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Assessment of the water quality of the Niger River in Bamako, Mali, based on the Water Quality Index

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ABSTRACT

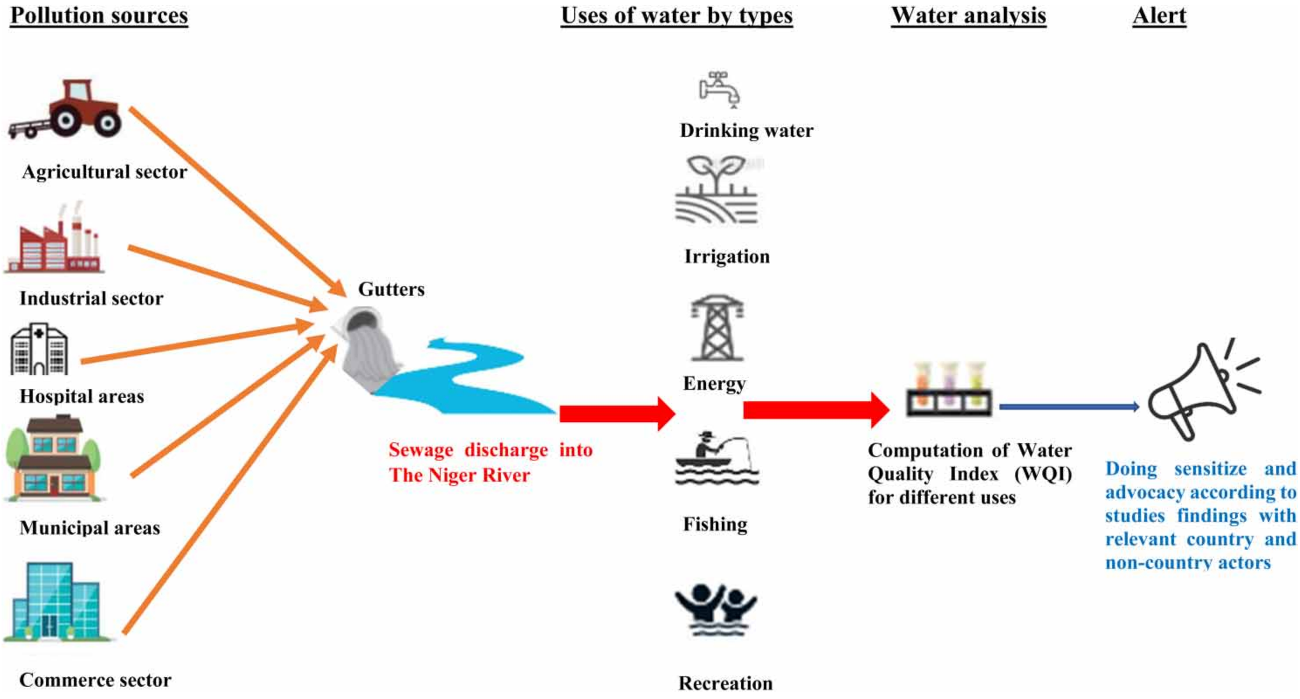
The Niger River, threatened by human activities, is the main drinking water source for the population of Bamako city. This study assesses the trend of Niger River pollution in Bamako using the Water Quality Index (WQI). Fourteen parameters, namely *Turbidity, Potential of Hydrogen* (*pH*), *Electrical Conductivity, Dissolved Oxygen, Total Dissolved Solids, Biochemical Oxygen Demand* (BOD_5), *Chemical Oxygen Demand* (*COD*), *Nitrate, Nitrite, Ammonium, Phosphate, Sulphate, Chloride and Copper*, were employed to characterise the Niger River water quality during the period from 2016 to 2020. Parameters were measured at 15 sampling locations. High values of *Turbidity, pH* and high concentrations of BOD_5, *COD, Nitrite, Ammonium and Phosphates* were recorded. The results showed that the Niger River water quality was good for 4 months and poor for 5 months during the dry season in a low flow period. Moreover, the water quality was poor during the 3 months of the wet season in the high flow period. The calculated WQI average values ranged from 75 to 100, indicating very poor water quality from upstream to downstream of Bamako city. Therefore, the Niger River water is polluted and cannot be used for drinking or industrial uses without any treatment.

Key words: Niger River, physicochemical, surface water, water pollution, water quality parameters, WQI

HIGHLIGHTS

- Human activities affected the Niger River in Bamako.
- Quantitative and qualitative assessments reveal the river pollution status.
- The water quality trend deteriorated further upstream to downstream of Bamako.
- WQI indicated that the Niger River water is poor and needs appropriate treatment before any use.
- Principal component analysis (PCA) showed ion distribution, indicating water mineralisation and the weak capacity of the Niger River for self-purification.

GRAPHICAL ABSTRACT



INTRODUCTION

Surface freshwater is a vital resource that is practically more accessible to meet the ever-increasing needs of humans. However, human activities threaten it. The Niger River is no exception to this rule while crossing Mali. The river is the third-longest in Africa after the Nile and the Congo rivers. The water source is 4,200 km long and the ninth-largest river system in the world (Amadou *et al.* 2011). Lienou *et al.* (2010) stated that the Niger River was essential for the population's survival in its catchment area because of its importance and significance. Bamako is the capital of the Republic of Mali, in which the Niger River serves as one of the principal drinking water sources for a large population. Besides, the river consists of four main components: irrigation, energy, fishing and water for tourism. Bamako is one of the largest riverine cities on the Niger River and certainly the largest one in Mali. Bamako represents nearly 40% of the urban population of Mali's estimated 20 million inhabitants in 2020, almost half of whom live in urban centres (UNFPA 2020).

Despite the river's immense importance, it is adversely affected by climate change and human activities. Thus, substantial variability of its flows on an annual basis was observed since 1907, with a sharp decrease since 1970 (Mahe *et al.* 2011). For decades, the demographic explosions of Bamako and the anarchic artisanal, industrial and agricultural activities around the river have raised concerns about the quality of its waters (Taha 2017). Public health requires a guarantee of safe drinking water. Poor water quality is a significant risk factor for the high incidence of water-related diseases in many developing countries. Therefore, monitoring drinking water quality should be a top policy priority for all countries. Indeed, access to safe drinking water must be a challenge for all actors involved in the Water, Sanitation and Hygiene (WASH) sector. In this context, numerous studies have been conducted to highlight any hypothesis of pollution of this country's longest river. Palangié (1998) reported that the physicochemical water quality generally remained good in the entire Niger Basin. Eight years later, Orange & Palangié (2006) worked on chemical and biological pollution in the Bamako-Koulikoro axis and concluded that the water quality remained chemically acceptable due to its high flow rate. Since the research has focused on the sources of pollution in Bamako. Recently, Toure *et al.* (2019) found evidence of chemical and bacterial pollution of the Niger River in the town of Ségou, 235 km long downstream of Bamako. In another study of the same year, the latter authors also established a correlation between river pollution and the recurrence of diseases. The typical limit of employed methods of studies is the use of quasi-empirical methods for the evaluation of the pollution of this river, from which the extent of the pollution remains poorly evaluated. Analysis of water parameters, alone or in a group, has failed to comprehensively understand the spatial and temporal trends in the overall Niger River water bodies. Then, several studies were not carried out on the water quality in Bamako. Therefore, there is limited published research regarding its pollution. Existing data on the research studies are obsolete and unreliable (Orange & Palangié 2006). At the same time, research conducted by the National Water Laboratory (NWL) remains limited and its methods of analysing the collected pollutants are rudimentary. As the method used by the authors mentioned above, the NWL assesses water quality by comparing the monitored parameters with the World Health Organisation (WHO) normative. In this condition, it is difficult to determine the available variations of the water bodies by assessing separate pollutants. In fact, for the sustainable protection of the Niger River and its riparian cities, it is imperative to conduct new studies using solid approaches that can establish the spatial and temporal pollution level of the Niger River in Bamako.

Based on the above context mentioned, this study aims (1) to find out the trend of the Niger River pollution through the computation of the Water Quality Index (WQI); (2) to highlight the spatial and temporal evolution of the water quality regime from upstream to downstream in Bamako and (3) to establish the WQIs for its different uses. The primary method used to achieve these purposes is based on the WQI calculation. The WQI is a mathematical tool, which provides spatial and temporal trends of the water quality of a specific water body. In this respect, the WQI has been recommended by several authors (Brown *et al.* 1970, 1972; Dutta & Sarma 2018; Talhaoui *et al.* 2020) as an easy means to convert large and complex water quality data sets into a single value with less expression. The method also explains the water quality for different uses.

