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Developing an approach for balancing water use and protecting water quality of an urban river ecosystem

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ABSTRACT

Urban stream syndrome is a growing phenomenon in tropical part of the world. Urban rivers face significant challenges due to pollution induce by anthropogenic activities, exacerbated by population growth and industrialization. The main objective of this study is to develop a generic approach to balance water use and the protection of water quality in urban rivers. Water quality physico-chemical assessments were conducted during the dry and rainy seasons at various points along the N'Djili River and its tributaries. Anthropogenic activities in the surrounding areas were also analyzed to determine water uses from each sampling site. Sites were classified based on their pollution level using multivariate analysis and hierarchical classification into management classes. The water quality assessment results have shown a physico-chemical pollution of the urban rivers water, with the tributaries being the most polluted. Three main water uses were determined namely: industrial, agricultural, and domestic water uses. The sites were placed into distinct management classes based on their pollution level and the interventions needed to protect them. This study contributes valuable insights for protecting and enhancing urban river ecosystems. The approach developed in this study is useful as it can be applied elsewhere, forming the basis of management decision on urban river system protection.

1. Introduction

Water is essential for the survival of all living beings (Feitelson, 2012; Kılıç, 2020). It is therefore a non-substitutable resource. Ensuring its availability in time and space and its supply in sufficient quantity and quality is a matter of major concern both globally and locally in the context of a growing human population, industrial growth and climate change (Tzanakakis et al., 2020). Freshwater ecosystems are vital for maintaining the balance of our planet's biodiversity and supporting human livelihoods (Hughes et al., 2019; Reid et al., 2019). However, these ecosystems are facing numerous threats that jeopardize their sustainability on a global scale (Bashir et al., 2020; Albert et al., 2021). One of the primary challenges facing freshwater ecosystems is pollution induced by human population growth and industrial development (Kibena et al., 2014; Bunn, 2016).

According to United Nations estimates, on November 2022, the world global population surpassed 8 billion people (UN-DESA, 2022). In the last 25 years, there has been a 33% increase in human population, equivalent to 2.1 billion more individuals on Earth (UN-DESA, 2022). Projections suggest that human population will further expand by approximately one-fifth, reaching nearly 10 billion by around 2050, with the majority of this growth occurring in developing countries (Emi, 2019). The increasing urbanization can be attributed, in part, to the expansion of industrial activities that generated job opportunities, thereby drawing people to urban centers (Cohen 2006; Castro et al., 2021). Across the annals of human civilization, urbanization trends have predominantly emerged in close proximity to water sources (Larsen et al., 2016; Bai et al., 2017). Industrial and agricultural hubs in many cities are often strategically situated in close proximity to rivers and streams (Hammelman et al., 2022). This inclination stems from the

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essential role that waterways play as crucial resources benefiting human societies (Li et al., 2017). Many nations are currently grappling with the challenge of balancing water use and protecting the ecosystems that supply water for societies. Novel approaches are needed to ensure that water resources are use sustainably without compromising important ecosystem function and attributes.

The lower course of the N'Djili River catchment (NRC) situated in an urban area of Kinshasa city, capital of the Democratic Republic of Congo, DRC is impacted by anthropogenic pressure, resulting in the deterioration of its water quality. For example, a recent work conducted by (Sani et al., 2024) analyzed the relationship between land use categories and four key water quality variables at multiple buffer scale using sentinel 2 satellite imageries coupled with redundancy analysis in the NRC. They found that 70% of water quality parameters correlated with land use categories with urbanized area being the most significant explanatory variable at all buffer scales, negatively impacting water quality. Conversely, trees and range lands had positive impact on water quality. Their study concludes that further research is needed to assess the extent of water pollution and that there was a need to develop integrated management strategies for minimizing pollution in this catchment.

The main objective of the present study is to develop a generic approach to balance water use and the protection of water quality of urban river ecosystems. The peculiarity of this approach is that it can be widely adapted to different contexts. In developing the generic approach, we provide a comprehensive description of the various study sites and collected some urban indicators; assess the water physicochemistry of the selected sites; determine the relationship between different water uses and river water quality; and then define management classes and mitigation measures for each class.

We hypothesize that implementing an integrated targeted management approach can effectively balance urban river water use with the protection of water quality. This study demonstrates that a comprehensive understanding of an urban river water quality, the factors influencing it, and their interrelationships are crucial for developing management strategies adapted to urban contexts. Its findings contribute to the broader knowledge base on urban river systems, offering valuable insights for policymakers, environmental managers, and researchers working towards effective water management in similar contexts.

2. Material and methods

2.1. Study area presentation

The NRC spans nearly 2000 km^2 between 15°9′ and 15°39′ East longitude and 4°22′ and 4°59′ South latitude, from rural Madimba and Kasangulu to urban Kinshasa (Muteba, 2002). Human activities heavily impact the urban section, constituting 31.2% of the watershed, with market gardens, livestock farms, sand quarries, and construction sites, being the main drivers of water quality deterioration (Sani et al., 2024). The NRC experiences a hot, humid climate with eight months of rainy season and four months of dry season. The average annual precipitation is 1470 mm, evenly spread across the entire catchment (Kimfuta, 2013; Ndolo et al., 2015). The average altitude of the NRC is 439.58 m (Bwira 2017). Our study area (NRC lower course) is mainly located in Kinshasa city, which is situated in a low-lying region characterized by a relatively flat terrain with an average terrain elevation of approximately 284 m (DB-city, 2024). The N'Djili River is as major tributary of the Congo River, and it originates from the hills of the province of Kongo Central in the Democratic Republic of Congo (DRC), traversing the city of Kinshasa, and then joining the Congo River via the Malebo Pool (N'kaya et al., 2020). Fig. 1 below shows the study area and sampling sites.

