Water quality degradation in urban rivers of Dar es Salaam, Tanzania: changes, status, and causes

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Abstract: Water quality degradation of urban rivers has become a serious constraint to the sustainable development of big cities in sub-Saharan Africa, and few systematic quantitative studies have been conducted on this issue. Here, we studied three main urban rivers, Mzinga River, Kizinga River, and Msimbazi River in Dar es Salaam, the largest port city on the west coast of the Indian Ocean. The spatial and temporal changes of the physicochemical parameters including DO, pH, oxidation-reduction potential (ORP), electrical conductivity (EC), total dissolved solids (TDS), turbidity, total nitrogen (TN), total dissolved nitrogen (TDN), dissolved inorganic nitrogen (DIN), chemical oxygen demand (COD_{Mn}), total phosphorus (TP), total dissolved phosphorus (TDP), soluble reactive phosphate (SRP), and water quality index (WQI) were investigated. Results showed that the middle and lower reaches of the three rivers were severely polluted with N (nitrogen) and P (phosphorus) with pollution increasing from the upstream to the downstream. WQI results showed that the water quality of Msimbazi River was in the "poor" category and fluctuated temporally and spatially. Principal component analyses (PCA) implied that redox status and N were the main factors affecting the water quality of the rivers. Unregulated discharge of untreated municipal and industrial wastewater were the main drivers of water quality degradation in the rivers. Rapid urbanization characterized by population explosion and the small handicraft industry aggravated the situation. Source control and end treatment are urgently needed to prevent the water quality of the urban rivers in Dar es Salaam from deteriorating further.

Keywords: Water quality index (WQI) · river · nitrogen · phosphorous · pollution

Statements and Declarations

Competing Interests

The authors have no relevant financial or non-financial interests to disclose.

1 Introduction

Urban rivers are important components of urban ecology, and their water quality has direct impacts on the health of water bodies, biodiversity, human health, and the sustainable development of socio-economic systems in the catchments/sub-catchments. The water quality degradation of urban rivers has continuously been a severe environmental problem facing urban development of human society since the first industrial revolution. Since the 21st century, under the guidance of the concept of sustainable development, protection of the water environment in inland water bodies has been greatly improved. However, the degradation of water quality in urban rivers remains one of the main pressures on surface waters in developing countries, particularly in the rapidly developing economies of Asia, Africa, and Latin America (Baştürk, 2019; Díaz-Casallas et al., 2019; Uddin & Jeong, 2021; Yu et al., 2018). In China, the so-called black-odorous rivers in built-up areas were listed as the number one problem in more than 600 Chinese cities during the national 12th and 13th five-year plans (Qin et al., 2022). These rivers often suffer from low water transparence (Secchi' depths, SD), low DO, and high nutrient loads (Wang et al., 2021). In Brazil, the deterioration of the water environment in the Comprido River in São Paulo caused health consequences to local residents (Rocha et al., 2022). In India, pollution of urban rivers in New Delhi induced the growth of bacterial and viral pathogens (Achee et al., 2015; Crump et al., 2004; McMichael, 2000). The heavy pollution from domestic wastewaters into the Umgeni River in South Africa has led to cholera outbreaks and serious health risks to the local residents (Edokpayi et al., 2021; N.Edokpayi et al., 2020; Singh & Lin, 2015). Degradation of water quality caused by various pollutions in urban rivers have become a major constraint for developing and less-developed countries to achieve the United Nations sustainable development goal SDG 6.3 (to improve water quality by reducing pollution, eliminating dumping, minimizing the discharge of hazardous chemicals and materials, halving the proportion of untreated wastewater, and significantly increasing global recycling and safe reuse by 2030) (https://sdgs.un.org/goals/goal6).

Water quality degradation of urban rivers is widely found in the sub-Saharan African region, which is influenced by factors including pollutant discharges, changes in land-use patterns, rainfall and flooding, small craft and commercial production activities, and sprawl of settlements (Madilonga et al., 2021; Mbuligwe & Kaseva, 2005; Wilson et al., 2021). An obvious common feature of these rivers is that overloading of nitrogen and phosphorus plays an important role on the degradation of water quality. High TN (13.5 ± 2.0 mg/L) and TP (2.6 ± 0.6 mg/L) concentrations in Malimba River in Harare, Zimbabwe, not only largely caused eutrophication of the downstream Lake Chivero, but also caused drinking water supply problems in local communities (Nhapi & Tirivarombo, 2004). Water pollution from nitrogen and phosphorus as well as organic matters in urban rivers resulted in both environmental degradation and disease outbreaks in Kenya and Ghana (Nhapi & Tirivarombo, 2004; Ntajal et al., 2022; Wilson et al., 2021). Legal and illegal waste disposal sites, slaughterhouses, and household on-site sanitation systems have caused severe water quality deteriorations of urban rivers in Tanzania (Mbuligwe & Kaseva, 2005; Mohammed, 2002).

Tanzania is one of the least developed countries classified by the United Nations, but it is experiencing rapid socio-economic and demographic growth as it enters the 21st century. In the first two decades of this century, Tanzania's economy quadrupled in size and the country's population almost doubled in the same period. As the economic capital and the largest city in Tanzania, Dar es Salaam has seen particularly dramatic demographic expansion and economic growth. The growing population and intense socio-economic activities have strongly affected the local water environment system, putting unprecedented pressure on the city's surface water bodies. Dar es Salaam's surface water bodies consist mainly of the three rivers Mzinga, Kizinga, and Msimbazi, which flow through the city all year round, and a dozen short seasonal rivers or drainage ditches. The three main rivers flow through agricultural areas, informal settlements, densely populated areas, commercial and industrial areas and eventually into the Indian Ocean. The water quality of these rivers has significant impacts on local agricultural and industrial productions, human health, and the environment and ecosystem along the Indian Ocean coast of Dar es Salaam. Machiwa (Mihale, 2021) suggested that industrial wastewater discharge into the upstream areas of Msimbazi River caused heavy metal pollution in the nearby coastal sediments. Direct discharge of sewage treatment and industrial effluent caused the levels of total and fecal coliforms in Mzinga River to exceed acceptable standards set by the World Health Organization and Tanzania (Saria, 2015). In Dar es Salaam, the waters from Mzinga, Kizinga, and Msimbazi Rivers are widely used in agricultural and industrial activities, and even for the daily life of inhabitants along some reaches of the rivers. A firmly accepted view is that agricultural products irrigated with untreated wastewater or contaminated rivers can lead to a variety of food-borne diseases such as cholera and gastroenteritis (Selma et al., 2010). However, to date, no systematic quantitative study of the main rivers in Dar es Salaam have been conducted to evaluate the water quality, and the understanding remains at basic levels. At the same time, lack of data is an obvious obstacle to the management and treatment of pollution in these rivers, which in turn affects sustainable urban development.

Therefore, we studied the three major urban rivers of Dar es Salaam, the Mzinga, Kizinga, and Msimbazi Rivers, and further analyze the causes of the degradation of their water quality based on investigation and analysis of the spatial and temporal changes in the physicochemical characteristics of the waters. The objectives of this study are 1) to characterize the spatial and temporal distribution of the physicochemical parameters of the water in the three rivers, 2) to quantitatively evaluate and clarify the environmental status of the rivers, and 3) to elucidate the influencing factors affecting the deterioration of water quality. The relevant results of this study will fill the data and cognitive gaps in the study area, provide scientific guidance for environmental protection and integrated management of urban rivers in Dar es Salaam, and will serve the sustainable development of human society in the study area.

2 Materials and methods

2.1 Study area and sampling

The city of Dar es Salaam is located on the coastal plain in the middle of the Indian Ocean coast of East Africa, at latitude 6°48′ S and longitude 39°17′ E, with an altitude of 8–15 m, an area of approximately 1393 km^2, and an annual precipitation of approximately 1100 mm (Mbuligwe & Kaseva, 2005). The main urban rivers flowing through Dar es Salaam are the Mzinga, Kizinga, and Msimbazi Rivers.