The present study on the 'Assessment of the Water Quality of the Niger River in Bamako', which adopted the WQI method for pollution analysis, has many scientific and socioeconomic advantages. Firstly, the study will provide an overall assessment of the water bodies of the Niger River in Bamako. Secondly, its results can be extrapolated to guide further research at the level of the nine (9) countries in the Niger River basin. On the socioeconomic side, this study could serve as a reference framework (quality standards, rules of use, adapted water treatment methods, mitigation of harmful effects and advocacy tools) within the strategies for managing and protecting surface water in general and the Niger River in particular. Given that Mali does not have surface water quality standards, it would be able to promote the development of these standards. Regarding the NWL, the results would serve as a model for monitoring and controlling the river water quality in Bamako. The water treatment could be regulated according to the different uses and thus mitigate the negative impacts on the health of the riparian population.

METHODS

Study area and data collection

This work is focused on the Malian largest city (Bamako), crossed by the Niger River. This study collected data from two technical services in Bamako city. The water flow data were obtained from the database 'Hydracess' of the 'Direction Nationale de l'Hydraulique' (DNH: National Directorate of Hydraulics). Collected data covered the monthly flow average of the Niger River for 5 years (January 2016–December 2020). Sample locations are located at geographic coordinates, west longitude (X): -7.99845982; north latitude (Y): 12.6312999725342 in Bamako city. The map of the study area is shown in Figure 1.

The physicochemical parameters were collected from the 'Laboratoire Nationale de l'Eau' (NWL). The study period was 5 years (January 2016–December 2020). The monthly data average was used to assess the river's water quality. Five (5) stations were studied upstream in Kabala to downstream in Moribabagougou, about 30 km along Bamako (Figure 1). The NWL measures pollutants' concentrations using a network of fifteen (15) sampling locations in five (5) stations (Table 1). The stations are located in the sub-watershed area of the Niger River hydrological measurement station in Bamako city. Three samples were vertically conducted in each site (left, middle and right bank).

Sampling and analysis were carried out using the instrument's procedure manuals (Jean Rodier 2009). Specific parameters were immediately measured *in situ*. These are *Turbidity*, *Potential of Hydrogen* (*pH*), *Electrical Conductivity* (*EC*), *Dissolved Oxygen* (*DO*) and *Total Dissolved Solids* (*TDS*). *Turbidity* and *DO* were determined using the Nephelometry method of HACH instrument HACH 2100-Q and HANNA instrument HI 9146, respectively. HANNA instruments HI 9828 and HI 2211's Potentiometry method were used to determine *EC* and *pH*, respectively. *Chemical Oxygen Demand (COD)* was analysed employing a Colorimetric analyser L200. The Conductivity method of the type HANNA instrument LF197 made it possible to estimate *TDS*. Samples were transported to the laboratory to analyse the remaining parameters. The BOD

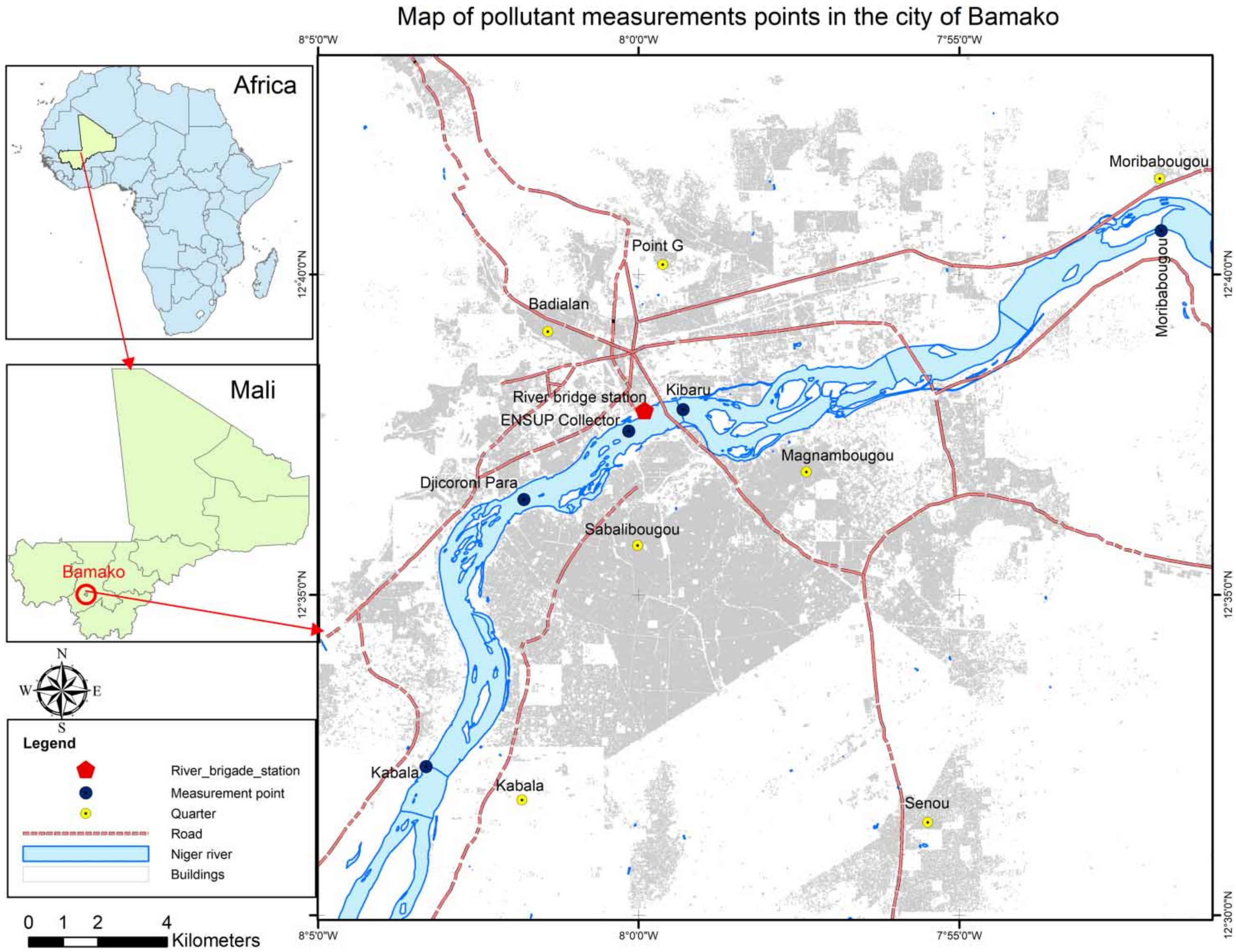


Figure 1 | Location map of water quality monitoring stations and the point of water flow measurement in Bamako city.

meter OxiTop (OxiTop Box WTW) respiratory measurement system was employed to estimate *Biochemical Oxygen Demand* (*BOD_5*). *Copper* was investigated by the spectrometry method of the Perkin Elmer instrument ELAN 400. *Nitrate, Nitrite, Ammonium, Sulphate, Phosphate, Calcium and Chloride* were analysed using the ionic chromatography method in Metrohm 881 Compact IC pro.

Data analysis

Analysis of variance (ANOVA) was used to compare the water flow periods and the WQI based on the ANOVA. Principal component analysis (PCA) was performed to notice the distribution and relationship among measured and calculated parameters. Hierarchical cluster analysis (HCA) was employed in the results of the WQI in sampling stations using the method of Euclidean distance. ArcGIS software was employed to map the study area. The Originpro 2021 software was used to visualise data analysis results.