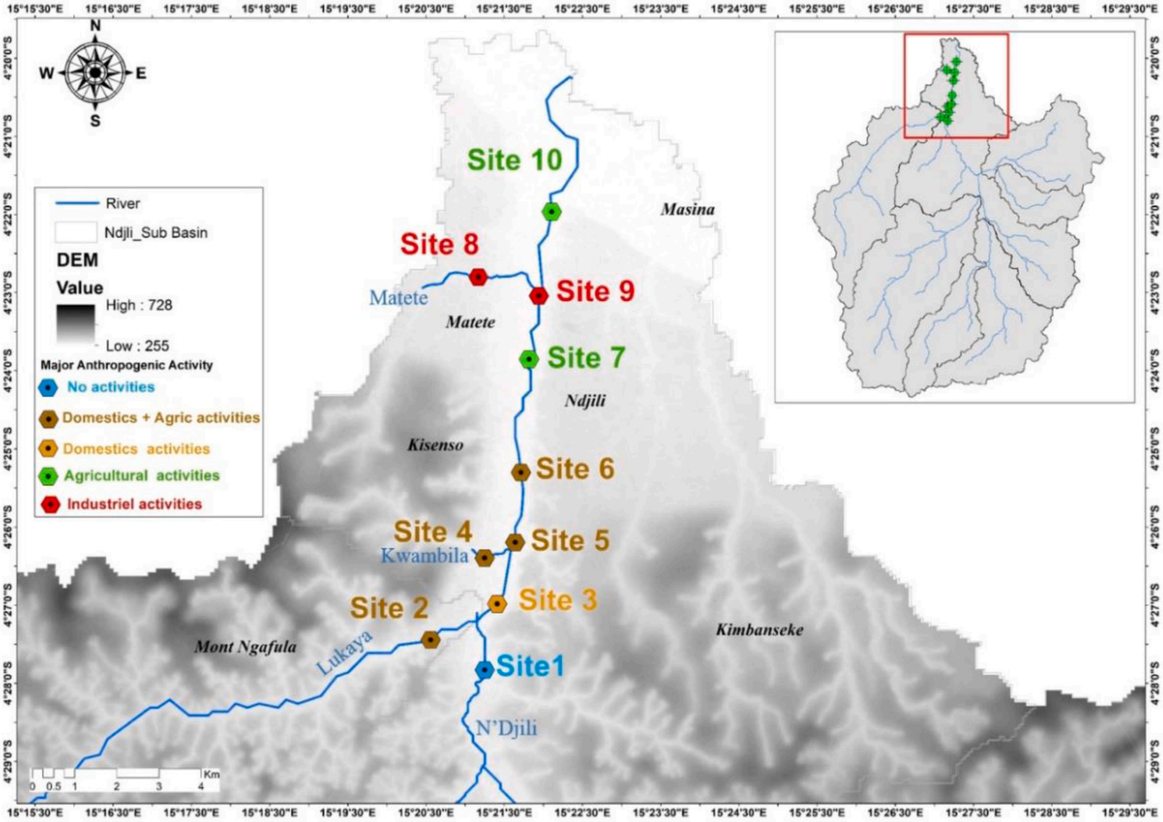


Fig. 1. Digital Elevation Model (DEM) of the NRC showing the sampling sites and main anthropogenic pressure/activities.

2.2. A summary of the developed approach

The approach comprises of five steps. In Step 1, the anthropogenic activities taking place along the river catchment were determined for an overview of the different types of water uses in the area. In Step 2, we assess the physico-chemical quality of the river sites. Water samples were taken during the dry and rainy seasons along N'Djili River and its major tributaries (Lukaya, Kwambila and Matete). The study followed a source to sink approach, starting from upstream point (source: less populated) and moving downstream towards the sink (most populated). In Step 3, we classified the sites based on their pollution levels. In Step 4, we define management classes following the classification in Step 3. In Step 5, we developed an integrated water quality management strategy following the two complementary approaches, resource directed measures and source directed controls, widely used in South Africa (Odume, 2022). The Resource directed measures (RDMs) are actions applied directed at the water resource to protect them. These are intended to protect water resources from over exploitation, and these may include the creation of a protection perimeter, regular monitoring of water quality, riparian buffer zone. The source directed controls are actions taken towards the sources of pollution along the river to minimize or eliminated their negative effects/impacts on the river ecosystem. Examples of source directed control actions may include improving the effluent quality of a wastewater treatment systems, imposing fines on polluters.

2.2.1. Anthropogenic activities and water uses

The study sites were selected, from a less populated area (Site 1) to a highly populated area (Site 9). Criteria such as accessibility, water uses, and proximity to sources of pollution e.g., sparsely populated areas, densely populated areas, presence of household waste, markets, gardening areas, pesticide use, animal breeding were considered when selecting the sites. The land use indicator percentages were determined based on Sani et al., (2024) using satellite imageries, a buffer scale approach and redundancy analysis.

2.2.2. Physico-chemical sampling and analysis

Four sampling campaigns were carried out through the dry and rainy seasons. The first campaign was carried out during the month of August 2022 corresponding to the long dry season; the second during the month of November 2022 corresponding to the long rainy season; the third during the month of February 2023 corresponding to the short dry season and the last campaign was done during the month of April 2023 corresponding to the short rainy season. Two water samples were collected per site for the hydro-chemical analysis which make a total of twenty samples for the ten sampling sites per campaign, and a total of 80 water samples for the four sampling campaigns. The water samples to be analyzed were taken in PET bottles according to the procedure described in the water analysis manual by Rodier and Legube (2009). Eighteen physico-chemical variables were measured. Five variables were measured in situ namely: the pH, the temperature (ºC) using a pH meter HANNA, dissolved oxygen (O_2) with a WTW oximeter, electrical conductivity (EC) with a conductivity meter HANNA and turbidity (Tb) using a turbid meter HANNA.

Thirteen variables were measured in laboratory namely: suspended matters (SM); oxidable matters (OM); five-day biological oxygen demand (BOD_5); chemical oxygen demand (COD); nitrites (NO_2^-); nitrates (NO_3^-); sulfates (SO_4^{2-}); ammonium (NH_4^+); phosphates (PO_4^{3-}); chlorides (Cl^-); alkalinity (TA-TAC); hydrometric title (THT); and total dissolved solids (TDS). (See Table S1 supplementary materials for the material and methods used for the laboratory analysis).