The Msimbazi River passes through Dar es Salaam City, separating the city center from the main suburbs. The valley of the Msimbazi River is home to human settlements, informal industrial and commercial activities, and urban agriculture. The river valley area has warehouses, industry and solid waste disposal sites, which permanently receive waste water from industries, slaughterhouses, large referral hospitals, and residential areas in the neighborhood. However, in some sections of the river, people still bathe and fish in the river. The river water is also used for irrigation and animal drinking, and to a limited extent for household purposes. The Kizinga River flows in a generally south-west- to north-east direction before emptying into the Indian Ocean, while the Mzinga River flows naturally from west to east into the Indian Ocean. The lengths and basin areas of Mzinga, Kizinga, and Msimbazi Rivers were showed in the SI Table 1. Both rivers flow from west to east in the municipality of Dar es Salaam, and Kizinga River is one of the city’s sources of water for agriculture and domestic use. The average temperature and precipitation in Dar es Salaam are 28.6°C and 25 mm in the dry season of July, and 24.4°C and 75 mm in the rainy season of January, respectively (Howorth et al., 2001; Ndetto & Matzarakis, 2015; Nyembo et al., 2022) (https://www.climatestotravel.com/climate/tanzania/dar-es-salaam).

The main urban rivers flowing through Dar es Salaam, the Mzinga, Kizinga, and Msimbazi Rivers were used for the study. The distribution of land use and land cover (LULC) types and sampling points is shown in Fig. 1. LULC data of Dar es Salaam was obtained from Resilience Academy's Climate Risk Database (CRD) (https://geonode.resilienceacademy.ac.tz/layers/lulc_esa_dar_2:geonode:lulc_esa_dar_2). Typical scene of the three rivers is shown in Fig. 2. Normally, the upstream of Mzinga and Kizinga Rivers are very turbid (Fig. 2 (a, b)) because of intense human being activities. For Msimbazi River, a large amount of garbage in the banks were found in the upstream, and the river emitted offensive odorous and the color of the river became dark-green in the midstream (Fig. 2 (c, d)). A total of 25 sampling sites were set in the three rivers. The sampling sites of Mzinga, Kizinga, and Msimbazi rivers were labeled as MZG1–MZG6, KZG1–KZG6, and MSB1–MSB13 from the upstream to the downstream, respectively.

Field investigation and sampling was carried out during the dry (July, 2019) and rainy (January, 2020) seasons in 2019 and 2020. Water samples were collected by using a 2.5 L plexiglass water sampler at sampling sites with water depth greater than 20 cm, then were collected into 100 mL polypropylene bottles. At sampling sites with water depth less than 20 cm, water samples were collected directly by submerging the 100 mL polypropylene sampling bottles below the water surface. Additional water samples were collected and immediately filtered by using disposable syringes (0.45 μm) at each sampling site, and then collected into 50 mL polypropylene sampling bottles. All samples at each sampling site were triplicated. All water samples were collected and stored in a 4°C cooler and transferred to Tanzania Fisheries Research Institute in Dar es Salaam after the sampling and then were deeply frozen and transferred to Nanjing Institute of Geography and Limnology of Chinese Academy of Sciences in China for further analysis.

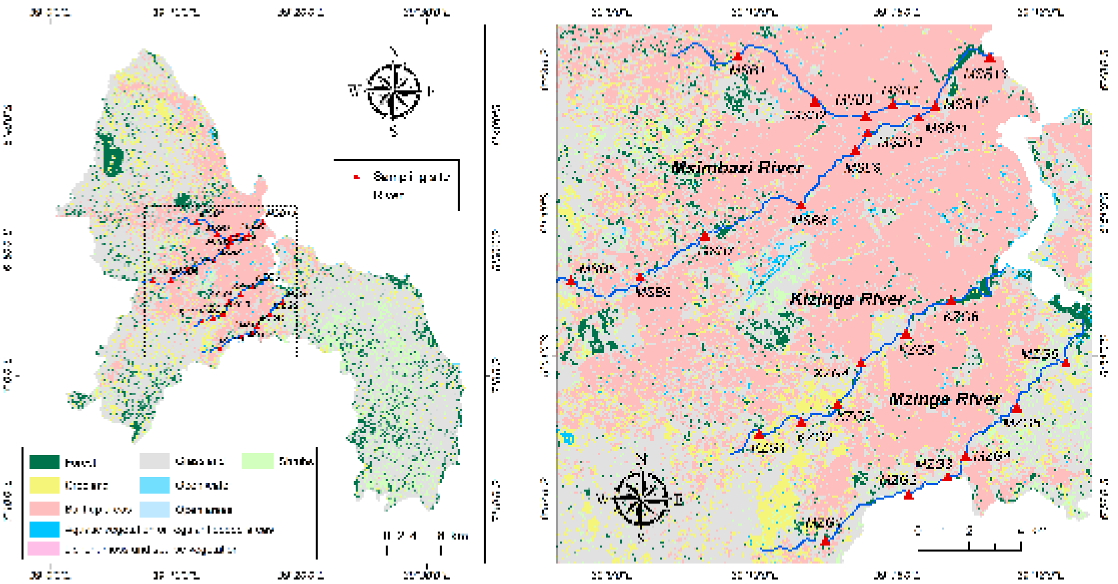

Fig. 1 Sampling sites in the three urban rivers and the land use and land cover types in Dar es Salaam

Fig. 2 Typical scene of different rivers in Dar es Salaam. (a) erosion and sand excavation in the upstream of the Mzinga River; (b) erosion caused by caused by agricultural activities on both banks of the upstream of the Kizinga River; (c) domestic waste on the banks of the upstream of the Msimbazi River; (d) informal settlements and high pollution section of the water in the midstream of the Msimbazi River. All photos were taken in July, 2019.

2.2 Monitoring and analysis

A multi-parameter water quality instrument (Horiba U 53, Japan) was used to monitor the physical parameters of surface water at each sampling site, including DO, ORP, pH, EC, TDS, and turbidity.

The raw water samples were used to analyze TN, TP, and COD_{Mn} and the filtered water samples were used to analyze TDN, TDP, NH_3-N, NO_3^--N, NO_2^--N, and SRP. Analysis methods for different water quality indicators are shown in SI Table 2. Chemical analyses of all water samples were carried out at the Technical Service Centre of the Nanjing Institute of Geography and Lakes, Chinese Academy of Sciences (CNAS L1628, China National Accreditation Service for Conformity Assessment).

2.3 Water quality evaluation

In this study, the WQI method was used for the comprehensive water quality assessment of the target water bodies in the study area. WQI is a comprehensive water quality assessment method that was originally developed in the 1960s and 1970s and has been improved in recent years (Naveedullah et al., 2016; Şener et al., 2017). It is widely used in inland water bodies such as rivers, lakes, and reservoirs. The formula for calculating WQI can be expressed as follows (Naveedullah et al., 2016):

$$WQI = k\frac{\Sigma_1^n C_i P_i}{\Sigma_1^n P_i}$$

where k is a constant ranging from 0.25–1, with 1 indicating unpolluted water bodies and 0.25 indicating black smelly water bodies; n is the content of the physio-chemical parameter used to calculate the WQI; C_i refers to the standardized value of an indicator, and P_i refers to the relative weight of the physio-chemical parameter, taking values between 1 and 4, where 1 refers to the least important and 4 to the most important (SI Table 3). For the purpose of eliminating subjective differences, the value of k was taken as 1 in this study.

The WQI values ranged from 0 to 100, and the water quality classification of the evaluated water bodies can be made according to the magnitude of the values (Jonnalagadda & Mhere, 2001; Şener et al., 2017). The WQI value of 0 –25 means the water quality is "very bad," 25 – 50 means the water quality is "bad," 50 – 70 means the water quality is "medium," 70 – 90 means the water quality is "good," and 90 – 100 means the water quality is "excellent."

2.4 Data processing and statistical analysis

The sampling site map with LULC data was created and analyzed using ArcGIS 10.7. Figures of other physicochemical data were created in OriginLab 2021. The mathematical and statistical analyses such as correlation analysis and principal component analysis used in this study were also analyzed using the relevant programs and APPs in OriginLab 2021.

