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Heavy Metal Pollution Status in The Main Surface Waters of The N'djili River Basin in Kinshasa, Democratic Republic of Congo: A Review with Application and Evaluation of Pollution Indices Evaluation

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Abstract: The aim of this study was to assess heavy metal pollution in the surface waters of the N'djili river watershed, as well as to determine the main sources of this pollution and their impact on water quality. Five sampling sites were selected in the watershed, representing a variety of urban and industrial influences. In these samples, trace metals such as lead (Pb), cadmium (Cd) and arsenic (As) were measured by atomic absorption spectrometry. The respective mean concentrations of lead (Pb), cadmium (Cd) and arsenic (As) in the surface waters of the N'djili basin are 0.066 mg/L, 0.006 mg/L and 0.310 mg/L. The mean value of the degree of contamination (Dc) in the surface waters of the N'djili basin is greater than 3, indicating heavy contamination of these waters (Lukaya river, Matete river, N'djili river, Ntshuenge river, Ngwele river). The average values of for the trace metal pollution index (HPI) are below the threshold value of 100, so overall, these waters are not very polluted. Nevertheless, particularly high concentrations were observed in the waters of the Matete River, with values exceeding 100, indicating severe localized pollution. Correlation analysis between trace metals and HPI indicates that lead and cadmium are the main contributors to surface water toxicity in the N'djili basin. These results highlight the urgent need to develop targeted strategies to reduce pollution in order to preserve public health and aquatic ecosystems.

Keywords: Pollution indices, degree of contamination, trace metals, N'djili river watershed

INTRODUCTION

Surface water pollution has become a major global problem due to the ease with which these waters carry domestic, industrial, and agro-industrial wastewater. Studies by Al Obaidy et al. (2010), Al Obaidy & Al-Khateeb (2013), and Al-Ani et al. (2014) have shown that in urban areas, surface water pollution is exacerbated by chaotic and rapid urbanization, the generation of urban and industrial solid waste, industrial and municipal wastewater, fecal discharges, excessive pesticide and herbicide use, and agricultural runoff. Heavy metals can also contaminate surface waters. According to Kumar et al. (2019), heavy metal pollution of aquatic environments is a significant concern due to their harmful and hazardous nature for the ecosystem.

In recent years, in-depth scientific studies have focused on the environmental and morphometric aspects of the N'djili River watershed. Indeed, Luboya (2002) has noted that the urban area of the N'djili River basin is facing an environmental and ecological crisis, the origins of which lie in human activities with extremely serious consequences for the entire watershed. The N'djili watershed is currently experiencing an unprecedented demographic and urban development crisis. Indeed, the total population in the watershed is estimated at around 4,682,874, corresponding to a population density of 7,493 inhabitants/km² (Nzomba, 2023). This demographic and urban growth has led to a proliferation of human activities, which have had a destructive impact on the environment as a whole and on the aquatic ecosystem in particular. These activities include the direct discharge of household waste into surface waters, as well as the discharge of urban and agro-industrial wastewater and fecal matter into these same surface waters.

The urban part of the N'djili River watershed presents specific challenges in terms of land use and management. Kinkela et al. (2017) counted nearly 7,411 market gardening centers throughout the watershed, occupying an available area of 719 ha and a cultivated area of 558 ha. The development of urban farming activities in this catchment area is causing a number of environmental problems, notably the loss of soil fertility due to the repeated cropping year after year in discontinuous spaces. This practice depletes the soil, compelling market gardeners to use chemical fertilizers, which are the main sources of heavy metals in agricultural contexts.

Numerous scientific studies have been published concerning the pollution of the N'djili River, mainly due to its capture by REGIDESO. According to Nitu (2018), the N'djili River exhibits contamination by certain metallic trace elements. Electrical conductivity measurements indicate values below 100 µS/cm (Nsiala, 2012). The main causes of this pollution, according to Boland et al. (2004), Muzingu (2010), Nsimanda et al. (2015), Kusonika et al. (2016), Mindele (2016), Kasuku et al. (2016), Kabamba et al. (2016), Bipendu et al. (2017), and Ilunga et al. (2021) include the discharge of purification sludge from the water treatment plant, industrial discharges, the direct disposal of untreated domestic and medical waste, the mixing of polluted water from the N'djili with that from the Congo River at the Malebo Pool containing Hg, Pb, and Cd, the mineralization of plants in swamps enriched in trace metal elements through bioaccumulation, rainfall laden with certain metals and metalloids polluting the air in Kinshasa (As, Pb, and Ni), and the use of pesticides. The results of these studies show that cadmium, cobalt, and copper concentrations in the water of the N'djili River were higher than 0.1 mg/l, 0.05 mg/l, 0.02 mg/l, and 0.2 mg/l, respectively, during the dry and rainy seasons of 2005 (Kifuani et al., 2018). According to samples taken in 2008, lead concentrations exceeded 3 mg/l (Lumbuenamo et al., 2010). Other trace metals such as zinc, arsenic, and selenium have also been detected in N'djili River water, although their concentrations are deemed acceptable for irrigation and drinking water consumption (UNEP, 2011). Nitu (2018) found concentration values by inductively coupled plasma mass spectrometry (ICP-MS) equal to 0.044 ± 0.043 mg/L for zinc during the rainy season. Overall, research has been carried out on the N'djili watershed, but other scientific aspects have not been taken into account. Previous studies on the N'djili do not sufficiently mention the other major tributaries that contribute significantly to its pollution. It is essential to understand the contribution of these tributaries, as they play a crucial role in contributing contaminants to the main river. By understanding the extent of pollution coming from these tributaries, it is possible to better assess the overall impact on the water quality of the main river. Moreover, by focusing solely on the main river, we run the risk of overlooking significant sources of pollution from tributaries. Understanding the specific contribution of each tributary enables us to identify priority areas for pollution prevention and reduction measures.

This new study provides valuable information for the management of surface water quality in the N'djili River watershed, as it quantifies the contribution of each tributary to the pollution of the main river. These results can inform decision-makers and guide water management policies and practices for better protection of the environment and public health. Additionally, studies on the pollution of the N'djili River and the environmental status of its watershed were carried out between 2002 and 2020. Since then, the water quality and environmental status of the N'djili watershed have undergone considerable changes. In this study, we assess the overall water quality of the N'djili River and its tributaries by calculating pollution indices such as the contamination factor (CF), degree of contamination (Dc), and heavy metal pollution index (HPI). Assessing heavy metal pollution in the N'djili River and its tributaries using these pollution indices is essential for monitoring the environmental health of watercourses, detecting potentially contaminated areas, and protecting human health. The N'djili and Lukaya rivers are used to supply drinking water to surrounding populations, for agricultural irrigation, and for fishing. Furthermore, using pollution indices to assess heavy metal pollution enables the establishment of appropriate regulations and the planning of effective remediation measures. Pollution indices provide quantitative indicators of heavy metal pollution, making it possible to compare contamination levels between different watercourses over time. This contributes to the preservation of aquatic ecosystems and the sustainability of water resources. The results of this study could inform water quality management strategies by implementing stricter regulations to control emissions and reduce pollution. These results may also have a direct impact on water management policies and practices in Kinshasa and serve as a scientific basis for developing more robust environmental policies and stricter regulations concerning heavy metal emissions from industries and human activities.