2.2.3. Sites classification

The sites were classified based on the pollution extent as indicated by the measured water quality variables. The sites classification was undertaken following a six-step process. These steps are (1) Assessing the river water quality, (2) Establishing the extent of the deviation of the site from the reference condition, (3) Running a MANOVA Multivariate analysis of variance to determine whether the site differed significantly from the reference site (4) Running two ways ANOVA in view to determine variables exhibiting significant differences, (5) Computing Principal Component Analysis PCA to see the strength of the contribution of each of the variables to the differences, (6) and finally computing hierarchical classification HC to see if they are sites which are replicated, that have similarities in terms of their water composition. XLSTAT life sciences 2023.2.0 software was used (Lumivero 2024).

2.2.4. Management classes

The sites were classified into management classes (MC) based on their deviation from the reference site (Site 1). Sani et al. (2024) have found that site 1 was positively correlated with Trees and Rangeland land use categories considered as natural environment indicator and negatively correlated with urbanized area. Site one in our study was then considered as control/reference site. The classification takes into approach current water uses and the need to protect the river system, thus balancing use and protection. The percentile method was adopted as summarized in Table 1.

3. Results

3.1. Anthropogenic activities and water uses

The summary of the site characterization and the predominant anthropogenic drivers of water quality deterioration are provided in Table 2 below.

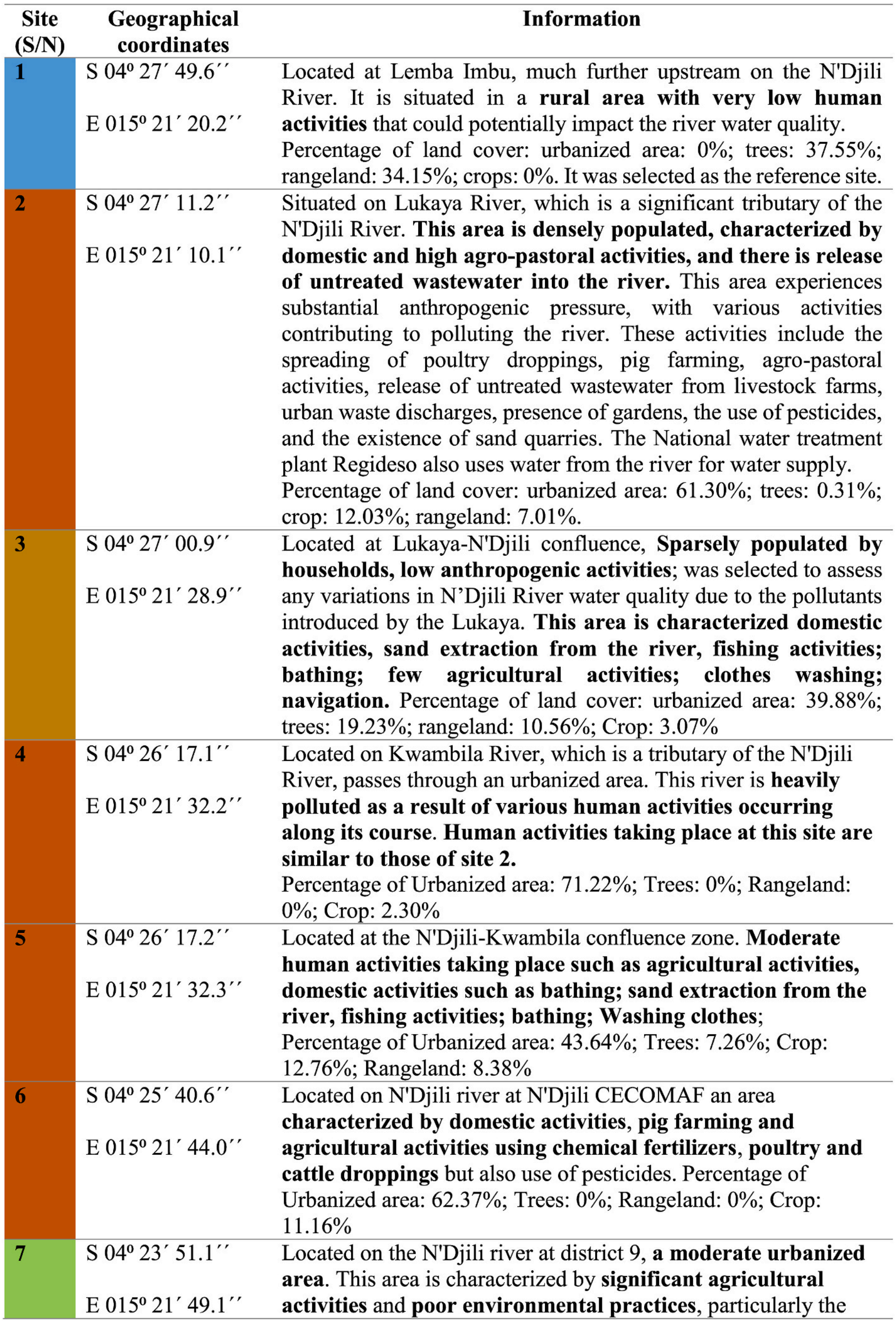
3.2. Descriptive analysis of the results

All temperature measurements where above the standard value 25 °C, rainy season temperatures tend to be higher (28.55 °C) than those of the dry season (27.51 °C). The temperatures recorded at sites located along the N'Djili River were found to be lower (< to 27.7 °C) compared to those recorded at its tributaries. The highest temperatures were recorded at Site 4 corresponding to Kwambila River (32.47 °C) followed by Sites 8 (29.30 °C) and 2 (27.9 °C). The (O_2) in the study area was very poor. Although all the O_2 measured values were below 6 mg/L, Site 1 as control site recorded the highest value (6.05 mglO_2/L). Indeed, dry season oxygen level was found to be slightly higher than those recorded during the raining season. Conductivity measurements taken during the

Table 1
A summary of the management classes.

Management class	Percentile	Description
MC 1	5th	Water quality data is similar to those of the reference site. Impact on water quality is very minimal and should be accorded high protection level to maintain ecosystem integrity and to serve as refugia.
MC 2	15th	A minimal deviation from the reference site. Low impact on water quality. High protection level to maintain ecological integrity and to serve as refugia.
MC 3	50th	A moderate deviation from the reference site. Noticeable water quality impact. Measures should be taken to ensure that key ecosystem function are maintained.
MC 4	75th	A serious deviation from the reference site. High, unacceptable water quality impact. Measures must be taken to move the site to MC3 at least.
MC 5	95th	A critical deviation from the reference site. Very high and extremely unacceptable water quality impact. Measures must be taken to improve the site to the condition of MC3 at least.