3 Results

3.1 DO, pH, ORP, EC, TDS, and turbidity

The results of main physical indicators of the different rivers are summarized in Table 1. The mean DO concentrations in the dry season of three rivers were significantly higher ($p < 0.05$) than the values during the rainy season. And the DO levels in the middle and lower reaches of the Msimbazi River were very low, approaching 0 mg/L at MSB11, MSB12, and MSB13. Spatially, the DO levels in the rivers generally decreased from the upstream, to the middle and the downstream. The pH of all rivers was weakly alkaline, the mean pH values in the dry season were relatively higher than the rainy season. The mean ORP levels for the Mzinga and Kizinga Rivers were significantly higher ($p < 0.05$) in the dry season than the rainy season, and the water bodies were weakly oxidized. For Msimbazi River, the mean ORP levels in the rainy season were significantly higher ($p < 0.05$) than the dry season, the water body were weakly reduced. Spatially, all three rivers showed large fluctuations in ORP levels in both seasons.

The mean EC for the Mzinga and Kizinga Rivers were slightly higher in the dry season than the rainy season. The spatial and temporal variability of EC in the Mzinga River was smaller, while the Kizinga River EC values increasing from the upstream to the downstream. For Msimbazi River, the spatial and temporal distribution of EC decreased from the upstream to the midstream and then increased after the confluence; EC was clearly higher during the dry season than during the rainy season. The trend of TDS is similar to that of EC.

The Mzinga and Kizinga Rivers were characterized by higher turbidity during the rainy season, with the Kizinga River having relatively higher turbidity than the other two rivers. In terms of spatial distribution, turbidity in the Mzinga River tended to increase from the upstream to the downstream. The high turbidity in the Kizinga River were mainly founded in the upper reaches, while turbidity in the Msimbazi River tended to increase from the upstream to the midstream and decreased after the confluence.

Table 1 Statistics of physical parameters of the rivers

	DO	pH	ORP	EC	TDS	Tur

			(mg/L)		(mV)	(mS/cm)	(g/L)	(NTU)
Mzinga River	Dry season	Mean	8.59	10.01	179.83	0.38	0.25	54.8
		Max	9.36	10.38	225.00	0.42	0.27	77.90
		Min	7.07	9.47	55.00	0.32	0.21	30.00
		CV[a]	9.31%	2.99%	35.76%	10.82%	11.40%	28.29%
	Rainy season	Mean	4.02	7.82	114.40	0.36	0.23	78.74
		Max	4.87	8.05	149.00	0.39	0.25	123.00
		Min	1.88	7.41	19.00	0.32	0.21	9.30
		CV	30.66%	3.17%	7.76%	6.72%	6.66%	54.26%
Kizinga River	Dry season	Mean	8.76	10.00	173.00	0.61	0.39	113.42
		Max	8.94	10.26	229.00	0.99	0.64	172.00
		Min	8.44	9.75	37.00	0.32	0.21	69.10
		CV	2.03%	2.07%	39.88%	47.44%	47.52%	31.21%
	Rainy season	Mean	4.07	7.99	134.67	0.64	0.41	184.38
		Max	4.92	8.22	147.00	0.88	0.57	512.00
		Min	3.44	7.73	119.00	0.31	0.20	72.30
		CV	13.25%	2.00%	7.76%	33.06%	32.73%	88.28%

Msimbazi River	Dry season	Mean	6.21	8.51	35.77	2.71	1.69	96.53
		Max	10.30	9.42	179.00	11.30	6.95	296.00
		Min	0.97	7.61	-190.00	0.81	0.49	26.00
		CV	46.72%	5.82%	343.41%	98.14%	96.70%	91.11%
	Rainy season	Mean	3.46	8.36	96.80	1.71	1.09	92.28
		Max	5.65	9.15	117.00	3.27	2.09	147.00
		Min	1.63	7.96	28.00	1.23	0.79	35.70
		CV	36.57%	3.48%	33.01%	30.52%	30.52%	56.06%

Note: [a], Coefficient of Variation

3.2 Nitrogen and COD_{Mn}

The mean TN concentrations in the dry season in the Mzinga, Kizinga, and Msimbazi Rivers were 2.09 mg/L (CV = 24.86%), 6.89 mg/L (CV = 34.74%), and 25.03 mg/L (CV = 96.01%), which were significantly higher ($p < 0.05$) than the values (1.44 mg/L (CV = 13.52%), 3.78 mg/L (CV = 23.82%), and 3.92 mg/L (CV = 40.65%)) during the rainy season. The Msimbazi River had the highest TN concentration, with a high TN concentration of 85.79 mg/L at MSB9 during the dry season. Spatially, the TN concentration in the Mzinga and Kizinga Rivers gradually increased from the upstream to the midstream in the dry season and decreased at the downstream estuary; in the rainy season, the TN concentration gradually increased from the upstream to the downstream. The TN concentration in Msimbazi River gradually increased from the upstream to the downstream during both seasons. The TN composition of the three rivers was mainly TDN. The percentage of TDN in TN in the Mzinga and Kizinga rivers was over 80%. The percentage of TDN in TN of Mzinga River was not significantly different between the two seasons. During the rainy season, the percentage of TDN in TN of Kizinga River decreased significantly, with the average percentage dropping from 88.15% to 80.17%. Spatially, the percentage of TDN in TN in the Mzinga and Kizinga Rivers during the dry season tended to increase gradually from the upstream to the midstream and decreased slightly in the downstream estuary. The percentage of TDN in TN of Msimbazi River was significantly higher in the rainy season than in the dry season. In the dry season, the proportion of the upper reaches was more than 80%, and the proportion of TDN in the middle and lower reaches dropped sharply to approximately 40%. There was no obvious spatial change during the rainy season, but the percentage of TDN in TN was above 90% at most sampling points.

Monitoring focused on three of the DIN fractions (NH_3-N, NO_3^--N, and NO_2^--N) and the results are shown in Fig. 3(c, d). The mean concentrations of NH_3-N during the dry season in Mzinga, Kizinga, and Msimbazi Rivers were 0.024 mg/L (CV = 11.32%), 0.026 mg/L (CV = 17.3%), and 12.09 mg/L (CV = 108.3%), respectively, while the mean NH_3-N concentrations in the rainy season were 0.067 mg/L (CV = 62.24%), 0.226 mg/L (CV = 45.45%), and 1.844 mg/L mg/L (CV = 102.27%). The concentration of NH_3-N in the water column of the Msimbazi River was relatively higher than the other two rivers, and the concentration of NH_3-N in the water column at MSB9 reached 40.07 mg/L during the dry season. In terms of temporal and spatial distribution, the NH_3-N concentration of Mzinga and Kizinga Rivers was higher during the rainy season than during the dry season. In the rainy season, the NH_3-N concentration of Mzinga River body first increased and then decreased from the upstream to the downstream, and the trend of NH_3-N in the Kizinga River was the opposite of that in the Mzinga River and reached the lowest value in the middle reaches. The NH_3-N concentration in the Msimbazi River was higher during the dry season than during the rainy season, and generally increased from the upper to the middle and lower reaches. The average concentrations of NO_3^--N in Mzinga, Kizinga, and Msimbazi Rivers during the dry season were 0.64 mg/L (CV = 72.3%), 3.59 mg/L (CV = 50.57%), and 0.97 mg/L (CV = 131.0%), which were higher than the values (0.46 mg/L (CV = 78.08%), 2.31mg/L (CV = 43.66%), and 0.94 mg/L (CV = 45.13%)) during the rainy season. The NO_3^--N concentration in the Kizinga River was the highest, with a high NO_3^--N concentration of 6.35 mg/L at site KZG5 during the dry season. The spatial distribution of NO_3^--N concentration in the three rivers gradually increased from the upstream to the midstream, and then decreased to the downstream estuary. The mean NO_2^--N concentrations during the dry season in the Mzinga, Kizinga, and Msimbazi Rivers were 0.003 mg/L (CV = 100.89%), 0.066 mg/L (CV = 87.15%), and 0.144 mg/L (CV = 113.84%), respectively, while the mean NO_2^--N concentrations during the rainy season were 0.006 mg/L (CV = 54.58%), 0.09 mg/L (CV = 43.49%), and 0.128 mg/L (CV = 83.34%), respectively. The spatial and temporal distribution of NO_2^--N in both the Mzinga and Kizinga Rivers increased from the upstream to the downstream, with a higher concentration during the rainy season than during the dry season. NO_2^--N levels in the Msimbazi River gradually increased from upstream to the midstream and decreased after confluence in the downstream.