METHOD

Study Area

Site Description

The N'djili River watershed, with a surface area of around 2,000 km² (Luboya, 2002), stretches from the province of Kongo-Central (rural part) to Kinshasa (urban part), located between longitudes East 15°9' and 15°39' and latitudes South 4°22' and 4°59' (Figure 1) (Luboya, 2002). Its boundaries are defined to the west by the Congo River basin, to the south and southwest by the Inkisi River basin, and to the east by the N'sele River basin. It comprises two distinct geomorphological units: the plain and the hills. The soils in the urban part of the basin are primarily composed of fine, medium, and coarse sands. Hydrographically, the N'djili River spans 30 km across the eastern part of the Kinshasa plain and is fed by several tributaries, including Lukaya, Luzumu, Didingi, Nshimi, Funda, Lususa, Wau, Mangoe, Musinga, Matete, Munfie, and Ludisa (Luboya, 2002; Nsiala, 2012).

Due to its vast size and strategic geographical position, the N'djili River watershed is poised to play a decisive role in supplying food to the population of Kinshasa, thus contributing to food security. The riverbed of the N'djili is fertile with alluvial soil, which supports robust agricultural activity focused on the cultivation of vegetables and essential foodstuffs. Several agricultural sites are located in the N'djili River valley, including Tshuenge N'sele, Tshuenge Masina, Tshangu, Masina rail 1, Masina rail 2, Kingabwa 1, Kingabwa 2, and Kingabwa 3 (Nitu, 2018).

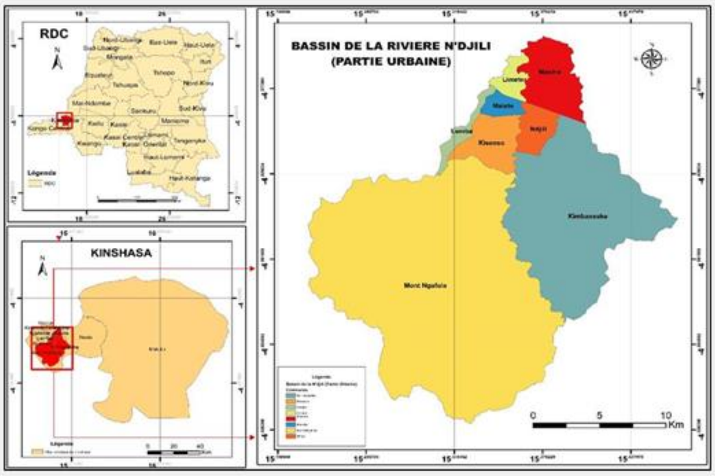

Figure 1. Location map of the urban part of the N'djili river watershed (Nzomba, 2023).

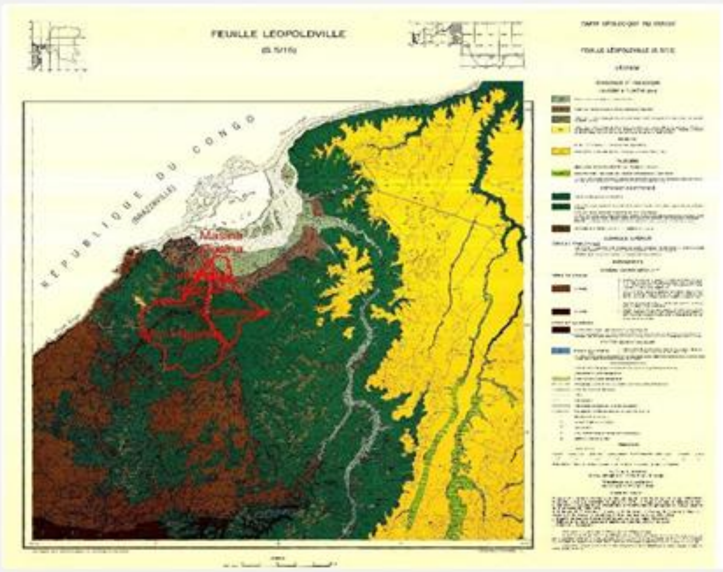

Figure 2. Geological map of Kinshasa with the N'djili watershed, urban section (Service Géologique, R.D. Congo, 1955).

Geology

In the lowland regions of the N'djili River watershed (Matete, N'djili, Masina, Lemba, Limete), various surface geological formations can be observed, including fine brown or yellow clayey sands, fine or medium white sands, and clays (Figure 2). The deeper geological formations consist of older alluvial sands, coarse sands, and clays; colluvium of eolian origin (medium coarse sands); as well as soft sandstone and polymorphous sandstone debris. In the hilly zone (Kisenso, Kimbanseke, Mont-Ngafula), the surface geological formations are primarily composed of fine yellow to brown clayey sands and fine to medium white sands. The deeper geological formations include coarse sand and polymorphous sandstones.

Sampling Method

Five surface water samples were collected in the watershed during the rainy season to capture the impacts of runoff and identify pollution sources. Runoff during this period can carry contaminants from various sources, including precipitation that causes surface water to run off, thus increasing the movement of contaminants into watercourses. Sampling during this period allows for an assessment of the impact of runoff on the concentration of heavy metals in water, deepening our understanding of specific pollution sources and evaluating their contribution to surface water contamination.

Sampling was strategically conducted in areas with significant agro-industrial activity, as well as in areas close to urban pollution sources such as landfills and sanitary facilities (Figure 3). Sampling points were recorded using a GARMIN 62S GPS, and samples were taken to a depth of 50 cm below the water surface using a water sump (Table 1). Samples were stored in 1L polyethylene bottles, which were previously washed and rinsed with the water to be analyzed. After filtering and acidification to stabilize the solutions at pH < 2, samples were transported to the CHANALTOXEN laboratory for various analyses.

Physico-chemical analyses were conducted within the first 24 hours at the laboratory to avoid altering the samples. Analyses of trace metals (arsenic, cadmium, lead) were performed using the Atomic Absorption Spectrometry (AAS) method in flame, in accordance with standard NFT90-112 (1986) (AFNOR, 2008). The use of AAS offers several advantages for the analysis of heavy metals, such as high sensitivity, which enables the detection and quantification of low concentrations of these metals in samples. Additionally, AAS provides high analytical precision, producing reliable and reproducible results. This method is relevant to heavy metal analysis as it is widely accepted and used in the field of analytical chemistry and environmental studies, ensuring compatibility with other studies and data.

Table 1. Sampling Locations

Sampling station	Name	Longitude	Latitude	Altitude (m)
S1	Lukaya river	15.276112	-4.472076	320
S2	Matete river	15.334812	-4.3932	306
S3	N'djli river	15.3609	-4.36486	290
S4	Ntshuenge river	15.39005	-4.38484	296
S5	Ngwele river	15.35786	-4.370569	278

Data Analysis and Processing Method

The water samples collected were subjected to various analyses, including physicochemical and trace metal analyses. The physico-chemical parameters analyzed included temperature (°C), pH, conductivity (EC [μS/cm]), total dissolved solids (TDS), salinity (%NaCl), turbidity (NTU), total acidity, strong acidity, simple alkalinity °F (TA), complete alkalinity °F (TAC), total hardness (THt), major cations (calcium [Ca^{2+}], magnesium [Mg^{2+}], potassium [K+], sodium [Na^{+}]), major anions (chloride [Cl^{-}], bicarbonate [HCO_3^{-}], sulfate [SO_4^{2-}], nitrate [NO_3^{-}]), and trace metals including lead (Pb), arsenic (As), and cadmium (Cd).