Table 2
Sites characterization.



Site (S/N)	Geographical coordinates	Information
1	S 04° 27′ 49.6′′ E 015° 21′ 20.2′′	Located at Lemba Imbu, much further upstream on the N'Djili River. It is situated in a **rural area with very low human activities** that could potentially impact the river water quality. Percentage of land cover: urbanized area: 0%; trees: 37.55%; rangeland: 34.15%; crops: 0%. It was selected as the reference site.
2	S 04° 27′ 11.2′′ E 015° 21′ 10.1′′	Situated on Lukaya River, which is a significant tributary of the N'Djili River. **This area is densely populated, characterized by domestic and high agro-pastoral activities, and there is release of untreated wastewater into the river.** This area experiences substantial anthropogenic pressure, with various activities contributing to polluting the river. These activities include the spreading of poultry droppings, pig farming, agro-pastoral activities, release of untreated wastewater from livestock farms, urban waste discharges, presence of gardens, the use of pesticides, and the existence of sand quarries. The National water treatment plant Regideso also uses water from the river for water supply. Percentage of land cover: urbanized area: 61.30%; trees: 0.31%; crop: 12.03%; rangeland: 7.01%.
3	S 04° 27′ 00.9′′ E 015° 21′ 28.9′′	Located at Lukaya-N'Djili confluence, **Sparsely populated by households, low anthropogenic activities**; was selected to assess any variations in N'Djili River water quality due to the pollutants introduced by the Lukaya. **This area is characterized domestic activities, sand extraction from the river, fishing activities; bathing; few agricultural activities; clothes washing; navigation.** Percentage of land cover: urbanized area: 39.88%; trees: 19.23%; rangeland: 10.56%; Crop: 3.07%
4	S 04° 26′ 17.1′′ E 015° 21′ 32.2′′	Located on Kwambila River, which is a tributary of the N'Djili River, passes through an urbanized area. This river is **heavily polluted as a result of various human activities occurring along its course**. **Human activities taking place at this site are similar to those of site 2.** Percentage of Urbanized area: 71.22%; Trees: 0%; Rangeland: 0%; Crop: 2.30%
5	S 04° 26′ 17.2′′ E 015° 21′ 32.3′′	Located at the N'Djili-Kwambila confluence zone. **Moderate human activities taking place such as agricultural activities, domestic activities such as bathing; sand extraction from the river, fishing activities; bathing; Washing clothes**; Percentage of Urbanized area: 43.64%; Trees: 7.26%; Crop: 12.76%; Rangeland: 8.38%
6	S 04° 25′ 40.6′′ E 015° 21′ 44.0′′	Located on N'Djili river at N'Djili CECOMAF an area **characterized by domestic activities**, **pig farming and agricultural activities using chemical fertilizers**, **poultry and cattle droppings** but also use of pesticides. Percentage of Urbanized area: 62.37%; Trees: 0%; Rangeland: 0%; Crop: 11.16%
7	S 04° 23′ 51.1′′ E 015° 21′ 49.1′′	Located on the N'Djili river at district 9, **a moderate urbanized area**. This area is characterized by **significant agricultural activities** and **poor environmental practices**, particularly the

🟩		indiscriminate disposal of various types of waste into the N'Djili river. Percentage of Urbanized area: 36.21%; Trees: 9.30%; Rangeland: 1.27%; Crop: 40.98%
🟥 **8**	S 04º 22′ 49.1′′ E 015º 21′ 10.2′′	Located on Matete River, one of N'Djili tributaries, in **a highly urbanized area with high population density and industries**, this river is **heavily polluted due to the spillage of effluents from the national water treatment plant Regideso**. Additionally, **direct discharges of garbage and untreated wastewater from industries, households, sewer pipes and septic tanks flow directly into the river** (Munduki), exacerbating the pollution levels. Percentage of Urbanized area: 99.95%; Trees: 0%; Rangeland: 0%; Crop: 0%
🟥 **9**	S 04º 22′ 57.1′′ E 015º 21′ 52.4′′	Located in **a highly urbanized area with high population density**, **presence of industries**, on N'Djili river just before Regideso water treatment catchment site, as the National water treatment plant Regideso also uses water from this river for water supply, we observed the **discharge of untreated sewage and solid waste from household** direct discharges of garbage and untreated wastewater from industries into the river. Percentage of Urbanized area: 99.99%; Trees: 0%; Rangeland: 0%; Crop: 0%
🟩 **10**	S 04º 21′ 58.0′′ E 015º 22′ 06.5′′	Located at N'Djili-Congo River confluence, **characterize by high agricultural activities,** and **poor environmental practices**, particularly the indiscriminate disposal of various types of waste into the N'Djili River. Selected to determine the contribution in pollutant load from N'Djili river to the large Congo River. Percentage of Urbanized area: 28.89%; Trees: 0%; Rangeland: 8.09%; Crop: 31.66%

Colors meaning: Each color designates the major anthropogenic activity carried out at the site, contributing to its water pollution. Blue: no anthropogenic activities; Dark Brown: domestic + agricultural activities; Light brown: domestics activities; Red: industrial activities; Green: agricultural activities.

rainy season were higher than those of the dry season with the exception of Site 8. Sites 4, 8 and 10 recorded the highest conductivity level (Figure s1 supplementary material). Rainy season BOD_5 values were higher than those recorded for the dry season. From the ten studied sites, seven sites all located along N'Djili River had a BOD_5 values inferior to 5 mg/L, these are sites 1, 3, 5, 6, 7, 9 and 10. Three sites recorded a BOD_5 values greater than 5 mg/L, these are sites 2, 4 and 8, all located on N'Djili River tributaries, namely Lukaya, Kwambila and Matete (see Fig. S1 supplementary materials for more details).

3.3. *Sites classification results*

Table S2 of the supplementary materials gives a summary of the descriptive statistical analysis findings.