Computation of the WQI

Fourteen physicochemical parameters (*Turbidity, pH, EC, DO, TDS, BOD_5, COD, Nitrate, Nitrite, Ammonium, Phosphate, Sulphate, Chloride and Copper*) were used to examine the Niger River water quality during the period from January 2016 to December 2020. The calculation of the WQI method applied by other researchers (Brown *et al.* 1970, 1972; Gorge & Jadhav 2013; Dutta & Sarma 2018; Talhaoui *et al.* 2020) was used. Thus, the WQI is calculated using the Weighted

Table 1 | The 15 sampling locations at the five stations in Bamako city

Number of sampling sites	Sampling sites	Sampling locations code	Sampling points	Latitude	Longitude	Location
1	Kabala	$S_{1\cdot 1}$	Left bank	12°32.211	−8°02.933	Upstream or entry point in Bamako
		$S_{1\cdot 2}$	Middle	12°32.318	−8°03.315	
		$S_{1\cdot 3}$	Right bank	12°32.319	−8°03.320	
2	Djicoroni Para	$S_{2\cdot 1}$	Left bank	12°36.332	−8°01.754	The first point after the entry point in Bamako
		$S_{2\cdot 2}$	Middle	12°36.487	−8°01.789	
		$S_{2\cdot 3}$	Right bank	12°36.666	−8°01.822	
3	ENSUP collector	$S_{3\cdot 1}$	Left bank	12°37.776	−8°00.154	The second point is after the entry point in Bamako
		$S_{3\cdot 2}$	Middle	12°37.555	−8°00.157	
		$S_{3\cdot 3}$	Right bank	12°37.396	−8°00.150	
4	Kibarou	$S_{4\cdot 1}$	Left bank	12°38.550	−7°59.337	The third point is after the entry point in Bamako
		$S_{4\cdot 2}$	Middle	12°37.891	−7°59.310	
		$S_{4\cdot 3}$	Right bank	12°37.725	−7°59.276	
5	Moribabougou	$S_{5\cdot 1}$	Left bank	12°40.784	−7°51.863	Downstream of outlet point in Bamako
		$S_{5\cdot 2}$	Middle	12°40.684	−7°51.851	
		$S_{5\cdot 3}$	Right bank	12°40.699	−7°51.859	

Arithmetic Index method. Its equation is given as follows:

$$\mathrm{WQI} = \frac{\sum Wi * Qi}{\sum Wi}$$

where Wi is the unit weight of nth water quality parameters and Qi is the quality rating of nth water quality parameters. The rating scale given by those authors is based on five simple terms used to appreciate the water quality on a scale of 0 to over 100%. Therefore, 0–25% implies ‘excellent (acceptable for human consumption)’, 26–50% to ‘good (requiring minor treatment before human consumption)’, 51–75% to ‘poor (using in irrigation and industrial)’, 76–100% to ‘very poor (using in irrigation)’ and >100% to ‘unsuitable (appropriate treatment is required before use)’. We remarked that the more the WQI value is high, the less the water quality is good.

The flowchart describing the article process is shown in Figure 2.

RESULTS AND DISCUSSION

Water flow assessment results

The yearly flow variability in the 12 months from 2016 to 2020 showed two periods of flow (Figure 3).

The two distinguished flow periods were the high flow (August, September and October) and the low flow (the remaining 9 months of the year). The increased flow period (wet season) started in August and ended with a peak in September. The decreased flow period (dry season) began in November and the river reached its lowest in February.

Overview of physicochemical parameters

The descriptive statistics of the physicochemical parameters used in this study were the minimum, maximum, mean and standard deviation values mentioned in Table 2. European Union (EU) (European Parliament, 2021) and World Health Organisation (WHO) (1970, 2011) standards were used to compare the water quality.

Results showed that the *Turbidity* varied from 2 to 90.82 NTU, with an average of 22.33 NTU. The maximum value was observed in the high flow period. The low flow period observed the minimum (4.52) and maximum (9.17) pH values. The pH was slightly basic, with an average of 7.43. Water mineralisation was low, with an average of 53.13 $\mu S\,cm^{-1}$ of EC. The minimum and maximum values were 29.20–173.40 $\mu S\,cm^{-1}$ in high and low flow periods. The *DO* concentration varied from 2.23 to 8.40 $mg\,l^{-1}$, with a maximum value registered in low flow. Its average value was 6.51 $mg\,l^{-1}$. The concentration of *TDS* was relatively low. The values of *TDS* varied from 29.20 $mg\,l^{-1}$ (high flow) to 173.33 $mg\,l^{-1}$ (low flow), with an average of 51.96 $mg\,l^{-1}$. Regarding the concentrations of *nitrate* (NO_3^-), *nitrite* (NO_2^-) and *ammonium* (NH_4^+), the results

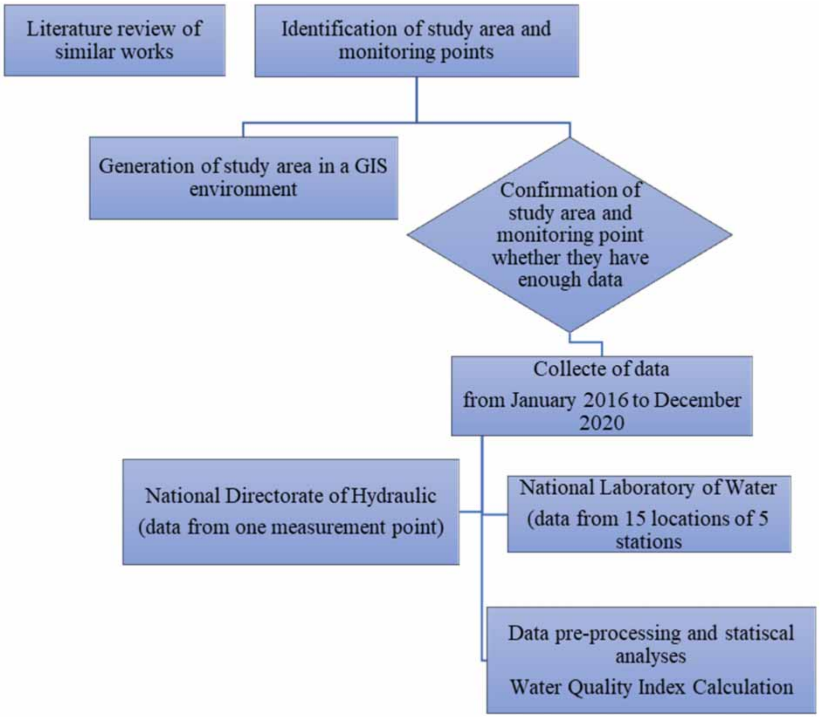


Figure 2 | Flowchart of the article process.

increased from 1.04 mg l^{-1} (high flow) to 10.18 mg l^{-1} (low flow), from 0.001 to 0.85 mg l^{-1} (low flow) and from 0.09 to 3.78 mg l^{-1} (low flow), respectively. The observed averages were 2.61, 0.06 and 0.6 mg l^{-1}, respectively. As the *Nitrate*, *Nitrite* and *Ammonium*, the content of BOD_5 increased from 1.00 to 268.00 mg l^{-1} in low flow, with an average of 38.52 mg l^{-1}. *COD* ranged from 2.00 mg l^{-1} (low flow) to 390.50 mg l^{-1} (high flow, with an average of 68.30 mg l^{-1}. The *phosphate* (PO_4^{3-}) value ranged from 0.001 to 1.64 mg l^{-1}, whose high value was registered in low flow. The average value of PO_4^{3-} was 0.13 mg l^{-1}. The *sulphate* (SO_4^{2-}) oscillated between 0.30 and 20.32 mg l^{-1} in low flow. The average value of sulphate was 3.07 mg l^{-1}. The maximum values of *chloride* (Cl^-) 10.54 mg l^{-1} and *Copper* (*Cu*) 2.01 mg l^{-1} were observed in low and high flow, respectively. Most parameters (*pH, EC, DO, TDS,* NO_3^-, NO_2^-, NH_4^+, BOD_5, PO_4^{3-}, SO_4^{2-} and Cl^-) had high concentrations during the dry season, while the opposite was true for *Turbidity*, *Cu* and *COD*. Descriptive statistics indicated that almost all variables had minimum and maximum values in the low flow period (dry season). However, the mean values of parameters in the high flow period were higher than in the low flow period.

Water quality assessment using WQI

The WQI was calculated to determine the Niger River's yearly water quality. The physicochemical parameters of the EU and the WHO standards were used to compute the WQI. The temporal variability of water quality according to the Niger River flow is shown in Figure 4.

The obtained WQI values indicated that the water bodies were excellent in April (15.19). It was good in March (27.16), November (45.63) and December (31.34). However, the water quality was poor in February (60.56), June (74.25), July (57.94) and October (61.37). Besides, it was very poor in May (75.81), August (76.18) and unfit for any use in January (347.74) and September (142.28). Therefore, the water quality was good to excellent for 4 months during the low flow period (dry season). Then, it was poor to unfit for any use for 8 months, 5 months in the low flow and 3 months in the high flow period. The highest and lowest pollution levels were observed during the low flow period in January–April. However, the second highest pollution level was observed in September during the high flow period (wet season). It was noticed that the water quality was good and sometimes poor during the low flow period. On the other hand, it was always poor during the high flow period.