Field measurements included temperature, pH, conductivity, total dissolved solids, salinity, and turbidity, carried out using a programmed and calibrated HANNA multi-parameter instrument. Laboratory measurements encompassed total acidity, strong acidity, simple alkalinity, complete alkalinity, total hardness, and concentrations of major cations and anions, as well as metallic trace elements. Various methods were employed to characterize the chemical composition of the water in the laboratory (Table 2).

The results of the chemical analyses were processed using XLSTAT 2018 software and statistical methods. The values obtained were compared with World Health Organization standards to determine the extent of surface water pollution. Additionally, metal pollution indices, such as the contamination factor, degree of contamination, and heavy metal pollution index, were calculated to assess the overall surface water quality in the N'djili River watershed. This method is considered reliable and has been successfully used in other studies, including those by Mohan et al. (1996), Prasad & Bose (2001), Tamasi & Cini (2004), Mahato et al. (2014), Goher et al. (2014), Tiwari et al. (2015), Panigrahy et al. (2015), Karaouzas et al. (2011), Djade et al. (2020), and Vualu (2020).

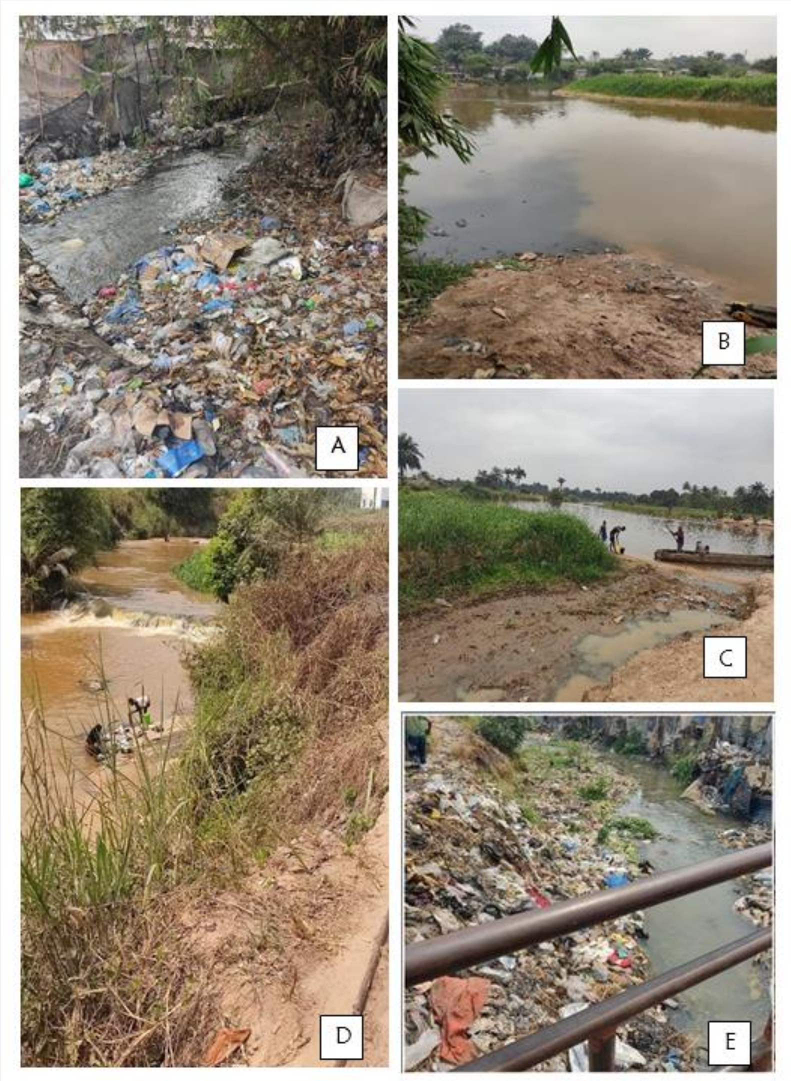

Figure 3. A) Ntsuenge river, B) Ngwele river, C) N'djili river, D) Lukaya river, E) Matete river.

Table 2. Parameters and Methods Used in the Laboratory

Parameters	Methods
TA°F	Titrimetry [(NaOH 0.02N/Phenolphthalein]
TAC°F	Titrimetry [(NaOH 0.02N/Methylorange]
Hardness	Volumetric method by complexometry with an EDTA solution
HCO3	TAC°F derivative
Calcium	Volumetric method by complexometry with an EDTA solution
Magnesium	Volumetric method by complexometry with an EDTA solution
Chloride	MOHR method AgNO3
Sodium	Derived from NFT 90 - 020 (with standard)
Potassium	Derived from NFT 90 - 020 (with standard)
Nitrates	UV-visible spectrometry method
Sulfates	UV-visible spectrometry method
Lead	Atomic absorption spectrometry method
Arsenic	Atomic absorption spectrometry method
Cadmium	Atomic absorption spectrometry method

Pollution Assessment Indices for Surface Water

Contamination Factor

Hakanson (1980) proposed the use of the contamination factor as a single index. According to Shen et al. (2019), this index is a simple and effective tool for assessing environmental contamination by heavy metals. The contamination factor can be used to determine the presence or absence of contamination in the environment and to assess its degree. Mathematically, this index is calculated by comparing the concentration of the element measured in the medium with a reference concentration, using the WHO (2017) standard for drinking water as the reference value (Djade et al., 2020):

$$CF = \frac{Concentration\ of\ trace\ metal\ element\ meausred\ in\ water}{WHO\ reference\ guide\ value} \tag{1}$$

Hakanson (1980) classified this index into four categories: CF < 1 indicates low contamination; 1 ≤ CF < 3 signifies moderate contamination; 3 ≤ CF < 6 denotes considerable contamination; CF ≥ 6 suggests very high contamination.

Degree of Contamination

The degree of contamination is an index that indicates the negative impact of heavy metals on surface waters (Backman et al., 1998). This index is used to estimate the level of metal contamination in water (Belkhiri et al., 2018). The degree of contamination is calculated from the following equation (Djade et al., 2020):

$$Cd = \sum_{i=n}^{n} CFi \tag{2}$$

where CFi is the contamination factor for the *i*-th parameter, and *n* represents the number of parameters assessed. The degree of contamination is classified into three categories: low (Cd < 1), medium (Cd = 1-3), and high (Cd > 3) (Edet & Offiong, 2002; Yari & Sobhanardakani, 2016; El-Hamid & Hegazy, 2017; Belkhiri et al., 2018).