3.3.1. *MANOVA analysis*

Fig. 2 below shows the mean of all water quality variables per study site. Sites 2, 4 and 8 stood out as they had the highest means for the Turbidity (Tb), Suspended matters (SM), Electrical conductivity (EC), Chemical oxygen demand (COD), Total dissolved oxygen and chlorides (Cl^-), Temperature (°C), Ammonium (NH_4^+), Biological oxygen demand (BOD_5) and (NO_3^-). These variables were different statistically different between the sites.

Table 3 below shows the results of the Wilks Lambda test. In this test, the lower the Lambda associated to an explanatory variable, the more important the effect of this variable is on the dependent variable

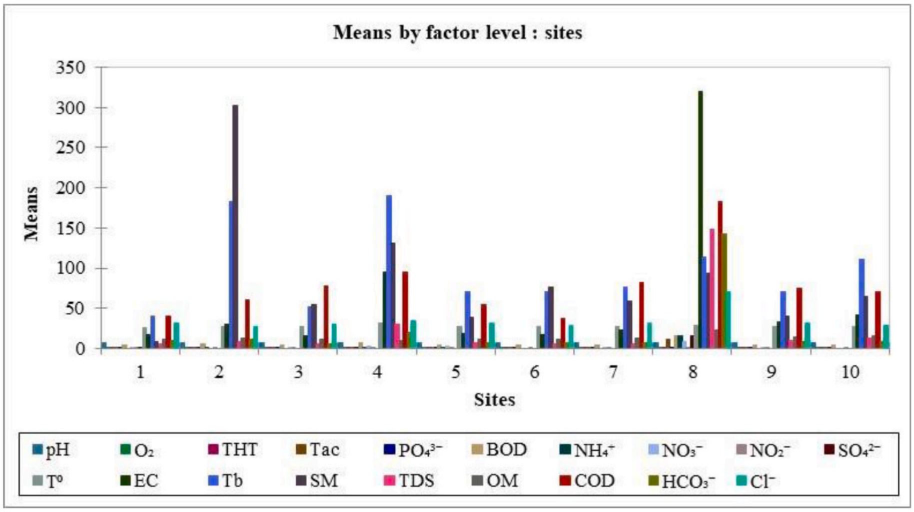


Fig. 2. Mean water quality variables recorded for the sampling sites in the N'Djili River over the study period.

Table 3
Wilks Lambda test results.

	Sites
Lambda	0.000
F Observed values	4.276
DF1	171
DF2	116
F Critical value	1.330
p-value	**<0.0001**

combination. Here the computed p-value is lower than the significance level alpha = 0.05.

3.3.2. *Two-ways ANOVA analysis*

Table 4 below is showing a classification of the study sites in terms of the pollution level. Site 8 recorded the highest level of BOD_5, NH_4^+, NO_3^-, EC, TDS, COD, and the lowest level of dissolved oxygen, followed by site 4 and 2, all of them are N'Djili River tributaries. Site 1 the control site recorded the highest level of dissolved oxygen. Followed by site 6 and 3.

Table 5 below shows the variables exhibiting significant differences between the sites. The P values of the ANOVA test are associated with F statistics and its significance for each variable. The P values of the BOD_5, NH_4^+, T, EC, TDS and COD are lower than 0.05.

3.3.3. *Principal component and ascendant hierarchical analysis results*

The eigenvalues of the PCA show that axes F1 and F2 represent 87.22% of the total inertia (see Table 4 supplementary materials). These two axes (F1 and F2) are largely sufficient to represent the global information. The study will focus on variables that have a significant contribution to the factor axes in order to facilitate the understanding of the source of variability explained by each axis. BOD_5, COD, TDS, EC, NH_4^+, NO_3^-, Temperature are positively correlated to axis F1 (Fig. 3A and B). It can therefore be described as the pollution axis. Turbidity is positively correlated to axis F2 described as the surface runoff axis. The principal component analysis helped us to determine three typologies of sampled waters in our study area (Fig. 3 C).

Group 1: Made of site 8 (Matete) characterized by mineralized, highly polluted water. The correlation between TDS and electrical conductivity with COD and BOD_5 shows that these are mainly controlled by the major element contents. This river waters are heavily polluted due to activities taking place in its surroundings (See Table 2).

Group 2: Site 1, 3, 5, 6, 7, 9 and 10 situated along N'Djili River, these sites waters are particularly low in terms of variables concentrations. They are of low pollution level compare to site 8, 4 and 2.

Group 3: corresponding to Site 2 (Lukaya) and 4 (Kwambila) corresponding to high turbid waters. This area is characterized by agro-pastoral activities and by soil surface runoff and erosion. This is confirmed by high concentration in NO_3^-, NH_4^+ and BOD_5.

The Agglomerative Hierarchical Clustering provides additional information about the process of site classification. In Fig. 3C below, the dotted line represents the point at which the clusters are automatically split, resulting in three distinct clusters. The first cluster (shown in green) is more homogeneous compared to other clusters which partitions were done by pair, except for cluster 3 made by site 8. Sites 2 and 4; 5 and 6; 7 and 9 are grouped into pairs, indicating similarities in their water physico-chemical qualities.

3.4. *Sites classification into management classes*

The management classes were calculated based on the deviation of the monitoring sites from the control site using percentile distribution. These were then further validated using PCA and the cluster analysis. All of these analysis corroborated each other, indicating the validity of the approach followed. Site 1, as a control site, was placed in MC 1. Sites 3 and 10, minimally impacted, were attributed to MC 2. Sites 5 and 6, moderately impacted, were attributed to MC 3. Sites 2, 4, 7, and 9, highly impacted, were attributed to MC 4. Finally, site 8, maximally highly impacted was attributed to MC 5.

4. Discussion

The temperature of surface waters essentially depends on the ambient environment. Our study area is located in the city of Kinshasa, which has a hot and humid tropical climate (AW4). This explains the high-water temperature values (>25) measured in the study area. This climate also includes a 4-month dry winter season from mid-May to mid-September, which explains the variation recorded between the dry and rainy season water temperature. During the dry season, the ambient air is cooler, and consequently, the temperature of river waters tends to be lower. The results obtained are quite similar to those obtain by Akatumbila et al. (2016) who worked on the evaluation of physico-chemical quality of Gombe River water in Kinshasa, the temperature values they recorded were higher than the standard (25 °C) and the rainy season values were slightly higher (26.15 °C) than dry season ones (25.05 °C). The observed variation between sampling sites is due to the local specifics human activities taking place at each sites as describe in Table 1, but as said earlier the temperature essentially depends on the ambient environment for surface water and cannot be correlated with any dynamics of pollutants in the river. But it is important to know that it influences the dissolved oxygen content and the multiplication of aquatic organisms.