The spatial variability of water quality at five stations was examined. The codification of the 15 sampling locations located in five stations is given in Table 1.

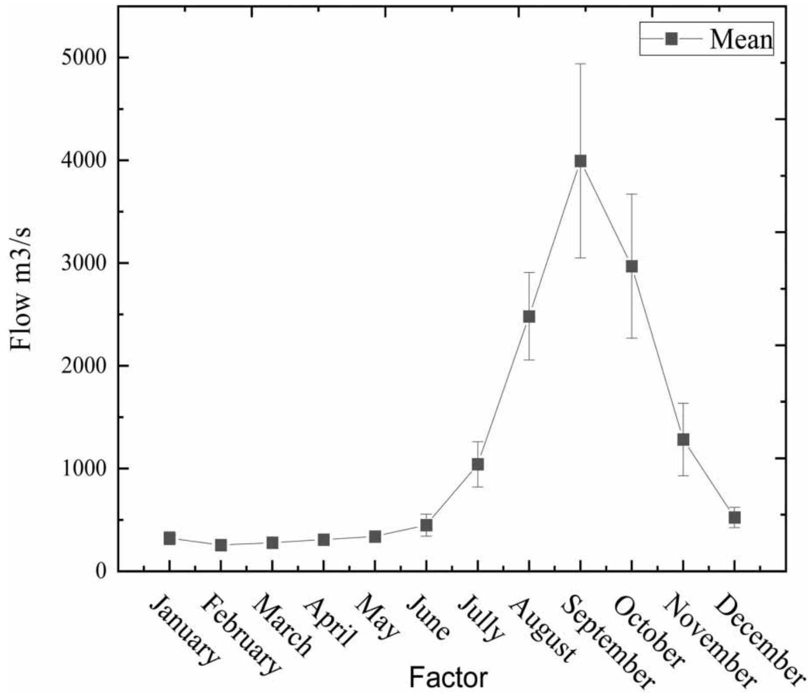


Figure 3 | The yearly variability of the Niger River flow from 2016 to 2020 in Bamako city.

Table 2 | Descriptive statistics of the physicochemical parameters relating to the 12 months of the years from 2016 to 2020 in Bamako city

Parameters	Minimum	Mean	Maximum	Standard deviation	Drinking water standards	Agencies
Turbidity (NTU)	2.00	22.35	90.82	14.93	5	WHO
pH	4.52	7.43	9.17	0.54	8.5	WHO
EC (μS cm^{-1})	29.20	53.28	173.40	27.54	250	WHO
DO (mg l^{-1})	2.23	6.50	8.40	0.98	5	EU
TDS (mg l^{-1})	29.20	52.08	173.33	25.74	500	WHO
BOD_5 (mg l^{-1})	1.00	38.52	268.00	47.84	5	EU
COD	2.00	68.30	390.50	84.17	30	EU
NH_4^+	0.09	0.6	3.78	0.47	0.5	EU
NO_3^- (mg l^{-1})	1.04	2.62	10.18	1.75	50	EU
NO_2^- (mg l^{-1})	0.001	0.06	0.85	0.10	0.5	EU
PO_4^{3-} (mg l^{-1})	0.001	0.13	1.64	0.34	0.2	EU
SO_4^{2-} (mg l^{-1})	0.30	3.02	20.32	2.96	500	WHO
Cl^- (mg l^{-1})	0.64	3.63	10.54	2.11	250	WHO
Cu (mg l^{-1})	0.01	0.02	2.01	0.15	2	WHO

The spatial variability of the water quality according to the two periods (the high and the low flow) of the Niger River flow is shown in Figure 5.

During the high flow period, the results revealed that the water quality was poor ($51 \leq WQI \leq 75$) in 20% of the sampling locations ($S_{1.2}$, $S_{2.2}$ and $S_{5.1}$). Then, the water quality was very poor ($76 \leq WQI \leq 100$) in 60% of the sampling locations ($S_{1.1}$, $S_{1.3}$, $S_{2.1}$, $S_{2.3}$, $S_{3.1}$, $S_{3.2}$, $S_{4.2}$, $S_{5.2}$ and $S_{5.3}$). Finally, the water quality was unfit for any use (WQI >100) in 20% of the sampling locations ($S_{3.3}$, $S_{4.1}$ and $S_{4.3}$). In the low flow period, the results indicated that the water quality was only good ($26 \leq WQI \leq 50$)

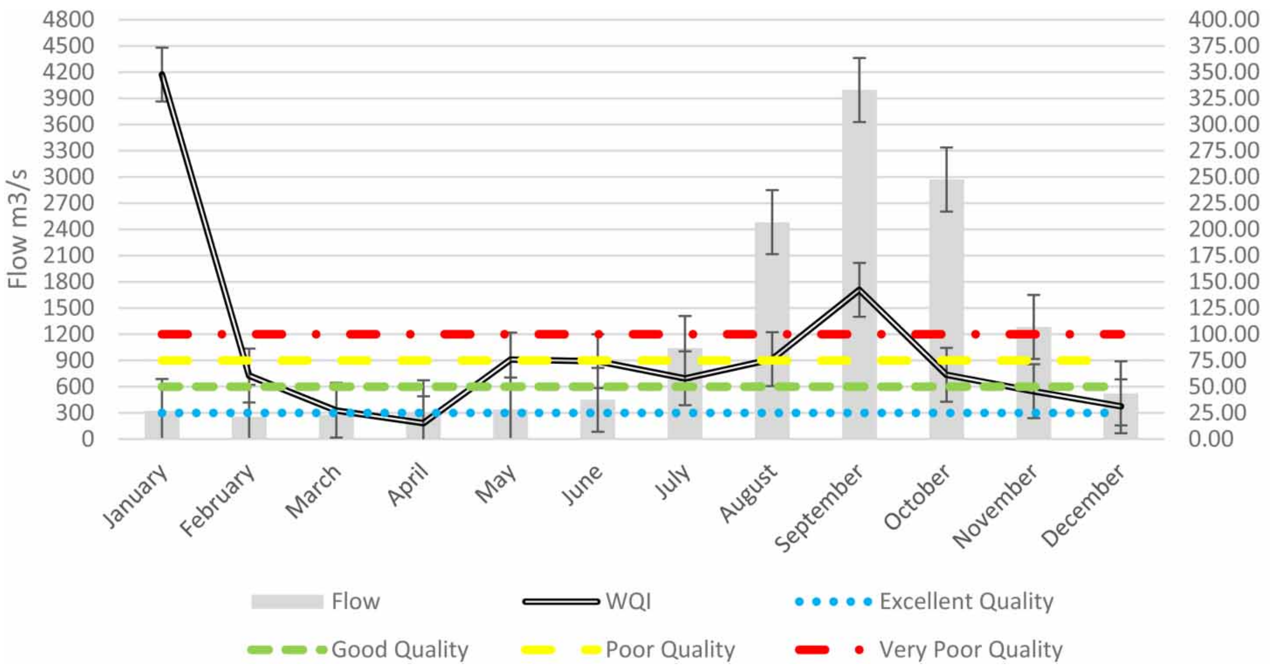


Figure 4 | Annual evolution of water quality of the Niger River based on the variability of flow rate.

in one location ($S_{1.3}$), representing 7% of the sampling locations. On the other hand, the water quality was poor ($51 \leq WQI \leq 75$) in 53% of the sampling locations ($S_{1.1}$, $S_{2.1}$, $S_{2.3}$, $S_{3.1}$, $S_{3.3}$, $S_{4.2}$, $S_{5.2}$ and $S_{5.3}$). Then, the water quality was very poor ($76 \leq WQI \leq 100$) in 33% of the sampling locations ($S_{4.1}$, $S_{4.2}$, $S_{5.2}$ and $S_{5.3}$). Finally, in 7% of the sampling locations ($S_{4.1}$), the water quality was unfit for any use ($WQI > 100$). It was noticed that, apart from the $S_{3.1}$ place in the low flow period, the water quality was from poor to unfit for use in all locations. Whether the water quality was good in the $S_{1.3}$ area during the low flow, its highest pollution was observed in the $S_{4.3}$ area during the high flow period.