Heavy Metal Pollution Index (HPI)

The trace metal pollution index was first introduced by Mohan et al. (1996) and is widely used to assess overall water quality (Prasad & Bose, 2001; Edet & Offiong, 2002; Giri & Singh, 2019; Sirajudeen et al., 2015; Tiwari et al., 2015; El-Hamid & Hegazy, 2017). The calculation of HPI is based on a weighted arithmetic quality method, carried out in two stages:

1. *Establishing a rating scale:* Each selected parameter is assigned a weight based on its relative importance to water quality. The weights are typically inversely proportional to the recommended standard *Si* for that parameter (Prasad & Bose, 2001).
2. *Establishing pollution parameters:* The parameters critical to assessing pollution are determined.

The HPI is calculated using the following equations (Djade et al., 2020):

$$HPI = \frac{\sum_{i=1}^{n} WiQi}{\sum_{i=1}^{n} Wi} \tag{3}$$

$$Qi = \sum_{n=1}^{n} \frac{(Mi-li)}{(Si-li)} * 100 \tag{4}$$

$$Wi = \frac{k}{MAC} \tag{5}$$

Here:

- *Wi* is the weight assigned to the *i*-th parameter.
- *Qi* is the quality rating for the *i*-th parameter.
- *Mi* is the monitored value for the *i*-th trace element.
- *li* is the ideal value for the *i*-th parameter.
- *k* is a constant of proportionality, typically set to 1.
- *Si* is the standard value for the *i*-th parameter, with WHO (2017) limits often used.
- *MAC* (Maximum Admissible Concentration): the maximum permissible concentration for each parameter.

Water quality based on HPI is classified into three categories: low risk (HPI < 100), threshold risk (HPI = 100), and high risk (HPI > 100). An HPI above 100 indicates that the water is unfit for consumption (Prasad et al., 2014; Aloueimine et al., 2017).

Table 4. ETM Standard Values for HPI Calculations

Trace metallic elements	Wi	Si	Ii	MAC
Hg	1	2	1	1
Pb	0.7	100	10	1.5
Cd	0.3	5	3	3
As	0.2	50	10	50
Fe	0.005	300	200	200

RESULTS

Physical Parameters of Surface Waters in the N'djili Basin (In Situ Measurements)

The results for physical parameters of surface waters in the N'djili basin are presented in Table 5 and Figure 4. Analysis of these results indicates that the surface waters of the N'djili basin ranged from acidic to neutral, with pH values spanning from 5.8 to 7.6 and an average of 6.9. Specifically, the waters of the Matete, N'djili, and Masina rivers were found to be neutral, with pH values recorded at 7.2, 7.1, and 7.6 respectively. According to Rodier et al. (2016), these pH levels typically indicate approximate neutrality, which is common for most surface waters. In contrast, the Rivière Ngwele and Rivière Lukaya exhibited acidic conditions, with pH values of 6.9 and 5.8 respectively. Rodier et al. (2016) suggest that such acidity could be due to the presence of mineral or organic acids in natural waters.

Temperature measurements in the surface waters of the N'djili basin varied from 25.7°C to 31°C, averaging 27.6°C. Temperatures in the Lukaya, N'djili, Ntshuenge, and Limete rivers were below the WHO standard, recorded at 27.2°C, 25.7°C, 27.5°C, and 26.8°C respectively. However, the water temperature in the Matete river reached 31°C, slightly exceeding the WHO reference value.

Table 5. Summary of Measurements of Physical and Chemical Parameters of Surface Waters in the N'djili Basin

Parameters	Min	Max	Moyenne	Median	Standard deviation	Standard OMS
pH	0.48	7.6	5.5	7.0	2.52	6.5 – 8.5
T°C	1.35	31.0	21.8	27.4	10.22	30 °C
CE (µS/cm)	157.23	695.0	337.6	249.1	178.71	1 200
TDS	78.37	350.0	169.9	125.7	90.04	600
Turbidité (NTU)	0.30	1.2	0.6	0.4	0.31	1
Salinité (%NaCl)	1.03	6.5	3.8	3.8	1.48	NGV
(THt)°F	40.96	182	108.4	105.4	37.96	NGV
TAC (méq/L)	1	2.7	1.5	1.2	0.60	NGV
Ca (mg/L)	13.51	45.1	27.3	25.4	8.88	NGV
Mg (mg/L)	3.51	16.9	10.2	10.2	3.60	NGV
Na (mg/L)	15.62	88.8	54.5	56.8	20.06	200 mg/L
K (mg/L)	12.20	32.9	18.4	14.2	7.28	PVG
HCO3 (mg/L)	135.01	689.9	331.4	250.3	179.27	PVG
Cl (mg/L)	68.09	263.3	158.4	151.1	52.44	250 mg/L
SO4 (mg/L)	12.14	55.6	30.4	26.9	12.84	250 mg/L
NO3 (mg/L)	21.44	98.1	53.6	47.5	22.67	50 mg/L
Pb (mg/L)	0.006	0.081	0.054	0.064	0.024	0.001 mg/L
Cd (mg/L)	0.003	0.013	0.007	0.005	0.003	0.003 mg/L
As (mg/L)	0.106	0.461	0.308	0.333	0.101	0.001 mg/L

Electrical conductivity measurements in the surface waters of the N'djili basin ranged from 30 to 695 µS/cm, with an average value of 273 µS/cm. None of these values exceeded the WHO recommended guidelines. The Lukaya River registered the lowest conductivity at 30 µS/cm, while the Matete and N'djili rivers recorded higher values of 695 µS/cm and 67 µS/cm, respectively. The Ntshuenge River had a conductivity of 157 µS/cm, and the Rivière Ngwele measured 414 µS/cm. According to Belghiti et al. (2013), these values indicate that the waters range from weakly to moderately mineralized.

Total dissolved solids in the basin's surface waters varied from 12 mg/L to 350 mg/L, with an average of 137 mg/L. The highest concentrations were observed in the Matete and Limete rivers at 350 mg/L and 210 mg/L, respectively. The Lukaya, N'djili, and Masina rivers displayed lower concentrations of total dissolved solids at 12 mg/L, 33 mg/L, and 78 mg/L, respectively, all below WHO standards.

The turbidity in the basin varied from 2.92 NTU to 6.5 NTU, with an average of 4.072 NTU, surpassing WHO limits at all sampling points. The highest turbidity was recorded in the N'djili River at 6.5 NTU, followed by the Ntshuenge and Ngwele rivers at 4.21 NTU and 3.61 NTU, respectively. The Lukaya and Matete rivers had relatively lower turbidity levels at 3.12 NTU and 2.92 NTU.

Salinity levels ranged from 0.1% NaCl to 1.2% NaCl, with an average of 0.48% NaCl. The highest salinity was observed in the Rivière Matete at 1.2% NaCl, while the Lukaya and N'djili rivers both had the lowest salinity at 0.1% NaCl. The WHO has not established thresholds for salinity in surface waters.