Table 4
Sites classification in terms of pollution level. (Use color when printing).

Site	O_2	BOD_5	NH_4^+	NO_3^-	T	EC	Tb	SM	TDS	COD
8	0.375	16.000	16.500	9.225	29.300	319.855	113.725	93.250	147.750	182.500
4	0.425	7.750	0.285	2.575	32.475	95.538	190.475	131.750	31.075	95.000
2	0.275	5.750	0.117	0.000	27.950	30.420	182.825	302.500	9.138	60.000
7	0.550	4.000	0.000	1.175	27.625	22.923	76.450	58.750	6.365	82.500
5	0.675	4.250	0.012	3.250	27.625	19.490	70.700	39.000	7.308	55.000
9	0.475	4.750	0.000	0.075	27.325	33.178	70.075	41.000	10.103	75.000
10	0.250	4.500	0.000	0.000	27.075	41.230	111.575	64.500	12.725	70.000
6	0.725	4.750	0.000	0.000	27.700	17.900	70.225	77.000	5.260	37.500
3	0.700	4.500	0.000	0.850	27.100	15.273	52.500	55.000	5.278	77.500
1	6.050	4.500	0.000	1.000	26.150	16.855	40.050	9.000	5.300	40.000

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High Low

Table 5
ANOVA test P values and variables exhibiting significant differences between the sites.

	O_2	BOD_5	NH_4^+	NO_3^-	T°	EC	Tb	SM	TDS	COD
Pr > F(Model)	0.104	**0.050**	**<0.0001**	0.126	**<0.0001**	**0.004**	0.140	0.107	**0.029**	**0.015**
Significant	No	**Yes**	**Yes**	No	**Yes**	**Yes**	No	No	**Yes**	**Yes**

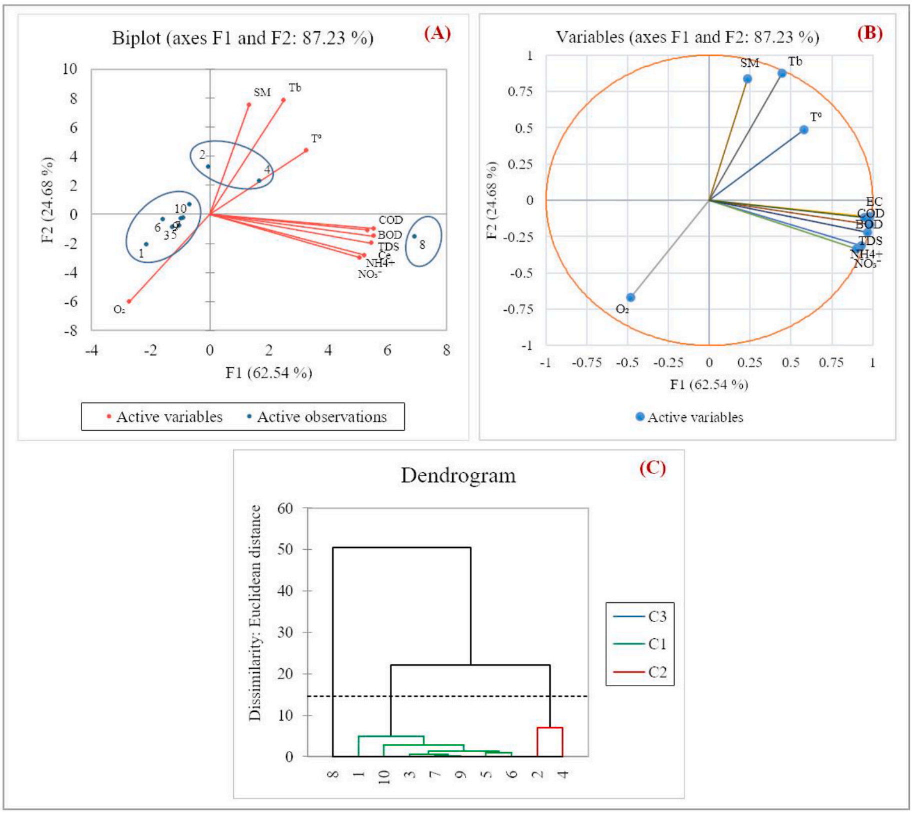

Fig. 3. PCA results: (A) factorial map of studied parameters; (B) circle of correlation and (C) Sites hierarchical clustering. (Use color when printing).

The poor dissolved oxygen levels observed in our study area are due to the combined effect of water temperature and the anthropogenic activities using river water. Higher temperatures can increase the metabolic rates of aquatic organisms, including microorganisms which leads to higher consumption of dissolved oxygen by these organisms for their respiratory processes. The different anthropogenic activities taking place in our study area describe in Table 2 have profound relationship with the low oxygen level through nutrient loading and organic pollution. Untreated sewage and solid waste disposal introduce organic matter and nutrients like nitrogen and phosphorus into river water. These nutrients fuel algal blooms, whose subsequent decomposition consumes oxygen, leading to hypoxic conditions. Agricultural runoff containing fertilizers and pesticides exacerbates nutrient inputs, further promoting algal growth and oxygen depletion. Domestic water use contributes to water stress and altered flow regimes, affecting oxygenation processes. Industrial discharges introduce pollutants such as heavy metals, organic chemicals, and thermal pollution, which directly harm aquatic life and indirectly reduce oxygen levels by altering ecosystem dynamics. The obtained study results are similar to those of Joseph et al. (2023) who worked on the determination of the physical and chemical quality of the Lukunga River in Kinshasa. Their study characterized water quality through the analysis of key physicochemical parameters at three highly urbanized sites along the river. The main findings of this study on the Lukunga River highlight severe environmental pollution attributed to various human activities, including industrial and domestic activities wastewater. Their study recorded dissolved oxygen levels were found to be lower than the standard (>6), ranging from 0.66 mg/L to 2.08 mg/L, with an average of 1.393 mg/L, indicating oxygen deficits exacerbated by discharge activities and suspended solids hindering light penetration.