Principal component analysis

PCA is the scattering of physicochemical parameters with WQI and environmental factors (Figure 6(a)) and their distribution in the different pollution locations (Figure 6(b)). According to the eigenvalues of the first case of PCA (Figure 6(a)), the first five principal components showed 81.44% of the variance and the remaining each contributed 5.71% or less. PC 1 and PC 2 explained 24.68 and 22.61% of the total variance, respectively. PC 3 illustrates 16.33% of the total variance, compared with 10.00% for PC 4 and 7.82% for PC 5. For the second case of PCA (Figure 6(b)), the four principal components showed 81.52% of the variance and the remaining each contributed 8.20% or less. PC 1 and PC 2 explained 39.96 and 16.14% of the total variance, respectively. The parts of PC 3 and PC 4 of the total variance were 13.74 and 11.68%, respectively.

The absolute loading values have been used to categorise element loadings as > 0.75 for 'strong', 0.75–0.5 for 'moderate' and 0.50–0.30 for 'weak', respectively (Liu *et al.* 2003). The biplot showed that PC 1 explained weak positive loadings on *EC, TDS*, BOD_5, Cl^- and weak negative loading on $NO_3{}^-$ (Figure 6(a)). In the second case, PC 1 indicated weak positive loadings *on EC, TDS*, $NO_2{}^-$ and Cl^-, weak negative loadings on *DO* (Figure 6(b)). However, PC 2 had weak positive loadings on *DO* (Figure 6(a)) and moderate positive loadings on *pH*, *Cu* and *COD* (Figure 6(b)). Furthermore, in the first case, PC 3 showed average positive loading on WQI and PO_4^{3-}, indicating a strong correlation between WQI and PO_4^{3-} ($R^2 = 0.97$, $P < 0.05$). In the second case, PC 3 showed moderate negative loadings on *Turbidity*. Then, PC 4 had moderate positive loading on $NO_2{}^-$, SO_4^{2-} and *COD* (first case). PC 4 had weak positive loading on BOD_5, NO_3^-, PO_4^{3-} and $NH_4{}^+$ and weak negative loading on SO_4^{2-} (second case). Finally, PC 5 in the first case of PCA showed weak positive loadings on *Turbidity, pH* and $NH_4{}^+$ and moderate positive loadings on *Cu*. All parameters were well distributed during the dry season except *Turbidity* and *Cu*, described in the PC 5 during the wet season. The stations located downstream of Bamako city had the most pollutants. The positive loadings of ions suggest the presence of natural and anthropogenic activities, including the geology and lithological processes within side the catchment and run-off from agricultural and sewage leakage into the river (Gyimah

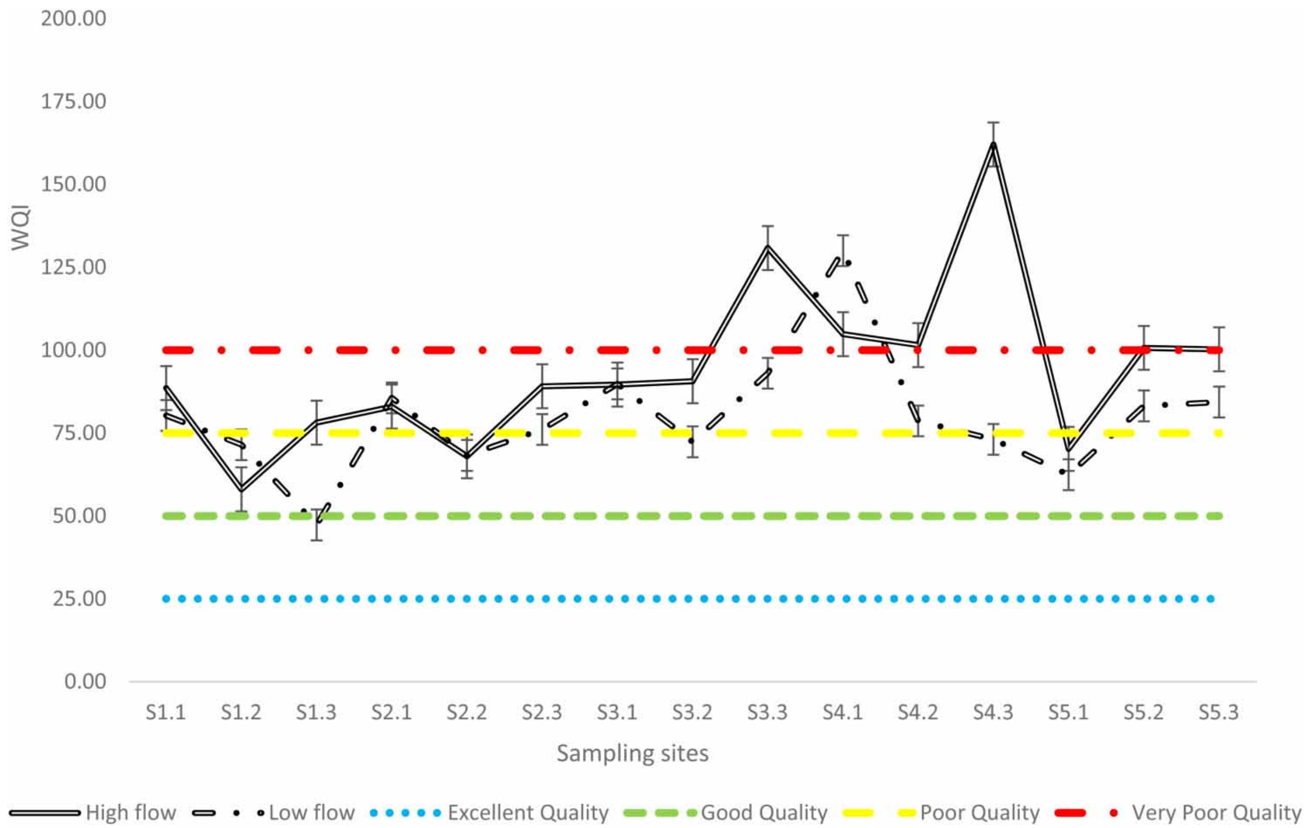


Figure 5 | Appreciation of water quality in 15 sampling locations during the Niger River high and low flow from 2016 to 2020 in Bamako city.

et al. 2021). Therefore, PC 1, PC 3, PC 4 and PC 5 in the first case, then PC 1 and PC 4 in the second case, could be represented as pollutants attributable to Bamako's anthropogenic and natural pollution sources. The corresponding period and location were the dry season and the area covering Bamako's middle (ENSUP collector) to downstream (Moribabougou).

DISCUSSION

The temporal distribution of pollutants analysis shows two clear trends. The Niger River water quality was good for 4 out of 9 months during the low flow period (dry season). Then, the water quality was poor during all the high flow periods (wet season) and the remaining months of the low flow period. Therefore, the temporal distribution of pollutants in the Niger River water was relatively unstable. The WQI values ranged from 15.19 (April) to 347.74 (January) during the dry season and from 61.37 (October) to 142.28 (September) during the wet season, indicating significant temporal variability among months. When the flow level started decreasing, the pollution followed this trend and suddenly rose to reach its maximum level in January. Then, the pollution reached its lowest level in April. Pollution increased from May to June onwards when the flow started rising and it reached its highest level of the high flow period in September. Therefore, the highest WQI value observed in the dry season was higher than in the wet season. However, the statistical analysis with ANOVA showed that the difference in the means of both periods (93.27 for increased flow and 81.73 for low flow) is not significant at the 0.05 level. That was because of the high pollution level during 5 of the 9 months of the low flow period, even if the water quality was good for 4 months in the same period. Even though the Niger River water was overall of poor quality, looking at the average WQI values, it was noticed that the Niger River was more polluted during the wet season than the dry season. That is explained by the fact that most parameters had high average values in the wet season. However, Mishra *et al.* (2017) found that the water quality of the Bagmati River was considerably better during the wet season. On the other hand, other researchers indicated that most water quality parameters were slightly higher in the wet season than in the dry season (Gorge & Jadhav 2013; Mishra *et al.* 2017). The run-off effect could explain the highest level of pollution shown during