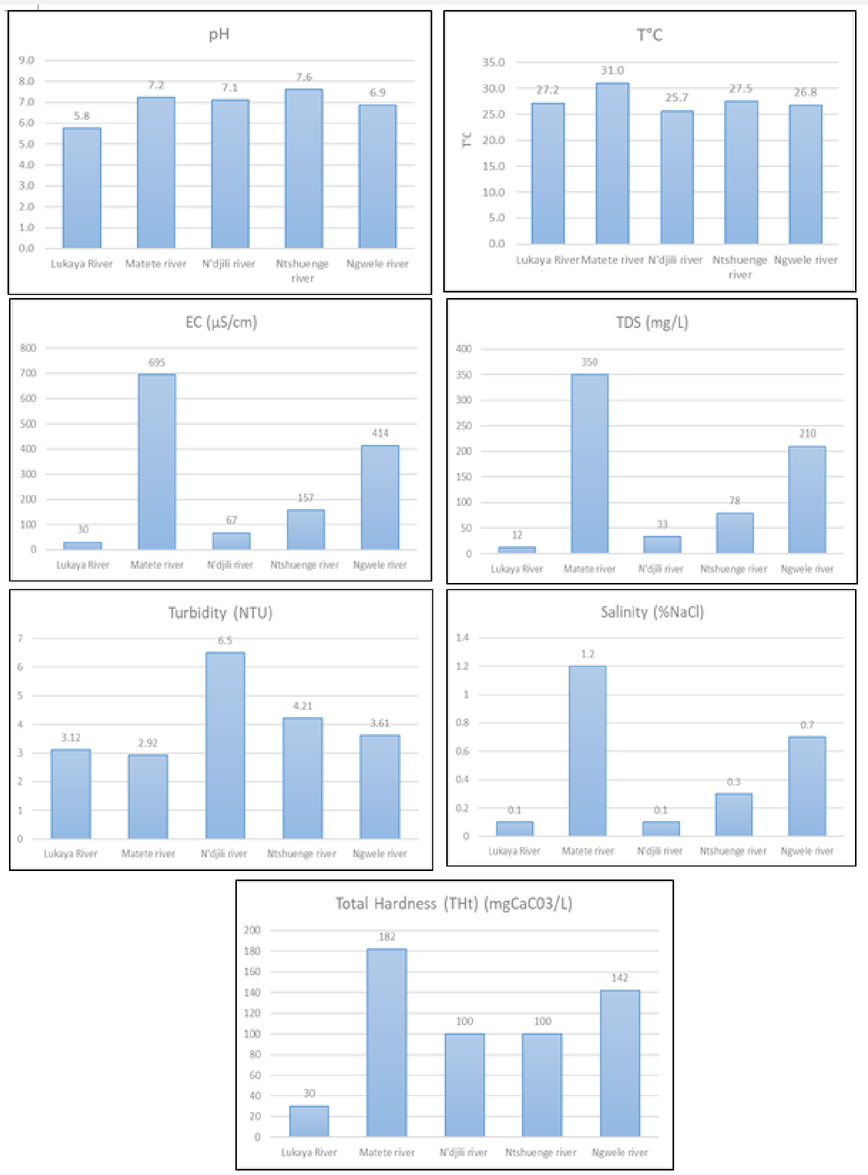

Figure 4. Results of physical parameters of surface waters in the N'djili basin (in situ measurements).

Total hardness in the basin's waters ranged from 30°F to 182°F, with an average of 110.8°F. According to Rodier et al. (2016), these values indicate a range from medium to very hard water. The Lukaya River exhibited medium hardness at 30°F, whereas the Matete, N'djili, Masina, and Limete rivers displayed very hard water, with the highest hardness recorded at 182°F in the Matete River.

Surface waters in the N'djili basin exhibit a range from acidic to neutral pH levels, with medium to high electrical conductivity and total dissolved solids, coupled with significant turbidity. These characteristics indicate altered water quality and the presence of both dissolved and suspended substances, potentially impacting the overall environmental health of the basin.

Chemical Parameters of Surface Waters in the N'djili Basin

The chemical parameters of surface waters in the N'djili basin are shown in Table 5. The cations analyzed in these waters included Na^+, K^+, Ca^{2+} and Mg^{2+}. The results for major cations, broken down by sampling point, are shown in Figure 5.

Sodium concentrations in the surface waters of the N'djili basin ranged from 32.82 mg/L to 98.09 mg/L, with an average of 54.52 mg/L. The highest Na+ concentrations were found in the waters of Rivière N'djili and Rivière Ngwele, measuring 98.09 mg/L and 64.54 mg/L, respectively. In contrast, the Lukaya and Matete rivers showed lower sodium levels at 32.82 mg/L and 36.67 mg/L, respectively. The Ntshuenge river reported a sodium concentration of 40.48 mg/L. All measured values were below WHO recommended levels.

Potassium levels across the various surface water sampling points in the N'djili basin varied from 18.59 mg/L to 55.57 mg/L, with an average of 33.4 mg/L. Notably, the N'djili and Ngwele rivers recorded significant potassium concentrations at 55.57 mg/L and 22.93 mg/L, respectively. The Lukaya, Matete, and Masina rivers displayed lower potassium levels at 18.59 mg/L, 20.77 mg/L, and 22.93 mg/L, respectively. The WHO has not established recommended values for potassium.

Calcium cation concentrations in the basin's waters ranged from 4.20 mg/L to 45.09 mg/L, averaging 26.69 mg/L. The Matete and Ngwele rivers exhibited high calcium levels at 45.09 mg/L and 42.08 mg/L, respectively. Conversely, the Lukaya, N'djili, and Masina rivers showed lower calcium values at 4.21 mg/L, 18.04 mg/L, and 24.05 mg/L, respectively.

Magnesium levels varied from 4.74 mg/L to 16.89 mg/L, with an average of 10.74 mg/L. The Matete river recorded the highest magnesium concentration at 16.89 mg/L. The N'djili river had a magnesium level of 13.37 mg/L, while the Lukaya, Ntshuenge, and Limete rivers reported lower concentrations at 4.74 mg/L, 9.72 mg/L, and 8.99 mg/L, respectively.

Calcium and magnesium are major contributors to water hardness. Notably, the WHO has not set limit values for these parameters. The variability in calcium and magnesium concentrations across different rivers suggests diverse levels of water hardness within the basin.

The chemical analysis of the N'djili basin's surface waters reveals a spectrum of mineralization, from low to moderately high. These findings are essential for understanding the overall water quality and potential impacts on the ecosystem and human health.

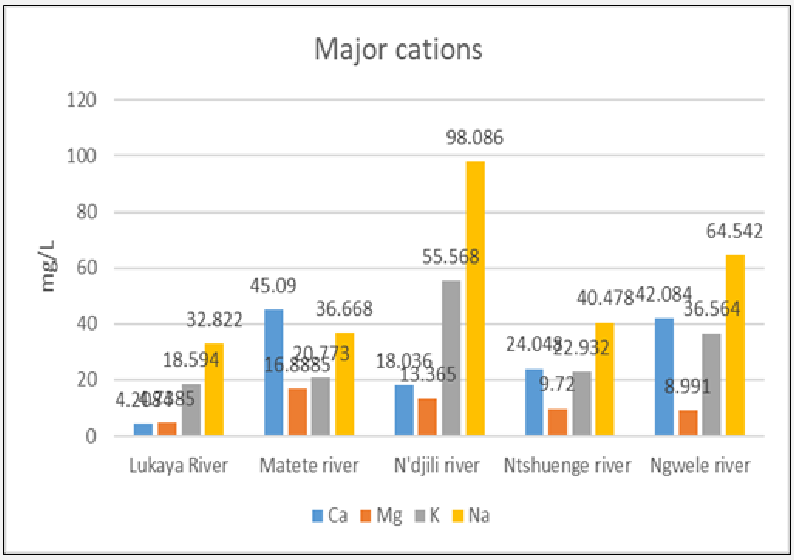

Figure 5. Major cation results for surface waters in the N'djili basin.

