N. D., Stoll, S. & Loizeau, J. L. (2014) Colloid characterization at the sedimentwater interface of Vidy Bay, Lake Geneva, *Fund. Appl. Limnol.*, **184**, 87–100.

Kapembo, M. L., Lafite, A., Bokolo, M. K., Manga, A. L., Maya-Vangua, M. M., Otamonga, J.-P., Mulaji, C. K., Mpiana, P. T., Wildi, W. & Pote, J. (2016) Evalution of water qualiy from suburban shallow wells under tropical conditions according to the seasonal varition, Bumbu, Kinshasa, Democratic Republic of the Congo, *Expo. Health*, **8**, 487–496. doi:10.1007/s12403-016-0213-y.

Kapembo, M. L., Al Salah, D. M. M. & Thevenon, F. (2019) Prevalence of water-related diseases and groundwater (drinking-water) contamination in the suburban municipality on Mont-ngafula, Kinshasa (Democratic Republic of the Congo), *J. Environ. Sci. Health Part A*, **54**, 1–11.

Kapembo, M. L., Mukeba, F. B., Sivalingam, P., Mukoko, J. B., Bokolo, M. K., Mulaji, C. K., Mpiana, P. T. & Pote, J. W. (2022) Survey of water supply and assessment of groundwater quality in the suburban communes of Selembao and Kimbanseke, Kinshasa in Democratic Republic of the Congo, *Sustain. Water Resour. Manage.*, **8**, 3. https://doi.org/10.1007/s40899-021-00592-y.

Kilunga, P. I., Kayembe, J. M., Laffite, A., Thevenon, F., Devarajan, N., Mulaji, C. K., Mubedi, J. I., Yav, Z. G., Otamonga, J.-P., Mpiana, P. T. & Poté, J. (2016) The impact of hospital and urban wastewaters on the bacteriological contamination of the water resources in Kinshasa Democratic Republic of Congo, *J. Environ. Sci. Health A*, **51**, 1034–1042.

Lin, L., Yang, H. & Xu, X. (2022) Effects of water pollution on human health and disease heterogeneity: a review, *Front. Environ. Sci.*, **10**, 880246. doi:10.3389/fenvs.2022.880246.

Mavakala, B. K., Le Faucheur, S., Mulaji, C. K., Laffite, A., Devarajan, N., Biey, E. M., Giuliani, G., Otamonga, J. P., Kabatusuila, P., Mpiana, P. T. & Poté, J. (2016) Leachates draining from controlled municipal solid waste landfill: detailed geochemical characterization and toxicity tests, *Waste Manage.*, **55**, 238–248.

Mwanamoki, P. M., Devarajan, N., Thevenon, F., Atibu, E. K., Tshibanda, J. B., Ngelinkoto, P., Mpiana, P. T., Prabakar, K., Mubedi, J. I., Kabele, C. G., Wildi, W. & Pote, J. (2014) Assessment of pathogenic bacteria in water and sediment from a water reservoir under tropical conditions (Lake Ma Valle ´e), Kinshasa Democratic Republic of Congo, *Environ. Monit. Assess.*, **186** (10), 6821–6830. doi:10.1007/s10661-014-3891-6.

Mwanamoki, P. M., Devarajan, N., Niane, B., Ngelinkoto, P., Thevenon, F., Nlandu, J. W., Mpiana, P. T., Prabakar, K., Mubedi, J. I., Kabele, C. G., Wildi, W. & Poté, J. (2015) Trace metal distributions in the sediments from river-reservoir systems: case of the Congo River and Lake Ma Vallée, Kinshasa (Democratic Republic of Congo), *Environ. Sci. Pollut. Res.*, **22**, 586–597.

Nienie, A. B., Sivalingam, P., Laffite, A., Ngelinkoto, P., Otamonga, J.-P., Matand, A., Mulaji, C. K., Biey, E. M., Mpiana, P. T. & Pote, J. (2017) Microbiological quality of water in a city with persistent and recurrent water borne diseases under tropical sub-rural conditions: the case of Kikwit City, Democratic Republic of the Congo, *Int. J. Hyg. Environ. Health*, **220**, 820–828. doi:10.1007/s11270-009-0005-0.

Pakasi, L. S. (2018) Health risks associated with recreational water activities, *IOP Conf. Ser.: Mater. Sci. Eng.*, **434**, 012329. doi:10.1088/1757-899X/434/1/012329.

Podewils, L. J., Mintz, E. D., Nataro, J. P. & Parashar, U. D. (2004) Acute, infectious diarrhea among children in developing countries, *Semin. Pediatr. Infect. Dis.*, **15** (3), 155–168. https://doi.org/10.1053%2Fj.spid.2004.05.008.

Thevenon, F., Regier, N., Benagli, C., Tonolla, M., Adatte, T., Wildi, W. & Poté, J. (2012) Characterization of fecal indicator bacteria in sediments cores from the largest freshwater lake of Western Europe (Lake Geneva, Switzerland), *Ecotoxicol. Environ. Saf.*, **78**, 50–56.

Tongesayi, T. & Tongesayi, S. (2015) 13 - Contaminated irrigation water and the associated public health risks, *Food Energy Water*, 349–381. https://doi.org/10.1016/B978-0-12-800211-7.00013-2.

Ugboko, H. U., Nwinyi, O. C., Oranusi, S. U. & Oyewale, J. O. (2020) Corrigendum to 'Childhood diarrhoeal diseases in developing countries', *Heliyon*, **6** (6), e04040. https://doi.org/10.1016%2Fj.heliyon.2020.e04040.

UNEP (2011) *Emerging Issues in our Global Environment: Post- Conflict Environmental Assessment in Democratic Republic of the Congo*. *Synthesis for Policy Makers.* United Nations Environment Programme. Geneva, Switzerland: World Health Organization.

WHO (2011) *Guidelines for Driking-Water Quality*, 4th edn. Geneva, Switzerland. World Health Organization. (Accessed: 14 November 2020).

WHO (2017) *Guidelines for Drinking- Water Quality: Fourth Edition Incorporationg the First Addendum*. Geneva, Switzerland: WHO (Accessed: 14 November 2020).

WHO (2018) *Guidelines on Sanitation and Health*. Geneva: WHO (Accessed: 14 November 2020).

WHO (2019) *World Water Day Report – World Health Organization*. Geneva, Switzerland: World Health Organization. Available at: https://www.who.int/news-room/fact-sheets/detail/drinking-water (Accessed: 4 November 2020).

First received 16 July 2024; accepted in revised form 1 March 2025. Available online 7 April 2025