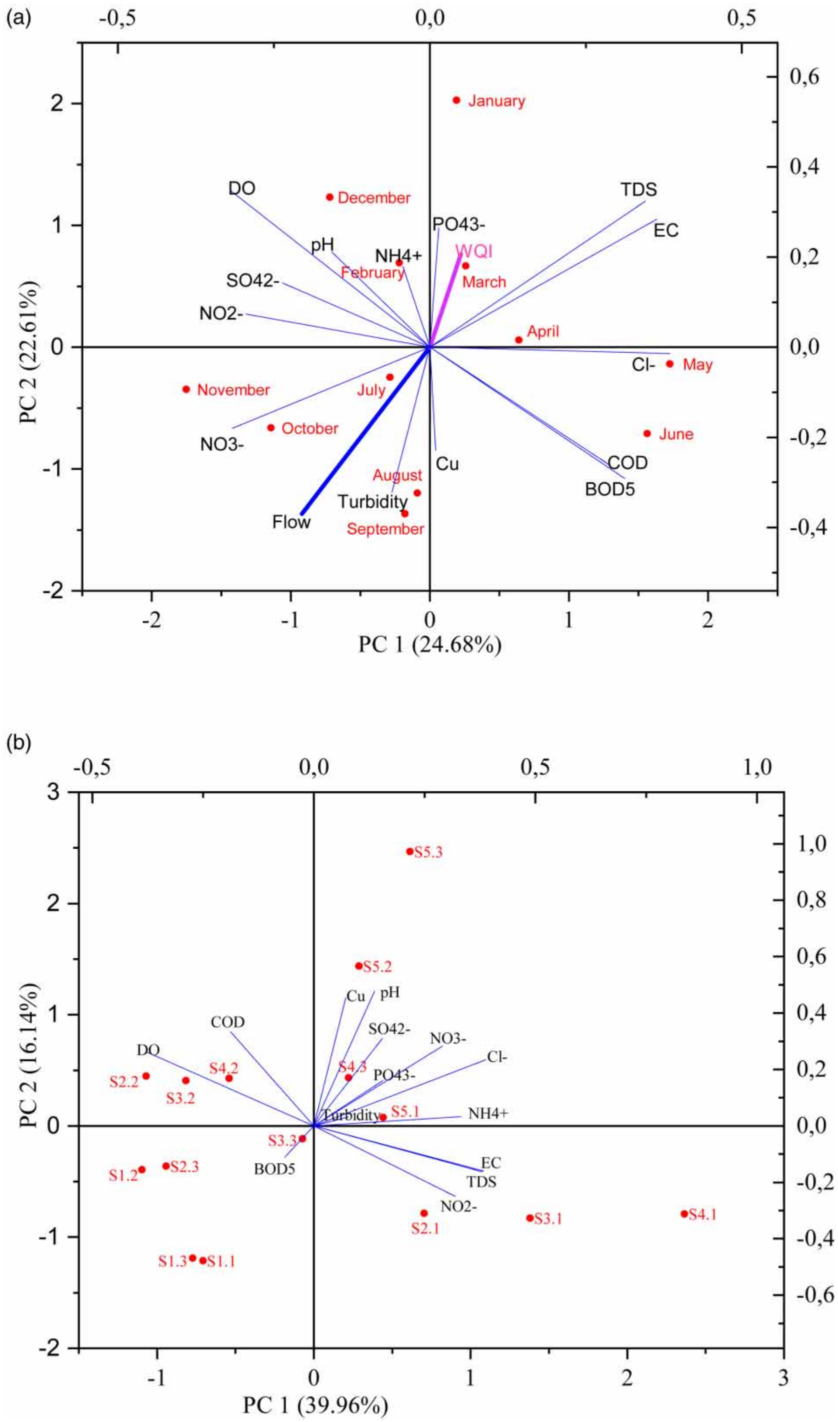


Figure 6 | Biplot of PCA showing: (a) the relationship among parameters, environmental factors and WQI; and (b) the distribution of pollutants at different sources of pollution.

the wet season. In Bamako city, there is currently an open network of gutters to evacuate wastewater and rainwater. During the wet season, large volumes of wastewater from the town, septic tanks and other domestic sources easily find their way into the Niger River waterway. In Bamako, the wet season is the period of maximum production for industries discharging effluents into the environment without adequate treatment (DNI 2015). All these effluents end up in the river due to the effects of run-off. The same result was obtained by the study of Orange & Palangié (2006) in Koulikoro and the Bani agricultural regions in Mali. Otherwise, Aschale *et al.* (2021) reported that the rapid population and urbanisation growth produced a considerable amount of wastes from the commercial, industries, domestic and public activities in Ethiopia. Finally, the large amount of untreated solid and liquid wastes are directly released into the Akaki River in Ethiopia. Dutta & Sarma (2018) explained the level of contaminants in the surface water by the high erosion of the land and direct discharges from stormwater drains. Consequently, such wastes discharged into the nearby river may remarkably raise the levels of pollutants in the water bodies. In order to reduce the Niger River pollution, the run-off collection system should be separated from the open networks of gutters. Moreover, industrial effluents should also be regulated by imposing water quality controls and treatment on the industrial units.

In this study, PCA analysis confirmed the water quality trends indicated by the WQI. PCA showed a high distribution of most pollutants in the dry season, contrary to the wet season. Those parameters were *pH*, *EC*, *DO* BOD_5, *TDS*, ${NO_3}^-$, ${NO_2}^-$, PO_4^{3-}, SO_4^{2-}, Cl^-, Ca^{2+} and Mg^{2+}. However, *Turbidity*, *COD* and *Cu* were observed in the wet season. The presence of many ions indicated the Niger River water mineralisation and its incapacity to eliminate pollutants during its crossing of Bamako city in many months of the dry season. For instance, if the *COD* played an essential role in the water quality deterioration during the wet season (Khullar & Singh 2022), the contrary was true for the PO_4^{3-} during the dry season. The highest level of pollution mainly observed in January (347.74 in the dry season) was explained by the increased PO_4^{3-} concentration (1.182 mg l^{-1}) compared with other months (the average of 0.037 mg l^{-1}). As shown in Figure 7, phosphate (82.7% of total weight) and ammonium (12.5% of total weight) were the primary pollutants contributing to the increase in WQI value in January.

January is a low flow period (dry season) where producers of farm vegetables on the river banks. In this study, the increase in phosphorus and ammonium concentrations could be due to the effects of chemical fertilisers applied by the active vegetable producers on the river bank in Kibarou. But this statement was contrasted by other researchers who reported that

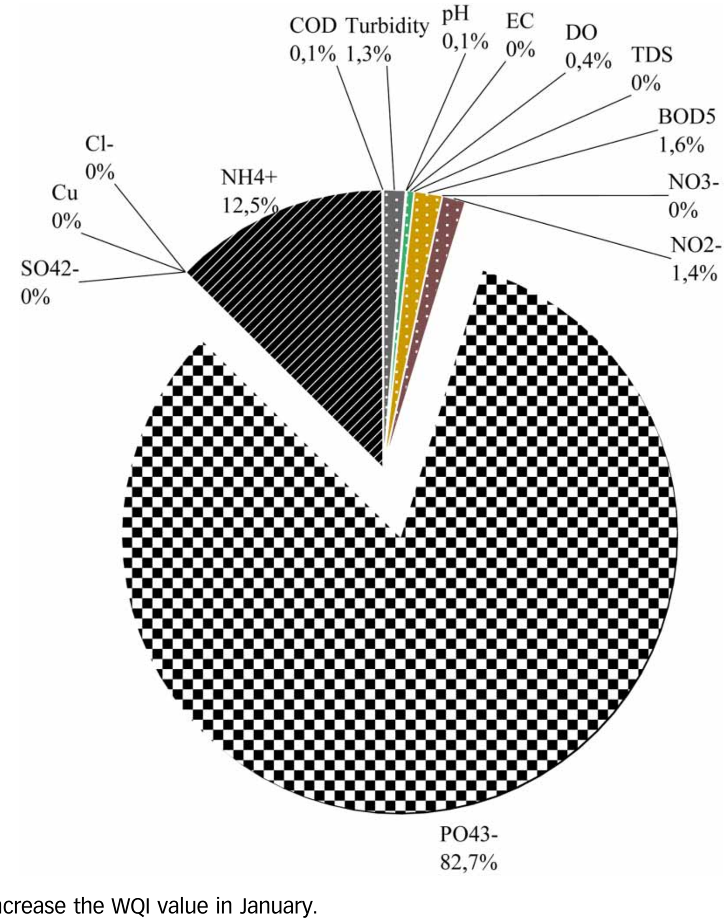


Figure 7 | Weigh of PO_4^{3-} to increase the WQI value in January.

phosphorus was mainly not detected in the dry season (Dirisu & Olomukoro 2015). Li *et al.* (2018) and Varol (2020) reported that irrigated agriculture and discharges of wastewater were the primary sources of water pollutants. Gyimah *et al.* (2021) reported the same conclusion and added that activities such as the geological-related processes inside the catchment and sewage leakage into the river were the sources of water contaminants. On the Niger River banks, farmers set up the cultivated plots in the dry season at the beginning of the low flow period (November). The active vegetative stage of the vegetables is reached in January and at that moment, the farmers use huge amounts of fertilisers. Those fertilisers could reach the river through the effect of run-off since they are used on the banks of the Niger River. Brraich & Saini (2015) reported that the sources of phosphorus include fertilisers, animal wastes and septic systems. Researchers revealed that phosphorus and nitrite concentrations greater than 0.02 and 0.2 mg l^{-1} could cause algal blooms in lakes and reservoirs (Gorge & Jadhav 2013). The dry season is essential for alga blooms in the Niger River. PCA showed that PO_4^{3-} had good correspondence with the WQI during the dry season. Therefore, the presence of the algae, which limits the use of the river's waters for different purposes, could be due to increased phosphorus and nitrite concentrations in the Niger River.