The high conductivity level observed during the rainy season in the NRC is explained by the increased runoff carrying dissolved ions from various pollution sources into the rivers. Rainfall washes away pollutants from urban surfaces, such as roads and pavements, which may contain salts, heavy metals, and other soluble substances. Agricultural runoff contributes fertilizers, pesticides, and soil particles rich in dissolved minerals, while domestic wastewater introduce household chemicals and organic matter. Industrial activities further add to the mix, discharging various soluble pollutants. This combined runoff significantly increases the concentration of dissolved ions in the water, leading to elevated conductivity levels during the rainy season.

The obtained results are similar to those of Mangenda et al. (2023) who worked on the urban growth and environmental degradation in the municipality of Kalamu, Kinshasa, their study reveals significant environmental degradation in the commune of Kalamu, Kinshasa, driven by rapid demographic growth and urbanization. They also found that the Funa River's water quality was notably poor, with high conductivity level during the rainy season (455 μS/cm) than the dry season (426 μS/cm). The study links this pollution to the effluents, household waste, and uncontrolled discharges, which pose significant public health and environmental risks in their study area.

According to Muamba (2017) and Kimfuta (2013) the high conductivity of Matete river water recorded during the dry season is due to the discharge of effluent from the national water treatment plant. Kimfuta (2013), further explains this exception by stating that the soil in the area is highly permeable, allowing rainwater to easily infiltrate. This infiltration leads to the degradation of rocks at a deeper level. The water resulting from this leaching process contains high levels of major ions, which then contribute to the groundwater. Ultimately, this groundwater feeds the Matete River during the low flood season or dry season.

Sites 4 and 8 recorded a BOD_5 values greater than the standard (6 mg/L), this result indicates a significant level of organic pollution in these sites. These sites experiences significant anthropogenic pressure from domestic, agricultural, and industrial activities, all contributing to water pollution. Agricultural practices such as the spreading of poultry droppings, pig farming, and agro-pastoral activities introduce organic matter and nutrients into the river through runoff during rainfall. Additionally, untreated wastewater from livestock buildings and urban waste discharge directly into the river, carrying pollutants and further increasing BOD_5 levels (Sites 4). The presence of industries at site 8 adds to the pollution burden, with direct discharges of effluents and untreated wastewater from industrial processes flowing into the river. Household sewage from sewer pipes and septic tanks also contributes to the pollution load. These inputs overwhelm the natural capacity of the river to assimilate and process organic matter, leading to elevated BOD_5 levels during the rainy season. These results are similar to those of Kakundika et al. (2022) who worked on the spatial and temporal characterization N'Djili River water quality. They found highest BOD_5 concentrations during the months of November (5.16 ± 1.52 mg/L) and October (4.66 ± 1.05 mg/L) than during the month of September (3.91 ± 0.94 mg/L). The statistical analysis of physicochemical parameters reveals that the water quality variables concentrations differ among sites and across seasons. Some variables were found to be above the international standards (Tb, COD, BOD_5, NH_4^+ and SM), while others were below (O_2, NO_2^-, SO_4^{2-} and Cl^-).

The significant difference between the sites in terms of the water quality variables being studied is due to the various anthropogenic activities taking place from one site to another. Based on the sites pollution extent from the reference site 1, five management classes were defined and each site was attributed to its corresponding class. Site 8 was classifying into the MC 5 due to its very high deviation from reference data indicating significant pollution levels due to contaminants such as heavy metals, organic pollutants, and nutrients from mainly industrial activities as said earlier and urban sources. This level of contamination not only degrades water quality but also disrupts the ecological balance, leading to the loss of biodiversity and ecosystem services. Site 2, 4, 7 and 9 has been added to MC 4 as these sites waters appear also highly polluted but not as much as site 8 pollution. It is important to note that the classification given to a site in a management category has ecological and socio-economic implications in terms of risks and development. For example, if a site with a moderate level of pollution is for some reason classified as MC 2 or 1, this implies that the risks of activities likely to have a negative impact on the water quality of the river on that site are maintained to a minimum, and this can contribute to poor pollution management at the site and promote rapid deterioration of the aquatic ecosystem, thus limiting the ecological and socio-economic development on that site. In our case, to avoid such kind of mistakes, site 7 and 9 has been added to MC 4 as site 7 on the ANOVA site classification comes after site 2 highly polluted and the HC is showing similarities between site 7 and 9 by grouping them into pair.

The validity of the developed approach lies in its adaptability and comprehensive framework, addressing the intricate challenges of urban river water quality management. Traditional water management strategies often fail to account for the multifaceted nature of urban ecosystems, where diverse water uses and varying degrees of anthropogenic influence interact dynamically. By focusing on a generic approach, this study transcends the limitations of context-specific solutions, offering a versatile methodology that can be tailored to different urban settings globally.

This study was necessary because it addresses the pressing need for integrated water management strategies in urban environments, where rapid urbanization and industrialization have significantly impacted water quality. Existing studies on the NRC often highlight the degradation of urban rivers but fall short of providing adaptable management frameworks. The approach developed in this paper fills this gap by offering a systematic method for balancing water use and protecting water quality. It does so through a detailed assessment of urban indicators, water physico-chemistry, and the relationships between water uses and water quality, followed by the classification of management strategies and mitigation measures tailored to specific urban contexts.

The value of the results and the implemented approach is multifold. Firstly, it provides a replicable model for urban river management that can be adapted to various contexts, ensuring its applicability in diverse geographical and socio-economic settings. Secondly, by integrating urban indicators and physico-chemical assessments, the approach offers a holistic understanding of the factors influencing water quality, enabling more informed decision-making. Thirdly, the classification of management strategies and mitigation measures into defined classes allows for targeted interventions, optimizing resource allocation and enhancing the efficacy of water management practices.