The percentage of DIN in TDN varied considerably in different rivers and was higher during the rainy season than the dry season in Mzinga and Kizinga Rivers. The percentage of DIN in TDN was lower in the Mzinga River, ranging from 5% to 60%. The spatial distribution of DIN as a percentage of TDN in the Mzinga River gradually increased from the upstream to the midstream and decreased to the downstream estuary during the dry season; during the rainy season it tended to increase from the upstream to the downstream. The percentage of DIN in TDN in Kizinga River was between 44% and

98%. The spatial distribution during the dry season and the rainy season was relatively consistent, and the proportion reached the highest value in the middle and lower reaches. The percentage of DIN in TDN in the Msimbazi River ranged from 33% to 99%, with a large fluctuation from the upstream to the midstream during the dry season, reached a maximum value in the midstream and then decreased in the downstream, and gradually increased from the upstream to the downstream during the rainy season and reached a maximum of 95.6% of DIN to TDN after confluence.

The characteristics of COD_{Mn} levels in the three rivers during different seasons are shown in Fig. 3(b). The mean COD_{Mn} concentrations during the dry season in the Mzinga, Kizinga, and Msimbazi Rivers were 6.74 mg/L (CV = 7.9%), 12.76 mg/L (CV = 17.85%), and 9.06 mg/L (CV = 79.49%), respectively, while the mean COD_{Mn} concentrations during the rainy season were 5.86 mg/L (CV = 10.97%), 10.77 mg/L (CV = 46.45%), and 12.31 mg/L (CV = 33.87%), respectively. Both the Mzinga and Kizinga Rivers had higher COD_{Mn} concentration in the dry season than in the rainy season. The COD_{Mn} concentration in the Kizinga River reached a maximum value of 15.91 mg/L in the middle reaches during the dry season, while the COD_{Mn} concentration at the most upstream site reached a maximum value of 20.96 mg/L during the rainy season. In the dry season, the COD_{Mn} concentration of Msimbazi north branch gradually decreased from the upstream to the middle reaches, and the COD_{Mn} concentration of the south branch gradually increased from the upstream to the middle reaches, but decreased after the peak of 14.71 mg/L at the MSB9 location, and then increased after the downstream confluence. During the rainy season, the COD_{Mn} concentration of Msimbazi River first increased, then decreased, and then gradually increased after confluence from the upstream to the midstream.

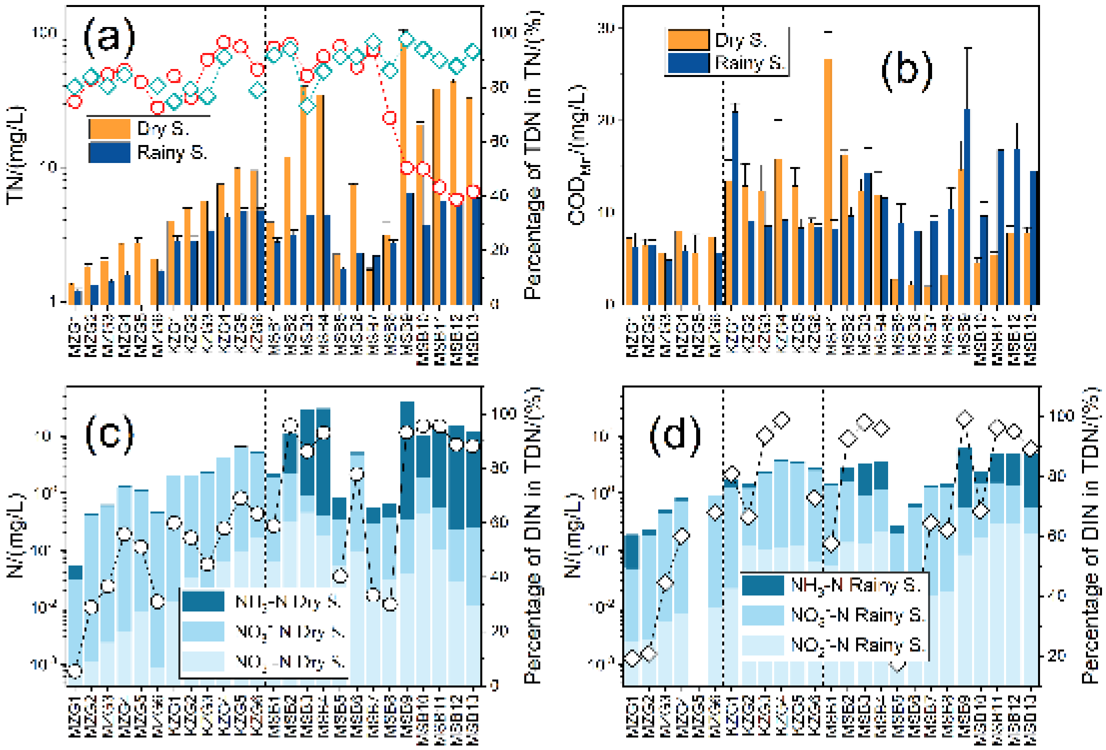

Fig. 3 Characteristics of nitrogen and COD_{Mn} distribution in different rivers. ((a): distribution characteristics of TN and TDN; (b): distribution characteristics of COD_{Mn}; (c): distribution characteristics of NH_3-N, NO_3^--N, and NO_2^--N in the dry season; (d): distribution characteristics of NH_3-N, NO_3^--N, and NO_2^--N in the rainy season; dot indicates the percentage of TDN in TN during the dry season and diamond indicates the percentage of TDN in TN during the rainy season in (a); dot indicates the percentage of DIN in TDN during the dry season in (c) and diamond indicates the percentage of DIN in TDN during the rainy season in (d).)

3.3 Phosphorus

The variation in water column phosphorus patterns is shown in Fig. 4. The mean concentrations of TP during the dry season of Mzinga, Kizinga, and Msimbazi Rivers were 0.03 mg/L (CV = 82.32%), 0.36 mg/L (CV = 62.46%), and 0.43 mg/L (CV = 127.35%), respectively, and the mean concentrations of TP during the rainy season were 0.06 mg /L (CV = 34.94%), 0.74 mg/L (CV = 62.09%), and 0.42 mg/L (CV

= 115.32%), respectively. The TP concentration in the Mzinga and Kizinga Rivers was relatively consistent, reaching a maximum in the middle and lower reaches of the river in both seasons, and the concentration was higher during the rainy season than during the dry season. The TP of Msimbazi River obviously change temporally, but fluctuated spatially. The concentration of TP in the water column of the Msimbazi River gradually increased from the upstream to the downstream.

The proportion of TDP in TP varied in the different river sections. The percentage of TDP in TP in Mzinga River was relatively low, ranging from 13% to 61% during the dry season and the rainy season, and the percentage of TDP in TP fluctuated to a certain extent from the upstream to the midstream, then increased to the downstream. The percentage of TDP in TP of Kizinga River was relatively higher than the other two rivers, ranging from 45% to 84%. During the dry season, the percentage of TDP in TP decreased from the upstream to the downstream; in the rainy season, the proportion gradually increased from the upstream to the midstream and decreased to the downstream river section. During the dry season, the percentage of TDP in TP in the northern branch of Msimbazi River gradually increased from the upstream to the midstream, while the southern branch gradually decreased from the upstream to the midstream. After the confluence of the two branches, the percentage of TDP in TP in the downstream reaches increased. During the rainy season, the percentage of TDP in TP in the north and south branches gradually increased from the upstream to the midstream. After the confluence, the percentage of TDP in TP reached a maximum of 91.2%.