Furthermore, the spatial distribution of pollutants analysis showed poor water quality in 93% of the sampling locations and good water quality in the remaining site. The inlet and outlet of the Niger River were chosen to determine the overall water quality upstream and downstream of Bamako city. The ANOVA made it possible to define the pollution trend of the Niger River. Figure 8 shows a difference in average water quality from the first station (upstream at Kabala) to the last station (downstream at Moribabougou). The statistical analysis showed that at the 0.05 level, the different values of WQI from upstream to downstream were significantly different.

There was no significant difference in water quality upstream in both periods. However, the water quality in the upstream area significantly differed from that in the middle and downstream areas. Besides, no significant difference was found between the midstream and the downstream areas' water quality except that of the midstream during the high flow

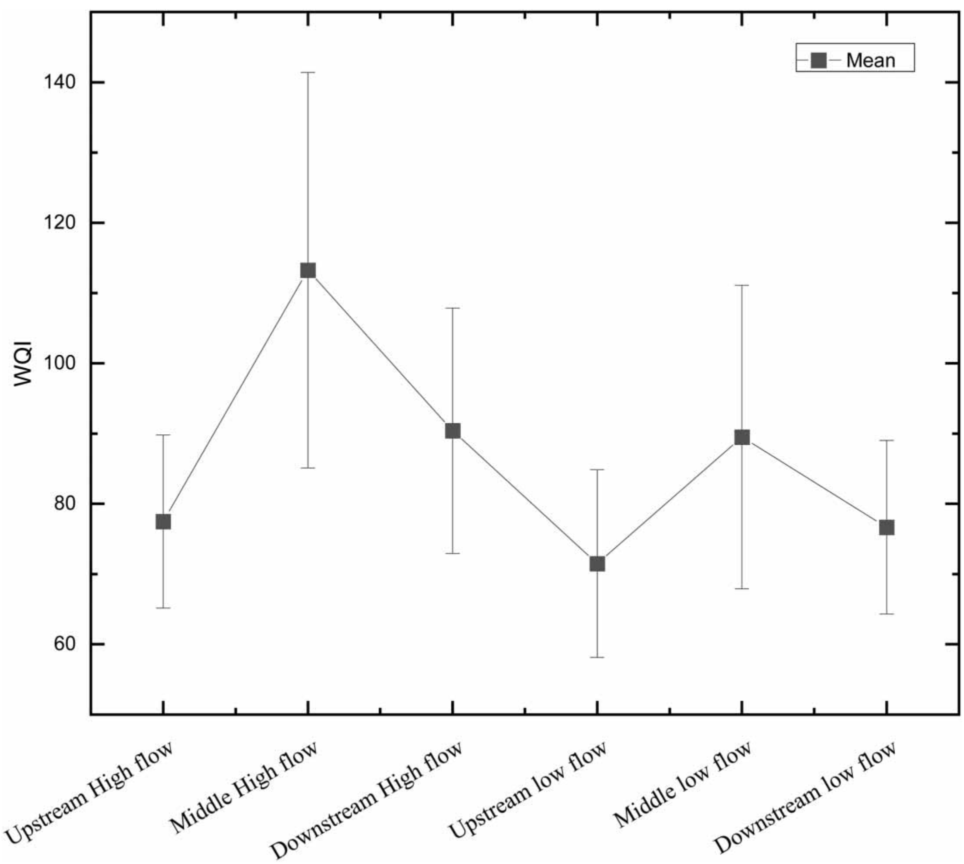


Figure 8 | Comparative study of water quality from upstream (Kabala) to downstream (Moribabougou) of Bamako city.

period. The water quality of the Niger River overall was poor in all stations. Already poor at the entrance to Bamako, it deteriorated further in the middle and reached the highest level in the high flow period.

Contrary to the middle, the WQI values decreased downstream of Bamako and kept a highly significant difference from those upstream. ANOVA analysis showed three areas of pollution. Those were the low, high and moderate pollution areas upstream (Kabala and Djikoroni), middle (ENSUP and Kibaru) and downstream (Moribabougou), respectively. Howladar *et al.* (2021) obtained the same findings and reported that the middle stream of the river was much polluted as this area is largely covered by the Sylhet City Corporation. In Figure 9, Hierarchical Clustering Analysis confirmed the obtained trend by ANOVA. Even though the water quality was highly poor in the middle area, there was a trend of improvement downstream. The average value observed upstream during the low flow was lower than that observed downstream. Similar results were obtained by others (Dutta & Sarma 2018; Talhaoui *et al.* 2020). They found that the increase in pollution was related to the decrease in river flow, while the discharge of effluent loaded with domestic and industrial water from the urban centres remains essential. Researchers also concluded that the water quality degradation was reflected by a vital mineral and organic load of anthropic origin from urban centres (Talhaoui *et al.* 2020). Alizadeh *et al.* (2017) study the prediction of the longitudinal dispersion coefficient in a natural river employing a cluster based on a Bayesian network (BN). They concluded that the BN model was suitable for predicting pollutant transport in a natural river. The accuracy criterion was raised from 70 to 83% by performing a clustering analysis on the BN model. Khullar & Singh (2022) also used the prediction method using deep learning Bi-LSTM to assess the water quality of the river. Compared with other models, they revealed that the proposed Bi-LSTM model outperforms all others in terms of the best forecasting accuracy and lowest error rates. Contrary to our study, the latter used one monitoring station to study the water quality. They concluded that in the future direction more monitoring stations could be included to examine the water quality in spatial dimensions under the hydrodynamic principle. However, Yang *et al.* (2021) studied spatial and temporal variations of water quality to