The main anions analyzed in the surface waters of the N'djili catchment include chloride (Cl-), sulfate (SO4^2-), bicarbonate (HCO3–), and nitrate (NO3-) ions. Figure 6 illustrates the results for these major anions across various water sampling points.

Chloride ion concentrations in the waters of Rivière N'djili ranged from 35.5 mg/L to 88.75 mg/L, averaging 60.35 mg/L. Although all sampling locations showed chloride levels below the WHO recommended values, considerable concentrations were observed in the Matete and Limete rivers, with levels of 71 mg/L and higher values up to 88.75 mg/L in Rivière Ngwele. In contrast, the Lukaya, N'djili, and Masina rivers displayed lower to medium chloride levels, with measurements of 53.25 mg/L in both Lukaya and N'djili, and 35.5 mg/L in Masina.

Sulfate ion concentrations across the catchment varied from 13.23 mg/L to 68.99 mg/L, with an average of 34.84 mg/L, maintaining levels below WHO guidelines. Specific measurements included 13.23 mg/L in the Lukaya River, 35.37 mg/L in the Matete River, and the highest concentration of 68.99 mg/L in the N'djili River. The Ntshuenge and Ngwele Rivers showed sulfate concentrations of 13.50 mg/L and 43.12 mg/L, respectively.

Bicarbonate levels in the catchment's surface waters ranged broadly from 0 to 32.94 mg/L, averaging 15.13 mg/L. Notably, the WHO has not established specific limit values for bicarbonate concentrations.

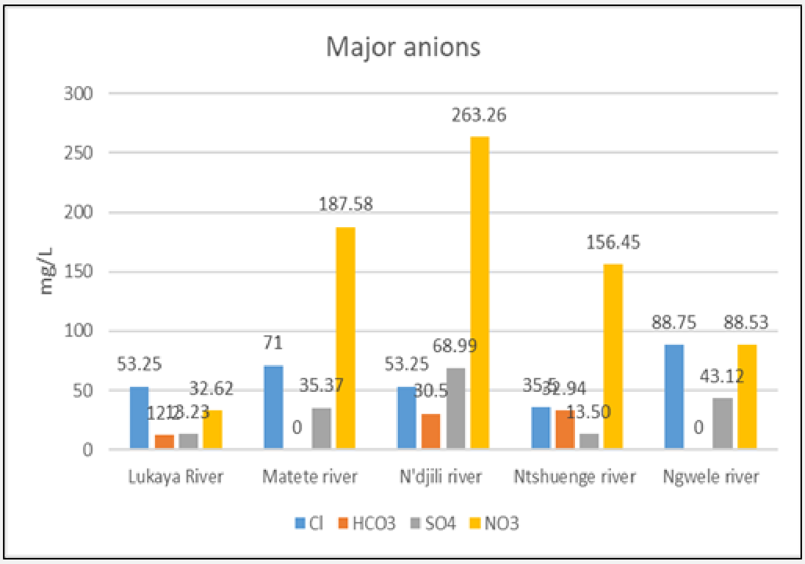

Figure 6. Major anions results for surface waters in the N'djili basin.

Lead (Pb), cadmium (Cd), and arsenic (As) were the trace metals analyzed in the surface waters of the N'djili watershed. The detailed results for these metals, broken down by sampling point, are illustrated in Figure 7.

Lead concentrations ranged from 0.058 mg/L to 0.081 mg/L, with an average of 0.066 mg/L, significantly exceeding WHO standards. Specific lead concentrations were 0.063 mg/L in the Lukaya River, 0.081 mg/L in the Matete River (the highest recorded), 0.058 mg/L in the N'djili River (the lowest recorded), 0.061 mg/L in the Ntshuenge River, and 0.065 mg/L in the Ngwele River. Cadmium concentrations varied from 0.003 mg/L to 0.013 mg/L, with an average of 0.006 mg/L, all above WHO standards.

The highest cadmium concentration was 0.013 mg/L in the Matete River, while the lowest was 0.003 mg/L in the Lukaya River. Other concentrations were 0.004 mg/L in the N'djili and Limete Rivers and 0.003 mg/L in the Masina River. Arsenic concentrations were alarmingly high, ranging from 0.063 mg/L to 0.461 mg/L, with an average of 0.310 mg/L, well above WHO standards. Specific arsenic levels were 0.293 mg/L in the Lukaya River, 0.461 mg/L in the Matete River (the highest recorded), 0.356 mg/L in the N'djili River, 0.063 mg/L in the Ntshuenge River (the lowest recorded), and 0.377 mg/L in the Ngwele River.

All sampling points exhibited concentrations that exceed the WHO recommended limits. Additionally, groundwater samples have revealed high concentrations of these heavy metals, which are often linked to industrial, urban, and agricultural activities. The presence of these metals represents a potential risk to human health and the integrity of the aquatic ecosystem.

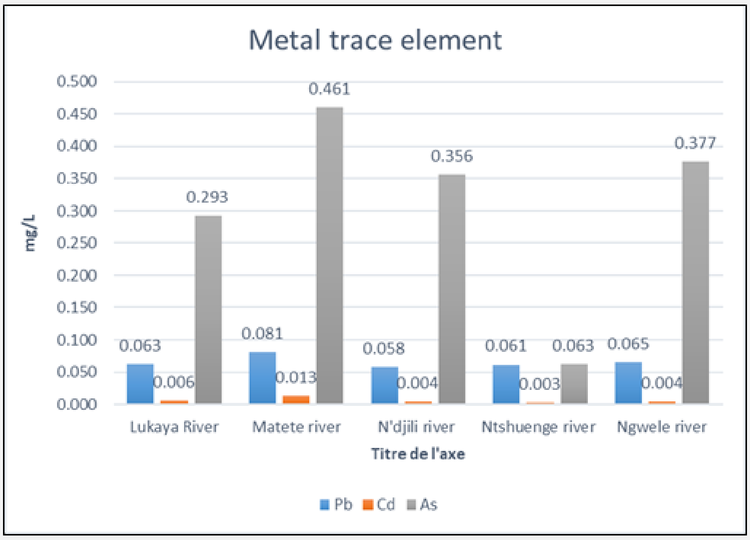

Figure 7. Results for trace metals in surface waters of the N'djili basin.

Calculation of Trace Metal Pollution Indices in Surface Waters of the N'djili Basin

Contamination Factor, Degree of Contamination and Heavy Pollution Index

The pollution indices presented in Table 6 show different average values. Analysis of this table reveals high Pb contamination of surface waters in the N'djili river basin, with an average contamination factor of 65.66. There is also moderate Cd contamination, with an average contamination factor of 1.99, and high As contamination, with an average contamination factor of 309.74.