The mean concentrations of SRP in the rainy season in the Mzinga, Kizinga, and Msimbazi Rivers were 0.012 mg/L (CV = 122.6%), 0.455 mg/L (CV = 75.2%), and 0.131 mg/L (CV = 75.2%), which were significantly higher ($p < 0.05$) than the values (0.004 mg/L (CV = 44.9%), 0.131 mg/L (CV = 110.6%), and 0.064 mg/L (CV = 96.7%)) during the dry season. In terms of temporal distribution, the higher SRP levels in the Kizinga River than in the other two rivers, reaching 1.15 mg/L at point KZG4 during the rainy season. The SRP in the Kizinga River showed a clear peak in the midstream section, while the SRP in the Msimbazi River gradually increased from the upstream to the downstream.

The proportion of SRP in TDP varied greatly in different rivers and river sections. During the rainy season, the percentage of SRP in TDP of Mzinga River gradually decreased from the upstream to the midstream and increased from the lowest value of 34% toward the downstream. In the dry season, the percentage of SRP in TDP fluctuated to some extent, but the overall trend was gradually increasing from the upstream to the downstream. During the rainy season, the percentage of SRP in TDP of Kizinga River was approximately 90%, which was relatively higher than the other two rivers. During the dry season, the percentage of SRP in TDP gradually increased from the upstream to the midstream and decreased toward the downstream. The percentage of SRP in TDP of Msimbazi River was between 20% and 93%, varied greatly in the different river sections, and was higher during the dry season than the rainy season. Spatially, the percentage of SRP in TDP of Msimbazi north branch generally decreased from the upstream to the midstream in the dry season, while the SRP in TDP in the southern branch first increased and then decreased from the upstream to the downstream to a certain extent, and gradually decreased after confluence. During the rainy season, the percentage of SRP in TDP of Msimbazi north branch gradually increased from the upstream to the midstream, and the percentage of SRP in TDP of the south branch gradually increased from the upstream to the midstream, then began to decrease after MSB8 reaches a maximum of 70.8%.

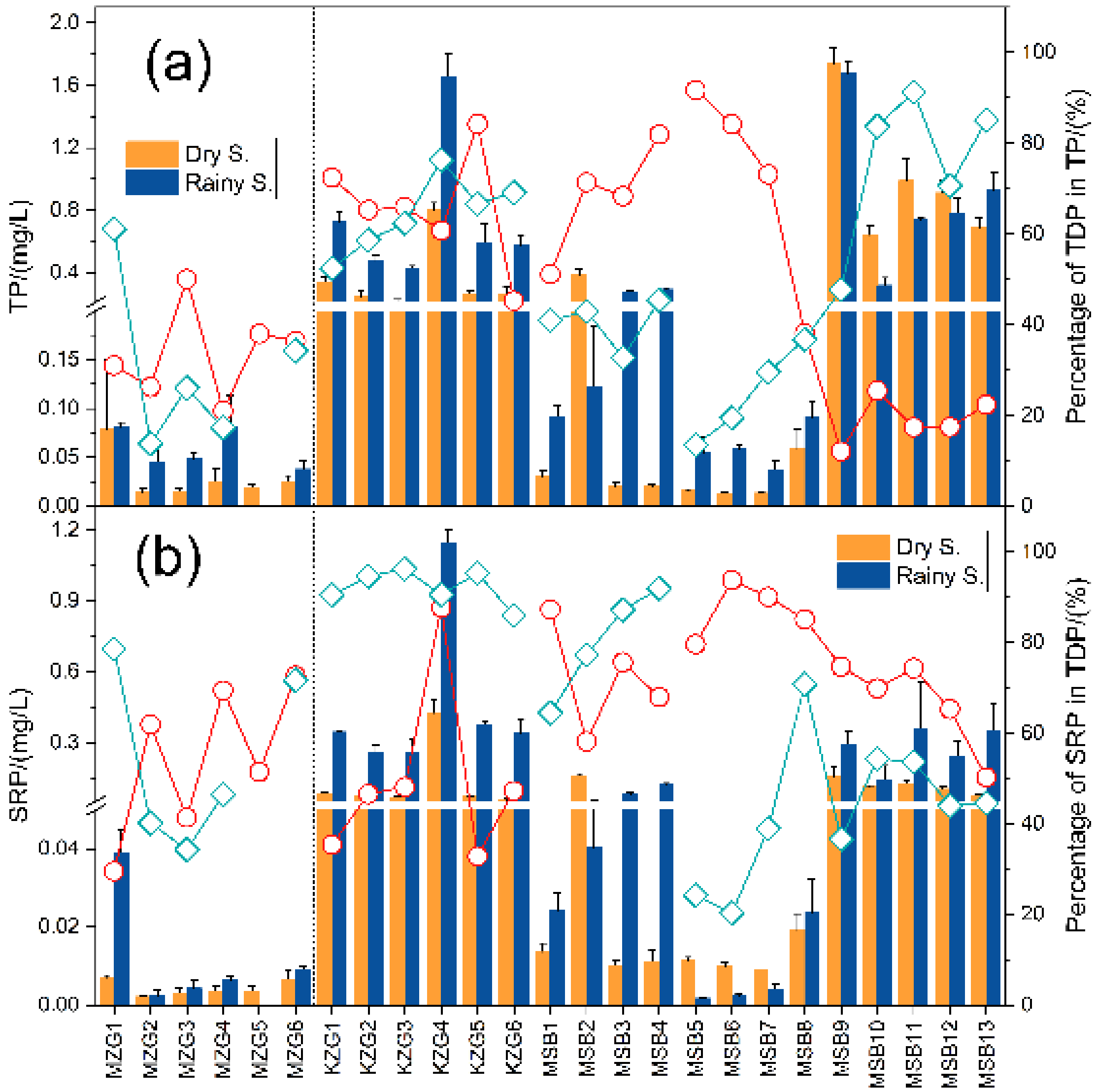

Fig. 4 Characteristics of phosphorus distribution in different rivers. ((a): distribution characteristics of TP and TDP; (b): distribution characteristics of SRP; dot indicates the percentage of TDP in TP during the dry season and diamond indicates the percentage of TDP in TP during the rainy season in (a); dot indicates the percentage of SRP in TDP during the dry season and diamond indicates the percentage of SRP in TDP during the rainy season in (b).)

3.4 Water Quality Index

The results of the comprehensive water quality assessment of the Mzinga, Kizinga, and Msimbazi Rivers are shown in Fig. 5. Water quality varies significantly between the different river bodies. During the dry season, the WQI of the Mzinga River ranged from 70 to 75, with an average value of 73.1 and an overall "good" rating; the WQI of the Kizinga River ranged from 62 to 65.5, with an average value of 63.9 and an overall "moderate" rating; the WQI of the Msimbazi River ranged from 24 to 74.5 with an average value of 48.9 and an overall rating of "poor." During the rainy season, the WQI of the Mzinga River ranged from 65.2 to 69.1 with a mean of 67.6 and an overall "medium" rating; the WQI of the Kizinga River ranged from 53.5 to 58.7 with a mean of 56.3 and an overall "medium" rating; the WQI of the Msimbazi River ranged from 33.5 to 62.6, with a mean value of 47.9 and an overall rating of "poor." Overall, the water quality of the Mzinga River was relatively good, the Kizinga River was generally second best, and the Msimbazi River was significantly worse. The water quality fluctuated significantly between the dry and the rainy seasons, with the Mzinga and Kizinga Rivers generally characterized by better water quality during the dry season than during the rainy season, and a 2.5%–16.4% decrease during the rainy season. The seasonal variation in water quality varies between different sections of the Msimbazi River, with water quality fluctuating more significantly than the other two rivers. The water quality of sites MSB1 and MSB5–MSB8 at the upstream sites decreased by 9%–27% during the rainy season, but the water quality in the middle and lower reaches improved.