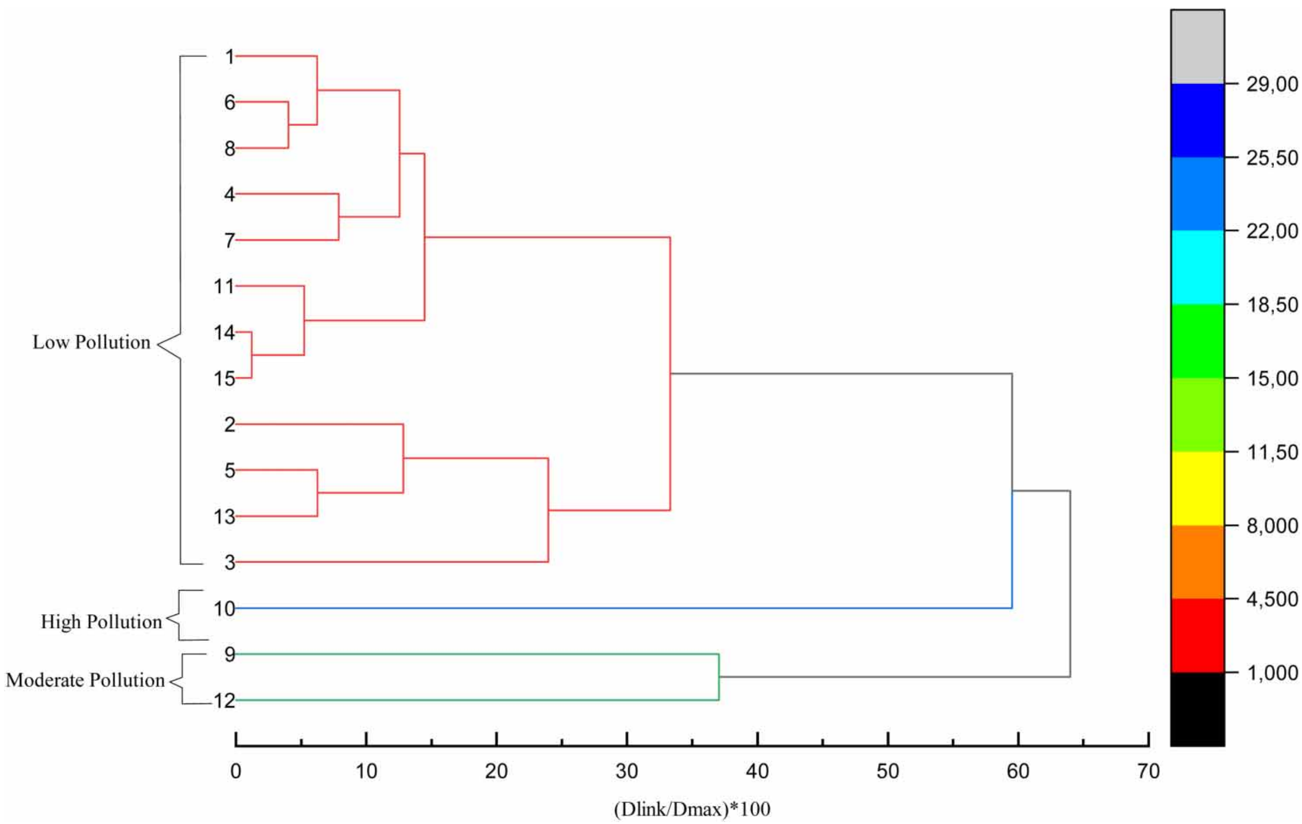


Figure 9 | Cluster analysis showing hierarchical clustering of 15 sampling locations: red colour (low pollution area), green colour (moderate pollution area) and blue colour (high pollution area). Please refer to the online version of this paper to see this figure in colour: https://dx.doi.org/10.2166/ws.2023.029.

identify pollution sources in urban rivers. They reported that the final object of the urban surface water quality assessment could be to accurately determine the site with the heavy loads and simultaneously formulate effective pollution reduction policies. This statement would be true when we refer to the results obtained by Yotova *et al.* (2021). They stated that the moderate water quality of the river may be due to the wastewater discharges from two sites. The municipal wastewaters directly discharged in the river were a local impact and did not spread along the river.

PCA analysis confirmed the same trend from ANOVA and cluster investigations by determining three distinguished areas according to the pollutants' distribution. Those were the areas of the low, moderate and high distribution of contaminants. PCA showed a large allocation of pollutants in the middle and downstream than upstream. The poor quality of the water in this part of the river was because the insufficient provisions were made for proper waste disposal before the urbanisation of Bamako. Indiscriminate waste disposal in drainage systems, marketplace and urban trash also contributes immensely to the pollution of the Niger River (Maïga *et al.* 2007). Consequently, foremost collectors discharge wastewater into the Niger River from the commercial centre, hospital and industrial units located between the middle and downstream of Bamako.

The overall average values of WQI obtained in different periods and on all the sites were an average of 85.84. Overall, the Niger River water quality was very poor ($75 \leq \mathrm{WQI} < 100$) and could be used only for irrigation without proper treatment. Other researchers reported different values of the WQI. The WQI values in the two sources ranged from 64 to 77 and 53 to 95, indicating deplorable water (Kangabam & Govindaraju 2017). Dutta & Sarma (2018) found a value of 58.87–216.53 and reported that water in all the sites was unsuitable for drinking. In this study, the maintenance of the water quality deterioration was due to the relatively high concentration of pollutants that exceed the standards of water potability. Indeed, 47% of the selected parameters do not meet international water quality standards and could negatively affect the population's health and cause negative consequences to aquatic life. Those parameters had the maximum influence on the WQI calculation. Among them were *Turbidity* (90.82 NTU against 5 NTU of WHO standards) and *pH* (9.17 against 8.5 of WHO standards). The same causes were observed in the west of Milloulou in Morocco (Talhaoui *et al.* 2020). *Turbidity and pH* of water have no direct negative consequences for human beings. However, they have indirect implications because of their capacity to modify other water quality parameters, including the preliminary chemical shape of metals and the survival of infectious agents such as bacteria and other parasites (WHO 2011). *pH* may purpose gastrointestinal inflammation in touchy people (Ho *et al.* 2003). Besides, bacteria and parasites could cause many diseases. Toure *et al.* (2019) determined drinking water quality and risk for human health in Pelengana Commune, Segou, Mali. The health survey showed diarrhoea, typhoid fever, gastroenteritis, amoebic dysentery, hepatitis A, B and C. Furthermore, BOD_5 (268 mg l^{-1} against 5 mg l^{-1} of European standards), NO_2^- (0.85 mg l^{-1} against 0.5 mg l^{-1} of European standards), PO_4^{3-} (1.64 against 0.2 mg l^{-1} of European standards), NH_4^+ (3.78 mg l^{-1} against 0.5 mg l^{-1} of European standards) and *COD* (390.5 mg l^{-1} against 0.5 mg l^{-1} of European standards) impacted water quality. Islam *et al.* (2012) almost reported the same trend, indicating that the water quality in Chini Lake varied both temporally and spatially. They observed that the most affected parameters were *Turbidity*, *pH*, NH_4^+, PO_4^{3-}, *TDS*, *DO* and *EC*. Brain ammonium concentrations between 0.5–1.0 mM and 2.5–5 mM cause central nervous system (CNS) symptoms and severe CNS disturbances, such as coma, respectively (Szerb & Butterworth 1992). The consequences of a high concentration of *phosphorus*, *ammonium* and *nitrite* lead to the hypereutrophic level, which causes an increase in BOD_5 concentration in the water bodies (Worako 2015; Shen *et al.* 2022). According to Garras *et al.* (2015), this phenomenon is not conducive to aquatic life. Its effects are stress, suffocation and death. The dead fish often seen on the surface of the Niger River in Bamako could be due to this phenomenon, which remains mysterious to fishermen. The minimum value of *DO* was 2.23 mg l^{-1} and Novotny (2003) reported that most fish could not survive when *DO* content was <3 mg l^{-1}. Therefore, the cumulative effects of the river's pollution have given consequences that could be observed in reducing fish stocks and the inability to derive maximum benefits from using the river water for different uses.

CONCLUSION

In this study, parameters from the monitoring network of five stations during 5 years made it possible to determine the Niger River water quality in Bamako. The average WQI values ranged from 75 to 100, indicating that the water bodies were very poor both in dry and wet seasons and from upstream to downstream of Bamako. Most pollutants had the highest concentrations during the dry season and Bamako's water quality deteriorated downstream. The parameters influencing the WQI calculation and did not meet international standards were *Turbidity, pH,* BOD_5, NO_2^-, PO_4^{3-}, NH_4^+ and *COD*. PCA confirmed the results obtained by WQI, indicating a significant distribution of pollutants during the dry season and from the midstream to downstream of Bamako. The water flow is insufficient, while the effluents from both riverbanks remain essential, indicating the weak capacity of the Niger River for self-purification to eliminate the pollutants received during its crossing in Bamako city. The obtained results enabled the conclusion that the Niger River is polluted in Bamako city. Indeed, its water bodies were unsuitable for domestic, industrial and drinking water without appropriate treatment. Using this water could negatively affect the health of the residents. Thus, measures to reduce pollution must be taken by the authorities to protect it from all types of pollution. This study shows that the WQI is essential in investigating surface water quality for different uses. Through the PCA application to identify the spatial and temporal distribution of pollutants, it can be coupled with the WQI to determine the general trend of surface water pollution, especially in the Niger River. Based on scientific criteria, results recommended that the WQI could be employed for assessing surface water quality in general and mainly could be used to examine the Niger River water bodies by the Malian NWL.

In perspective, an assessment of the Niger River between Bamako and Koulikoro (the second most crucial city downstream of Bamako) must be made. This study will enable us to know the pollution level of the Niger River before it undergoes that of the town of Koulikoro, located 60 km from Bamako. Furthermore, forecast studies are necessary to examine the quality of the river's water and its ability to meet the needs of the population of Bamako in the medium and long term.

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AUTHOR CONTRIBUTIONS STATEMENT

L.O.S.: Conceptualisation, Methodology, Software, Validation, Formal Analysis, Writing – Original Draft, Visualisation, Data Curation, Project Administration. S.B.: Conceptualisation, Validation, Supervision. A.T.: Validation, Supervision. M.S.: Conceptualisation, Methodology, Software. T.Z.: Conceptualisation, Validation, Supervision.

DATA AVAILABILITY STATEMENT

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

CONFLICT OF INTEREST

The authors declare there is no conflict.

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