The study's findings contribute to the broader knowledge base on urban river systems, offering valuable insights for policymakers, environmental managers, and researchers. The developed approach not only enhances the current understanding of urban water quality management but also provides a robust framework for future studies, encouraging the replication and adaptation of the methodology to other urban catchments globally. This forward-looking discussion underscores the importance of adaptable and integrated water management strategies, paving the way for sustainable urban water ecosystems in the face of ongoing urbanization and environmental challenges.

There is an urgent need to apply the corresponding resource-directed measures and source-directed controls design in this study to address the severe water quality issues at the study sites in particular and the NRC lower course in general (Table 6).

5. Conclusion

In conclusion, the NRC lower course located in Kinshasa is facing significant pollution due to uncontrolled urbanization and anthropogenic activities taking place in the area. This study findings indicate that the waters collected from the N'Djili River by the national treatment plant are polluted by solid waste as well as urban and domestic waste discharges. This pollution poses a threat to the city's water supply and the health of its residents. The study conducted a comprehensive assessment of the urban rivers water quality and identified the sources and nature of pollution as well as their interconnections. Based on these findings, an integrated water resources management strategy was developed to minimize pollution and ensure effective use and protection of the urban water resources. There is an urgent need to apply this measures on the NRC in particular and such studies to other urban rivers in general. The ten sampling sites of this study were classified into five management categories based on their pollution level. A strategy based on both resource-directed measures and source-directed controls was develop in this study. Together, these two strategies not only protect urban rivers from degradation but also enhance their ecological resilience and improve water quality. By integrating these approaches into urban planning and policy frameworks, cities can foster sustainable development while preserving invaluable urban river ecosystems for future generations. This holistic approach is crucial in mitigating environmental risks and ensuring that urban rivers continue to provide vital ecosystem services and recreational opportunities for urban dwellers.

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Table 6
Integrated water resource management strategies to be taken per management class.

Sites	MC.	Integrated water resource management actions to be taken	
		RDMs	SDCs
1	MC 1	(1) Regular monitoring: implement a comprehensive monitoring program to continuously assess water quality parameters such as temperature, pH, dissolved oxygen, nutrient levels, and presence of pollutants. This will help identify any deviations from reference data and enable timely action. (2) Riparian zone protection: preserve and restore riparian zones, which are the areas adjacent to water bodies. These areas play a crucial role in filtering pollutants, preventing erosion, and providing habitat for aquatic and terrestrial species. Implement buffer zones and enforce regulations to restrict development and human activities in these areas.	(1) Implement measures to minimize the introduction of pollutants into water bodies. This can include strict regulations and enforcement to control industrial discharges, agricultural runoff, and sewage treatment. Encourage the use of sustainable and environmentally friendly practices in these sectors. (2) Strengthen regulatory measures: review and update existing water quality regulations to ensure they are comprehensive, enforceable, and aligned with current scientific knowledge.
3–10	MC 2	(1) Water quality regular monitoring. (2) Restoration and conservation: implement measures to restore and conserve the natural habitats and ecosystems in and around the water bodies. This can help support diverse biota and enhance the overall resilience of the ecosystem. (3) Riparian zone protection: Buffer zone.	(1) Pollution prevention: emphasize pollution prevention measures to minimize any potential impacts on water quality. This may include implementing best management practices in industries, agriculture, and residential areas to reduce the use and release of pollutants into water bodies. (2) Public awareness and education: educate the public about the importance of maintaining water quality and the potential impacts of their actions on sensitive organisms. Promote water conservation practices, responsible waste disposal, and sustainable land use practices
5–6	MC 3	(1) Increase monitoring and data collection: Implement a comprehensive water quality monitoring program to regularly assess the current state of water quality and track any changes over time. This will help identify specific areas or sources of contamination that need remediation efforts. (3) Riparian zone protection: buffer zone.	(1) Launch public education campaigns to raise awareness about the importance of water quality and the role individuals can play in protecting it. Provide information on proper household waste disposal, the impact of certain activities on water quality, and the importance of conserving water resources. (2) Adaptive management: Continuously review and update management strategies based on new scientific findings, emerging threats, and changing environmental conditions. Implement adaptive management practices to ensure that management strategies remain effective and relevant over time. (3) Promote the use of green infrastructure practices, such as rain gardens, green roofs, and permeable pavements, to reduce storm water runoff and improve water quality. These practices help filter pollutants and reduce the amount of pollutants reaching river water bodies.
2-4-7-9	MC 4	(1) Establish restoration and remediation projects: these projects may involve habitat restoration, pollutant remediation to improve overall water quality in the affected areas. (2) Water quality regular monitoring. (3) Riparian zone protection: buffer zone.	(1) Strengthen pollution control measures: implement stricter regulations and enforcement mechanisms to control and reduce pollution sources. This may include implementing industrial wastewater treatment requirements, enforcing agricultural best management practices, and promoting sustainable practices in urban areas to minimize runoff and non-point source pollution. (3) Promote sustainable agricultural practices: encourage farmers to adopt environmentally friendly farming methods, such as reducing pesticide and fertilizer use, implementing nutrient management plans, and promoting conservation tillage, to minimize agricultural runoff and its negative effects on water quality.
8	MC 5	(1) Restoration and protection of the ecosystem: implement measures to restore and protect the affected ecosystem. This may include re-establishing riparian vegetation, creating buffer zones, and implementing sustainable land management practices. (2) Enhance monitoring and data collection: establish a comprehensive monitoring program to track water quality parameters regularly. (2) Riparian zone protection: buffer zone.	(1) Identify and prioritize the pollution sources that are contributing the most to the water quality degradation. (2) Implementing industrial wastewater treatment requirements; (3) Improve waste management infrastructure. (4) Promote public awareness and participation: educate the public about the importance of water quality and the impact of their actions on the ecosystem. Encourage individuals and communities to actively participate in conservation efforts, such as reducing chemical use, properly disposing of waste, and participating in local cleanup initiatives.

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CRediT authorship contribution statement

Zouera Sani: Writing – original draft, Methodology, Formal analysis. **Raphaël Muamba Tshimanga:** Writing – review & editing, Supervision. **Oghenekaro Nelson Odume:** Writing – review & editing, Supervision, Methodology. **Twaha Ali Basamba:** Writing – review & editing, Supervision. **Haddy Mbuyi Katshiatshia:** Writing – review & editing, Supervision, Methodology.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

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