The degree of contamination (Dc), used as a reference to assess the intensity of water contamination, indicates a high degree of contamination of surface waters in the N'djili basin, with a calculated mean value of 377. According to research by Edet & Offiong (2002), Yari & Sobhanardakani (2016), El-Hamid & Hegazy (2017), these values indicate high contamination. The results for the degree of contamination (Dc), broken down by sampling point, are shown in Figure 8.

Applying the HPI to surface waters in the N'djili river watershed to assess their pollution level reveals significant pollution of these waters, with an average value of 102.98. According to Prasad et al. (2014), this value exceeds the critical threshold for the heavy metal pollution index. Figure 9 shows the results of the trace metal pollution index (HPI) based on the different surface water sampling points. More specifically, the waters of the Matete River were found to be heavily polluted, with a calculated HPI value of 225.42. The HPI value obtained in the waters of the Lukaya River was 98.21, approaching the critical value of 100 defined by Prasad et al. (2014). The other HPI values obtained in the waters of the N'djili, Masina and Limete rivers are relatively low to medium. These calculated HPI values are 67.73 for N'djili River waters, 47.04 for Ntshuenge River waters and 76.48 for Ngwele River waters, respectively. The various sampling points according to degree of contamination and pollution level are listed in Table 7. Analysis of this table reveals that all surface water sampling points in the N'djili basin show a high degree of contamination. As far as HPI is concerned, only the waters of the Matete river show high pollution, while the other waters show low pollution.

Pollution indices such as contamination factor, degree of contamination and heavy metal pollution index indicate a significant deterioration in surface water quality. This pollution is mainly due to industrial discharges, intensive agricultural practices and unregulated urbanization. These activities contribute to water pollution and compromise the health of aquatic ecosystems.

Table 6. Contamination and Pollution Indices for Trace Metals (HPI and Cd) in Surface Waters in the N'djili River Basin

Statistic parameters	Heavy Pollution index	Contamination degree
Min	47.04	124.83
Max	225.42	546.22
Mean	102.98	377.40
Standard deviation	48.98	108.96

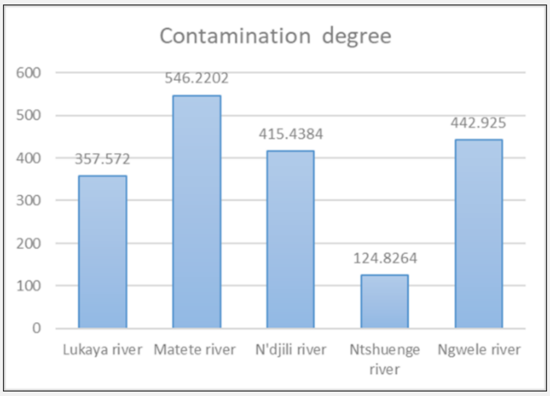

Figure 8. Level of heavy metal contamination in surface waters of the N'djili river watershed.

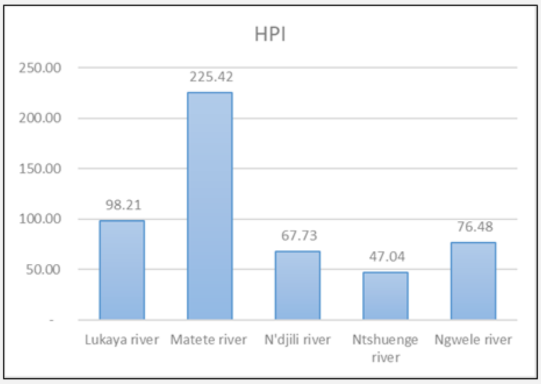

Figure 9. Heavy metal pollution index in surface waters of the N'djili river watershed.

Table 7. Classification of Surface Water Quality in the N'djili Basin According to Modified Pollution Index Categories

Indices	Classification	Degree of contamination and pollution	Number of samples	Station names
Degree of contamination	< 1	Low		
	1–3	Moderate		
	> 3	High	5	Lukaya river, Matete river, N'djili river, Ntshuenge river, Ngwele river
Heavy Pollution index	< 100	Low	4	Lukaya river, N'djili river, Ntshuenge river, Ngwele river
	= 100	Moderate		
	> 100	High	1	Matete river

Correlation between Trace Metals and the Trace Metal Pollution Index

The relationship between lead (Pb), cadmium (Cd), arsenic (As), and surface water pollution in the N'djili basin was analyzed using Pearson's correlation coefficient. This statistical analysis, represented in a correlation matrix shown in Table 8, focuses on understanding how these trace metals individually and collectively influence the Heavy Metal Pollution Index (HPI), a key indicator used to assess trace metal pollution in surface waters.

Table 8 reveals strong correlations between Pb and Cd with the HPI, showing Pearson correlation coefficients of 0.96 for Pb and 0.98 for Cd. These high values indicate that both lead and cadmium significantly impact the HPI, reflecting their strong contributions to overall trace metal pollution. Additionally, when considering pairwise relationships among the trace metals themselves, Pb and Cd are strongly correlated with a coefficient of 0.94, suggesting a potential common source or similar pathways of contamination. The correlation between Pb and As is less pronounced but still moderate, with a coefficient of 0.57, while Cd and As show a correlation of 0.67.

Table 8. Correlation matrix between trace metals and trace metal pollution index

	Pb	Cd	As	HPI
Pb	1			
Cd	0.94	1		
As	0.57	0.67	1	
HPI	0.96	0.98	0.68	1

The overall high correlation observed particularly between Pb and Cd not only underscores their significant roles in influencing the pollution levels measured by the HPI but also suggests that these metals might share common pollution sources within the watershed. This analysis aids in pinpointing primary contaminants and understanding their interactions within the aquatic environment, which is crucial for targeted remediation and pollution control efforts.

DISCUSSION

The average pH of surface water in the N'djili river basin is 6.9, indicating slight water neutrality (Rodier et al., 2016). It is important to note, however, that this pH value is within the range recommended by the WHO (WHO, 2013). As such, these waters present no danger to fish survival. According to HCEFLCD (2006), the tolerance threshold for fish survival in water generally ranges from 5.5 to 8.5. Similar studies were carried out by Nsiala (2012) and Konunga et al. (2018) on the waters of the Lukaya and N'djili rivers. The results of Konunga et al. (2018) show that the waters of the Lukaya River have an average pH of 6.7, a higher value than that found in this study. It should be noted that the water in the Lukaya River has become acidic over time, due to the presence of mineral or organic acids in natural waters, according to Rodier et al. (2016). Studies by Nsiala (2012) on the waters of the N'djili River show conformity of pH values (7) with the pH value found in this study (7.1).