For Mzinga River, the WQI gradually decreased from the upstream to the downstream during the dry season, while the water quality at the most upstream observation point decreased more during the rainy season, but also decreased slightly overall from the upstream to the downstream. The WQI of Kizinga River water body changed slightly overall, with a certain degree of fluctuation during the rainy season. The water quality of the most upstream observation point had more of a decrease, and the overall decreasing trend was from the upstream to the downstream; this was similar to the pattern of change in the WQI of the Mzinga River during the rainy season. In both seasons, the WQI of the most downstream sites of the Kizinga River increased significantly, and the water quality of the corresponding river sections improved. The WQI of Msimbazi River body changed greatly overall. In the dry season, the WQI of the north branch gradually decreased from the upstream to the midstream. The WQI of the south branch decreased significantly in the middle and the downstream, and the water quality of the corresponding river section decreased significantly. After the confluence, the water quality continued to decline. During the rainy season, the water quality of both branches of the Msimbazi River decreased at the most upstream observation points, and the WQI of the water body as a whole decreased from the upstream to the downstream.

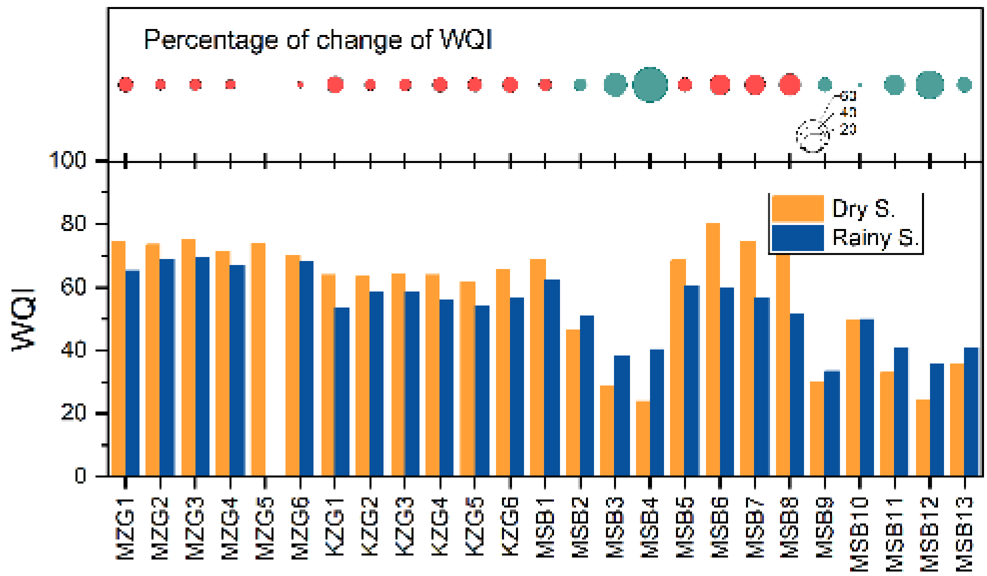

Fig. 5 Seasonal changes of WQI in Mzinga, Kizinga, and Msimbazi Rivers (red bubbles represent decreased percentage of WQI from the dry season to the rainy season (negative values); green bubbles represent increased percentage of WQI from the dry season to the rainy season (positive values))

4 Discussion

The results of this study showed that the main physicochemical indicators of the water bodies of the Mzinga, Kizinga, and Msimbazi Rivers showed obvious fluctuations in spatial and temporal distribution. The DO concentration in the upstream of Msimbazi River was significantly higher than that in the downstream. These results were consistent with those reported by Chen et al.(Chen et al., 2022). It was also found that COD_{Mn} and NH_3-N responded to the trend of DO, with higher concentrations of COD_{Mn} and NH_3-N in the downstream. The main reason for this phenomenon was that the Msimbazi River was greatly affected by urban non-point source pollution after flowing through the urban area. DO concentration in three rivers were lower in the rainy season than in the dry season. The generally higher temperature and lower air pressure make the water column DO holding capacity decrease, which is an important reason for the low DO in the rainy season (Mihale, 2022). The level of NH_3–N which is an important inorganic oxygen-demanding substance is about three times higher than in the dry season, which also contributed to the DO decrease in the rivers. The high COD content and oxygen-consuming substances in the water column of Msimbazi River also contribute to the low DO in the rainy season. The ORP levels in the Kizinga and Mzinga Rivers were relatively lower in the rainy season, which could be the result of the decrease of DO levels for solid phase terminal electron acceptors can be used for oxidation under oxygen-depleted conditions, which finally resulted the decline of ORP levels in the water column (Aeppli et al., 2022). Moreover, the surface runoff in the rainy season inevitably brings land-derived organic pollutants previously trapped in the sub-basin. Higher organic pollutants, requires more electron acceptors for decomposition and degradation, which also contributed to the decrease of ORP (Silva et al., 2017). The ORP levels of Msimbazi River in the rainy season was significantly higher than that in the dry season ($p < 0.05$). Since the middle and lower reaches of the river were generally in anaerobic decomposition during the dry season, the large discharge of the flow during the rainy season played a role in diluting pollutants, which led to a certain degree of alleviation of its low ORP problem and an increase in ORP levels. Nevertheless, the ORP level of the Msimbazi River was still low during the rainy season and the water body was in a weakly reductive state. The significant decrease in pH in the Kizinga and Mzinga rivers during the rainy season may be related to the large amount of soil leachate brought in by surface water during the rainy season ($p < 0.05$) (Macdonald et al., 2007).

The higher EC levels in the lower reaches of the Msimbazi River could be related to the high concentration of strong electrolytes of the major anion and cation classes. During the rainy season, the high concentration of anions and cations in the water column was massively diluted by incoming flood water, causing the EC in the downstream water column to drop significantly. The pattern of change in TDS was similar to the pattern of EC, with an increase or decrease in EC leading to a corresponding change in TDS (Yenugu et al., 2020). The downstream of the Msimbazi River was typically influenced by the Indian Ocean tides, which could be the main reason for the significant high EC and TDS levels in the downstream regions. Turbidity had typical seasonal differences, with lower turbidity during the dry season and generally higher turbidity during the rainy season in the studied rivers, probably because of the increased terrigenous sediments entering the water along with the rainy season floods (Shen et al., 2022). LULC data (Fig. 1) show that the upper reaches of the Kizinga and Mzinga Rivers flowed mainly through agricultural cultivation areas, where the soil erosions is always high (Polidoro et al., 2021), causing the high turbidity in the upper reaches. In the case of the Msimbazi River, the middle and lower reaches flowed through densely populated settlement areas and the water body received a large amount of domestic sewage drainage, resulting in a significant increase in turbidity in the middle and lower reaches. Residential and urban agricultural runoff is an important cause of increased turbidity in the urban rivers (Nhapi & Tirivarombo, 2004).

The spatial and temporal fluctuations of nitrogen and phosphorus in water bodies in the three rivers were more complex than the physical indicators. The TN concentrations in the three rivers were all moderately or severely polluted (>1.0 mg/L) according to the National Environmental Standards Compendium of Tanzania (TZS 789:2003-Drinking (potable) water–Specification). The main reason for the relative decrease of TN in these rivers in the rainy season could be attributed to the greatly increased river flow during the rainy season, which diluted and diffused the dissolved N pollutants trapped in each river sections. This result was consistent with reported by Chen et al. (Chen et al., 2022). The waters in the middle and lower reaches of the Msimbazi River had extremely high TN and were heavily polluted by nitrogen, probably because of the discharges from small-scale handicraft production and untreated discharges of domestic sewage. The high concentration of TN in waters of the Mzinga and Kizinga Rivers, on the other hand, was clearly influenced by the discharge of urban agriculture and informal residential settlements. The percentage of TDN in TN of Mzinga and Kizinga River water bodies were found similar pattern in other water bodies (Gao et al., 2019). The proportion of TDN to TN decreased during the rainy season because of the increase in the total particulate nitrogen with increased particulate substances introduced by the surface runoff. The proportion of TDN to TN in the middle and lower reaches of the Msimbazi River decreased sharply during the dry season, with the input of urban surface sources of particulate nitrogen being the main cause. The composition of DIN was significantly different between the rivers, with the Kizinga and Mzinga Rivers dominated by NO_3^--N, while the Msimbazi River was dominated by NH_3-N. This difference in distribution was particularly significant in the middle and lower reaches. Generally, NO_3^--N concentrations were higher in rivers polluted by agriculture, but NH_3-N concentrations were higher in rivers polluted by domestic wastewater (Gao et al., 2019). The high levels of TN, TDN, TPN, and NH_3-N in the middle and lower reaches of the river were mainly because of the uncontrolled discharge of domestic–type pollution from inadequate sewage treatment system coverage, which in turn leads to contamination of surface water and groundwater, significantly increasing the health risk to the community (Mapunda et al., 2018; Pacheco & Fernandes, 2016).