Measurements of electrical conductivity (EC) and total dissolved solids (TDS) revealed that surface waters in the studied basin were low mineralized and moderately mineralized. Nsiala (2012) and Konunga et al. (2018) also reported similar concentrations of electrical conductivity (EC) and total dissolved solids (TDS) in the waters of the Lukaya and N'djili rivers. The findings of the study conducted by Konunga et al. (2018) highlighted electrical conductivity levels below 23 μS/cm and total dissolved solids concentrations below 13 mg/L in the waters of the Lukaya River. Similarly, results published by Nsiala (2012) for the waters of the N'djili River showed that measured conductivity values were below 100 μS/cm. What's more, N'djili waters are low in dissolved mineral elements, as the average TDS (total dissolved solids) is lower than the global (100 mg/L) and African (± 60 mg/L) average for river waters (Nitu, 2018). The threshold mentioned represents no risk to drinking water or fish survival, given that the tolerable threshold is set at 500 µS/cm (Konunga et al., 2018).

Concentrations of heavy metals such as lead, cadmium and arsenic in the surface waters of the N'djili basin far exceed the drinking and irrigation standards set by the WHO and FAO. These waters present a danger for human consumption, agricultural use and aquaculture (HCEFLCD, 2006; WHO, 2013; FAO & WHO, 2013). Comparable studies have been carried out on the N'djili River, a few meters from our study area (Nitu, 2018). In 2005, trace metal concentrations were measured downstream and upstream of a market gardening site, both in the rainy and dry seasons. Downstream trace metal element concentrations during the rainy season were measured at 0.264 mg/L for lead and 0.122 mg/L for cadmium. In the dry season, trace metal element concentrations were measured at 0.239 mg/L for lead and 0.132 mg/L for Cadmium. Upstream trace metal element concentrations in the wet season gave respective values of 0.347 mg/L for lead Pb and 0.184 mg/L for Cadmium. In the dry season, trace metal concentrations gave respective values of 0.162 mg/L for lead Pb and 0.108 mg/L for Cadmium (Nitu, 2018). UNEP (2011), measured the concentration of trace metal elements in raw water sampled at the REGIDESO station on the N'djili River. According to their findings, trace metal concentration values in filtered samples gave 0.002 mg/L for arsenic, 0.0016 mg/L for lead and < 0.001 mg/L for cadmium. In unfiltered samples, trace metal concentration values gave 0.0021 mg/L for arsenic, 0.0015 mg/L for lead and < 0.001 mg/L for cadmium. A study of another section of the N'djili River revealed lead concentrations in the water of up to 0.00317 mg/L (Lumbuenamo et al., 2010), well above the previously mentioned limit for this element in drinking water. These values are as high as those found in this study in the waters of the N'djili River (0.061 mg/L for lead, 0.004 mg/L for cadmium, 0.356 mg/L for arsenic). Industrial emissions and waste from certain industries and factories, such as metallurgical and chemical plants, contain lead, cadmium and arsenic. For example, the Ngwele River in the industrial zone of Limete commune receives effluent from steel bar manufacturing plants, as well as effluent from paint manufacturing plants. In other cases, the use of pesticides and chemical fertilizers containing lead, cadmium and arsenic can lead to an accumulation of these heavy metals in the soil and their subsequent transfer to cultivated plants. The Lukaya and N'djili rivers are therefore close to large-scale agricultural plantations. In urban areas such as those drained by the Matete and Ntshuenge rivers, sources of arsenic, lead and cadmium come from a variety of sources, including old paint containing these metals used in buildings, plumbing systems containing products based on these metals, vehicle exhaust emissions, industrial waste and landfill sites containing heavy metal residues, and the past use of pesticides and fertilizers containing these metals in urban green spaces.

Trace metal pollution in the N'djili River has had several consequences, including contamination of fish in the N'djili River, similar to what occurs at the Malebo pool on the river, with high levels of lead (Pb) and cadmium (Cd) (Nsimanda et al. 2015), even leading to fish mortality. In addition, the soils of rice plots can be contaminated by trace metals during floods, as can rice crops exposed to these elements. Long-term exposure to lead, cadmium and arsenic can have adverse effects on human health. These heavy metals can accumulate in body tissues, causing health problems such as neurological disorders, kidney problems, immune system disorders and even cancer.

The application of principal component analysis highlighted the correlation between Pb, Cd, As and HPI. The association of certain metallic trace elements taken in pairs showed significant correlations. The strong link between lead (Pb) and Cd (0.94) suggests similar input sources and similar geochemical behavior, as reported by Lu et al. (2010) and Saeedi & Salmanzadeh (2012). The strong correlations between HPI and lead (0.96) and HPI and cadmium (0.98) indicate that lead and cadmium are the main contributors to surface water pollution in the N'djili river basin. The hydrogeochemical process responsible for the incorporation of these elements is associated with human activities, particularly those linked to agro-industry. According to Levallois & Phaneuf (1992), Akil et al. (2014), and Yuan et al. (2017), human activities such as the use of chemical fertilizers, effluent discharge from chemical and metallurgical industries, household waste deposits and incineration, and domestic effluents are the main sources of production of these trace metal elements. Identifying the high degree of contamination and the high heavy metal pollution index has enabled us to target the most problematic areas and sources of contamination, namely the area drained by the Matete River. This can alert health authorities to areas where the population is exposed to an increased risk of heavy metal poisoning.

CONCLUSION

This study examines heavy metal pollution of surface waters in the N'djili river watershed, providing an overview of contamination levels and their spatial variability. The results show high levels of contamination at all sampled sites: Lukaya river, Matete river, N'djili river, Ntshuenge river, Ngwele river as well as the high heavy metal pollution index specifically located in the Matete river site. The most polluted sites are generally located near urban and agro-industrial areas. Industrial activities, such as the production and processing of steel bars, as well as the use of pesticides and fertilizers containing heavy metals, are identified as potential sources of pollution. In addition, domestic discharges and untreated urban waste also contribute to pollution. This analysis highlights the need to control and regulate these sources in order to reduce surface water contamination.

High levels of heavy metal pollution in the waters of the N'djili River pose potential risks to human health and the environment. Heavy metals have the capacity to accumulate in the tissues of living organisms, leading to adverse effects such as neurological disorders, kidney disease and immune system problems in humans. In addition, surface water pollution can disrupt aquatic ecosystems and biodiversity, while impacting soil quality, compromising agricultural productivity and food security.

It is important to note that this study has certain limitations. The temporal scope of sampling may not reflect seasonal variations in pollution. In addition, the range of pollutants tested may be limited and may not cover all the heavy metals of concern. These limitations may influence the results and underline the need for continuous monitoring to fully assess the extent of pollution and its evolution over time. For future research, it would be beneficial to conduct longitudinal studies to assess seasonal variations in pollution and their effects on aquatic ecosystems. Studies on the bioaccumulation of heavy metals in local flora and fauna would deepen our understanding of the ecological effects of pollution. In addition, it would be interesting to explore the effectiveness of different pollution mitigation strategies, such as the decontamination of industrial sites and the adoption of sustainable agricultural practices.

Metal pollution in the surface waters of the N'djili river catchment shows high levels of contamination, highlighting potential sources of pollution. This highlights the risks to public health and the environment. Despite certain limitations, this study provides important information for environmental management and policy development aimed at reducing pollution and protecting ecosystems as well as human health. Future research is needed to deepen our understanding of pollution and to develop effective mitigation and prevention strategies.

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