The TP concentration ranged from 0.01 – 1.7 mg/L in the three rivers. Referring to the US-EPA and EU standards, the Mzinga, Kizinga, and Msimbazi Rivers all had moderate to severe TP pollutions (> 0.1 mg/L) (Awoke et al., 2016; Chen et al., 2022). Emissions from detergents and household food consumption were the main sources of phosphorus pollution in Dar es Salaam's surface water (Xiong et al., 2020). Severe TP pollution was found in the waters of the middle and lower reaches of the Msimbazi River. However, the TP pollution in the water column was reduced during the rainy season because of dilution from the large water discharge. The concentrations of N and P decreased at the mouth of the lower reaches of Kizinga River, which was caused by the purification of a natural wetland that the main stream flowed through. The composition of TP in the three rivers also differed, with TDP accounting for a higher proportion of TP in the Kizinga River, averaging 65.1%, and particulate P accounting for a higher proportion of TP in the Mzinga River, averaging 67.9%. The percentage of TDP to TP in the Msimbazi River decreased significantly in the middle and lower reaches during the dry season, with the input of urban surface sources of particulate P–containing pollutants being the main cause of this phenomenon. The SRP levels in the three rivers were higher in the rainy season than in the dry season. The Msimbazi River showed a typical trend from the upstream to the downstream, with the discharge of domestic sewage from the urban core area and the discharge of wastewater from artisanal workshops being the main causes of the increase in SRP in its middle and lower reaches (Mohammed, 2002).

As a comprehensive indicator, the WQI distinguished and reflected the changes in water quality in the three rivers in this study. From the WQI results, there were clearly large spatial and seasonal fluctuations in water quality in the Mzinga, Kizinga, and Msimbazi Rivers. Typically, water quality in the Kizinga and Mzinga Rivers was relatively good and the water quality in the Msimbazi River was relatively poorer. A decreasing trend in WQI from the upstream to the downstream was clear in the three rivers. The lack of basic wastewater treatment facilities resulted in the direct discharge of untreated municipal sewage and wastewater from commercial and industrial activities into the rivers, leading to a significant deterioration in water quality in the middle and lower reaches of the river after it flowed through the urban core area. This phenomenon is commonly found in medium and large cities in developing countries with rapid urbanization (Haddis et al., 2012; Hoven et al., 2017; Juma et al., 2014; Yu et al., 2018).

To further analyze the influencing factors on WQI in the three rivers, we conducted correlation analysis and PCA. WQI was significantly negatively correlated with TN, TP, COD_{Mn}, NH_3-N, NO_3^--N, NO_2^--N, TDN, TDP, EC, TDS, and turbidity ($p < 0.05$) (Fig. 6). The results of the PCA showed that the first two principal components explained 62.7% of the total variance during the dry season and 68.1% of the total variance during the rainy season (Fig. 7). The main variables on the first principal component affecting the WQI in both seasons were DO, ORP, and nitrogen. The main variables on the second principal component were EC, TDS, TDP, and SRP. Therefore, the first principal component affecting the WQI of water bodies can be defined as the combined indicator of water body redox status and N, and the second principal component was defined as the strong electrolyte indicator represented by EC and dissolved P. The results of the analysis showed that the physical and chemical indicators of various nutrient salts, represented by DO, ORP, and TN, were the main influencing factors on the water quality status of Mzinga, Kizinga, and Msimbazi Rivers.

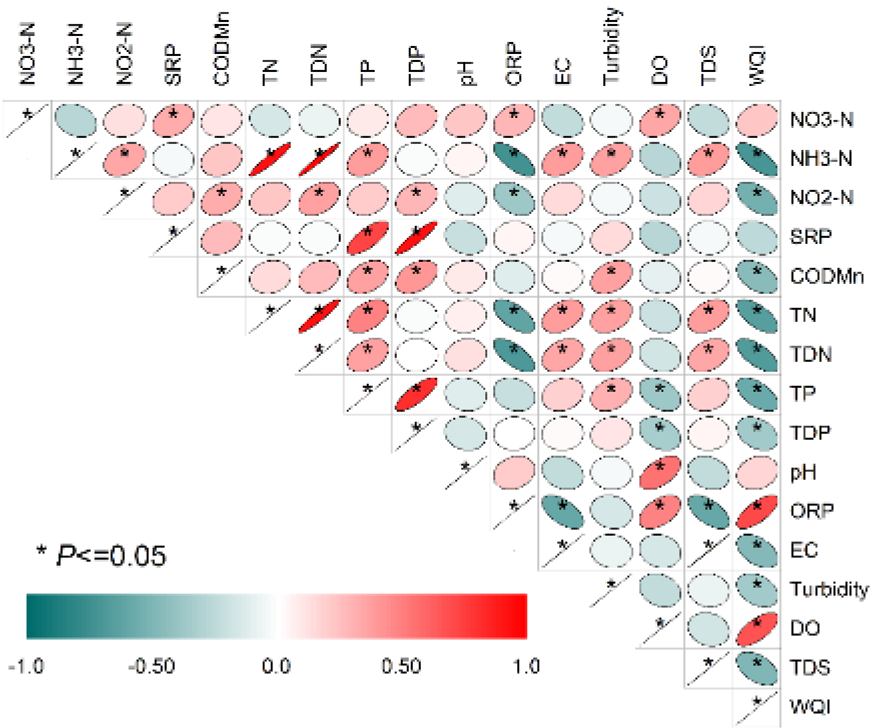

Fig. 6 Correlation analysis between WQI and physicochemical parameters of the rivers

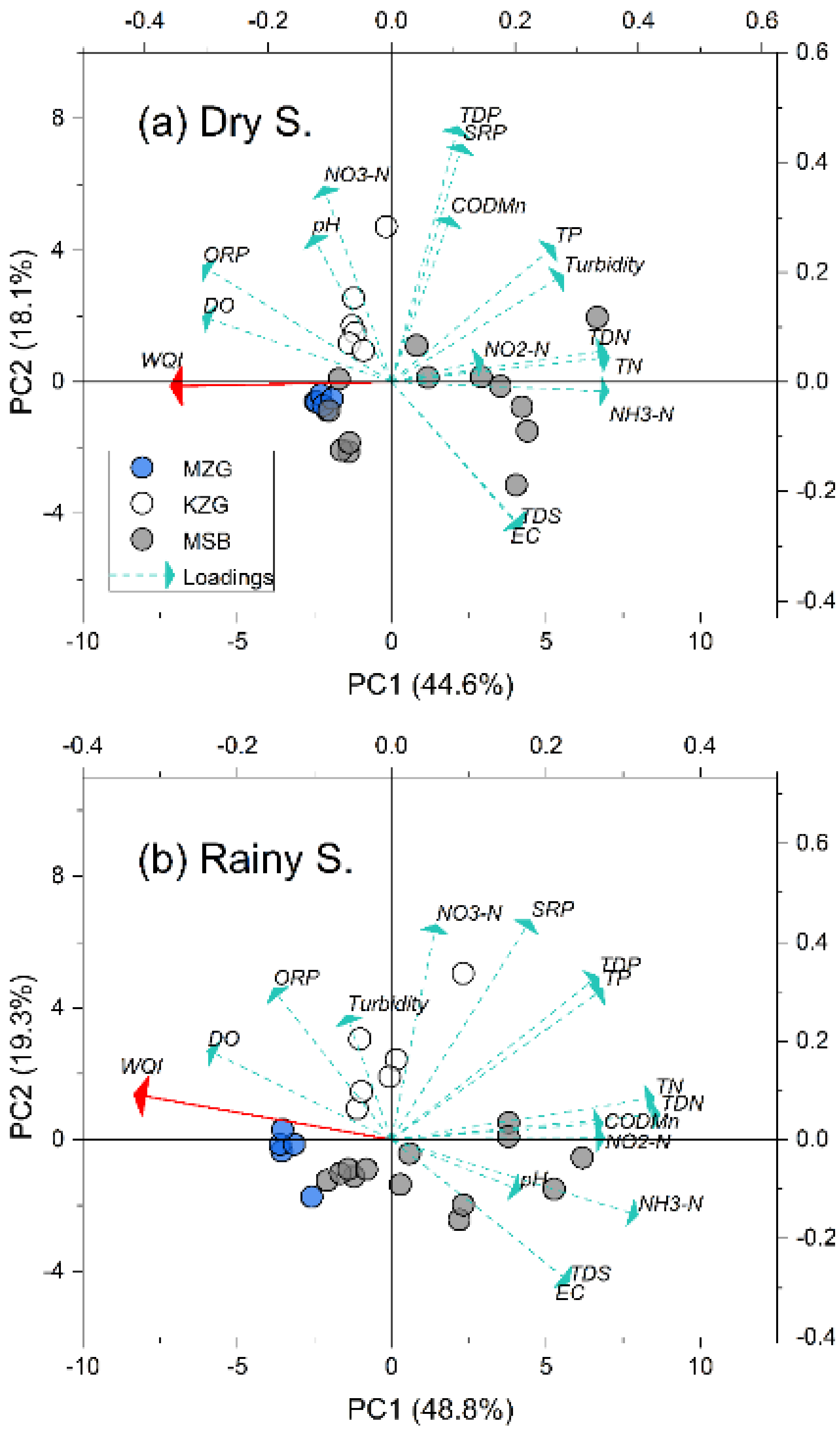

Fig. 7 Principal component analysis of WQI and physicochemical parameters in the Mzinga, Kizinga, and Msimbazi Rivers (where (a) is the dry season and (b) is the rainy season)

Numerous studies have demonstrated that land use change and human socio-economic development in watersheds or sub-basins have significant impacts on the water quality of rivers (Gorgoglione et al., 2020; Khan et al., 2017; Liu et al., 2022). Agriculture and untreated wastewater pose two of the greatest threats to environmental water quality globally: they release excess nutrients into rivers, lakes and aquifers and damage ecosystem function (UNEP 2021, Progress on Ambient Water Quality: Global indicator 6.3.2 updates and acceleration needs). The city of Dar es Salaam has experienced rapid growth in terms of both total population and economic size over the last few decades. Its total population has grown from 1.607 million (1992) to 4.327 million (2012) and its average population density has reached 3133 persons/km^2 (Dar es Salaam region socio-economic profile, 2014). We have not found accurate and reliable economic growth data for the city, but according to the Tanzania National Bureau of Statistics, its total gross domestic production (GDP) reached 2,527.37 billion shillings (approximately US$10.11 billion) in 2020, which accounted for more than 15% of Tanzania's total national GDP. However, in such a large and rapidly urbanizing city, the development approach was relatively crude, with significantly inadequate wastewater treatment facilities and a large urban population living in informal settlements without wastewater treatment capacity; the resulting uncontrolled discharge of municipal wastewater and small and medium-sized artisanal, commercial, and industrial wastewater, and domestic waste disposal places enormous pressure on the urban river water environment (Chen et al., 2022; Mohammed, 2002).

LULC results (Fig. 2) showed that the main land use types of Mzinga and Kizinga Rivers in the upstream are croplands and grasslands and in the midstream are built-up areas. For Msimbazi River, the land use types are mainly built-up areas, with a large number of informal settlements distributed on both banks in the upstream. Our field investigation confirmed the land use types interpreted from remote sensing data. These LULC types could greatly affect the water quality of the corresponding rivers. Soil erosion and agricultural non-point pollution can cause severe pollution in rivers (Falkenberg et al., 2018), which could be the reason for the high turbidity and nitrogen concentrations in the upstream of the Mzinga and Kizinga Rivers. For Msimbazi River, emission of untreated domestic water and wastewater from informal settlements and small handicraft industries in the middle reach is the main cause of the degradation of the water quality. Garbage disposal sites along the banks of Msimbazi River also caused additional pollutant input to the water and degradation of the water quality. A large amount of solid waste can flow into nearby rivers with natural precipitation and surface runoff, polluting surface water bodies (Grytdal et al., 2018). Printing and dyeing industry wastewater discharge is another main cause of water quality deterioration and the black-green color of the middle reach of the river (Chen et al., 2022; Mohammed, 2002). Also, the large amount of uncontrolled wastewater and municipal sewage discharge from informal settlements puts the area at risk for infectious diseases (Kamba et al., 2016; Miller & Hutchins, 2017). As a result, a combination of population explosion, fast and uncontrolled development, rapid expansion, and lack of wastewater treatment facilities in Dar es Salaam has led to a rapid decline in river water quality, with significant ecological and health risks.

5 Conclusions and Implications

Our study on water quality of the three major urban rivers of Dar es Salaam showed that the water environment of Mzinga, Kizinga, and Msimbazi Rivers are under great stress and are largely polluted. Low DO and high nitrogen and phosphorus pollution characterizes the water of the Msimbazi River, where the middle- and downstream regions were typical black and odorous water bodies. WQI results show that the water bodies of Mzinga and Kizinga Rivers were generally in “good” and “moderate” condition, while the WQI of Msimbazi River was more variable. From the spatial and temporal distribution, the water quality of Mzinga and Kizinga Rivers was better in the dry season than in the rainy season, and gradually deteriorated from the upstream to the downstream. The water quality of the middle- and downstream of Msimbazi River deteriorates sharply. PCA results indicated that the combined indicator of redox status and N was the major component affecting the water quality of the rivers. The LULC types have great impacts to the water quality of all three rivers. Agricultural activities and soil erosion affected the water quality of the upstream of Mzinga and Kizinga Rivers. Uncontrolled wastewater emission from the built-up areas (informal settlements) was the main cause of the water quality degradation in the middle- and downstream of Msimbazi River.

Based on the results found in this study, it is strongly suggested that the water environmental management and treatment of polluted rivers in Dar es Salaam should adopt a strategy of both source control and end treatment, such as reducing uncontrolled sewage discharge from urban area, enhancing the wastewater treatment percentage, reducing soil erosion and non-point emissions from farming fields. Plus, long-term monitoring of the physiochemical parameters of the rivers are needed in order to help environmental protection and benefit the sustainable development of the social-environmental system in the region.

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Author Contributions

All authors contributed to the study and manuscript. Qiushi Shen and Sophia Shuang Chen designed the investigation and research protocol. Qiushi Shen, Zhaode Wang, Yadong Wang, Ismael A. Kimirei, Mary A. Kishe, Qun Gao, Chuanhe Xiong, Zheng Guo, and Yuke Yuan conducted the field investigation and sampling. Qiushi Shen and Yadong Wang conducted the chemical analysis of all samples. Qiushi Shen, Cunjing Yao, Chao Han, Zhaode Wang, Yadong Wang, and Jiaqi Zhang analyzed the data. Cunjing Yao and Qiushi Shen drafted the manuscript. Chao Han, Kurt Friese, Shengpeng Zuo, Lu Zhang, and Sophia Shuang Chen revised the manuscript.

Data Availability

The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethical approval

Participation of human subjects did not occur in this study.

Consent to Participate and Publish

This manuscript was approved for participate and publication by all the authors.

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