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Research article

Impact of parametric seasonal variations on water quality in the Crocodile River and Inyaka Dam in the Mpumalanga Province, South Africa

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A R T I C L E I N F O

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A B S T R A C T

This study assessed seasonal variations in water quality and their impact on the Inyaka Dam and Crocodile River in Mpumalanga Province, South Africa. A total of 206 water samples were collected across four seasons to analyse parameters including pH, turbidity, electrical conductivity (EC), temperature, Manganese (Mn), Iron (Fe), phosphate (PO_4^{3-}), nitrate-nitrogen (NO_3-N), *E. coli*, total coliforms, faecal streptococci, and Bifidobacteria. Principal component analysis (PCA) and Pearson correlation identified major pollutants and their seasonal variations, while cluster analysis grouped water quality by parameter fluctuations.

Findings indicated that water quality in both the Inyaka Dam and the Crocodile River exceeded permissible limits. In the Inyaka Dam, summer rainfall (202.68 mm) spurred microbial growth, including *E. coli* and Bifidobacteria, while winter saw elevated levels of PO_4^{3-}, EC, Fe, and NO_3-N. The Crocodile River exhibited its poorest water quality in summer, with high levels of conductivity, turbidity, Fe, Mn, and NO_3-N, driven largely by rainfall. Winter pollution in the river was marked by *E. coli*, PO_4^{3-}, total coliforms, NO_3-N, and Bifidobacteria.

The study highlights significant pollution in the Crocodile River, particularly in summer, linked to rainfall and effluent discharges. Microbial pollution persisted across seasons, influenced by both weather and point-source contamination. The winter season exacerbated water quality deterioration in the Crocodile River due to reduced flow, while Inyaka Dam's winter pollution was attributed to lake stratification.

1. Introduction

Water security has recently emerged as a major global challenge, exacerbated by climate change, pollution, and population growth, which contribute to over-abstraction of water resources [1,2]. Although the United Nations General Assembly declared access to clean and safe water a human right in July 2016, a significant number of people still lack access to this essential resource [3]. Surface water

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quality has long been subjected to continuous degradation due to both natural processes and human activities, posing a serious concern for sustainable human and economic development [4]. Many third-world countries face the dilemma of balancing water quality with the need to prioritise water supply, while even some developed nations struggle to maintain water quality due to nutrient enrichment in their water resources [5,6].

Natural factors affecting water quality include variations in the hydrological cycle, climate, stratification, and topography [7,8] which can degrade water quality through seasonal fluctuations of physicochemical and biological characteristics. Additionally, anthropogenic factors such as undertreated or untreated industrial effluents, agricultural runoff, and improper waste disposal are significant contributors to water quality degradation [9,10]. Contaminants from these activities including metals, pesticides, nutrients, salts, and other hazardous chemicals are often released into water bodies [11]. Furthermore, nitrates from sewage effluent are common in municipal wastewater that are discharged into freshwater systems [12].

In South Africa, like many other parts of the world, industries are located near rivers and dams, discharging semi-treated or untreated effluents into these bodies of water [13]. For instance, the Crocodile River in Mbombela, Mpumalanga, is surrounded by informal dumping sites, agricultural activities, and industrial operations, making it a direct discharge point for wastewater. The Inyaka dam, in Bushbuckridge, also in Mpumalanga, was primarily constructed for irrigation and is surrounded by agricultural activities although and a wastewater treatment plant that discharges effluent directly into the dam [14].

Both the Inyaka Dam and Crocodile River are subject to target water quality guidelines that monitor the quality of effluent discharges from surrounding activities [15]. National monitoring programmes such as the National Microbiological Monitoring Programme (NMMP), National Chemical Monitoring Programme (NCMP), National Toxicity Monitoring Programme (NTMP), National Eutrophication Monitoring Programme (NEMP), and the River Eco-status Monitoring Programme (REMP), along with municipalities and catchment agencies, conduct routine water quality monitoring at standardised sampling sites. Despite these monitoring programmes, and legislation like Chapter 3 of the South African National Water Act 36 of 1998 and Chapter 7 of the National Environmental Management Act 107 of 1998, which provides guidelines for pollution control and subsequent enforcement steps, South Africa still experiences significant pollution levels in its water resources [16,17]. These examples underscore the critical role of water quality monitoring plays in restoring and maintaining healthy ecosystems [18,19].

To the best of our knowledge, very few studies, if any, have reported on the temporal variation in the physicochemical and microbiological properties of water conducted in the Crocodile River in Mbombela and the Inyaka Dam in Bushbuckridge. This study, therefore, assessed and compared the temporal variations and potential pollutants in the two water resources over different seasons. Understanding of temporal variations in water quality is essential for improving watershed management.

2. Materials and methods

2.1. Study area description and land use information

2.1.1. The Crocodile River

The Crocodile River catchment is located entirely within the Mpumalanga province in South Africa (Fig. 1). The river originates from areas that lie in the vicinity of Dullstroom, where it flows into the Kwena Dam, passing through Mbombela. The catchment receives rainfall in the summer and has a subtropical climate. In addition, the Crocodile River bears with it some considerable ecological significance as it passes along the southern boundary of the Kruger National Park (KNP). There are notable activities in the surrounding areas of the catchment that may affect water quality. Closer to the sampling areas of the study are a dumping site (Fig. S1) and a wastewater treatment plant that discharges its effluent into the river. Fig. 1 shows the sampling site with coordinates (25°

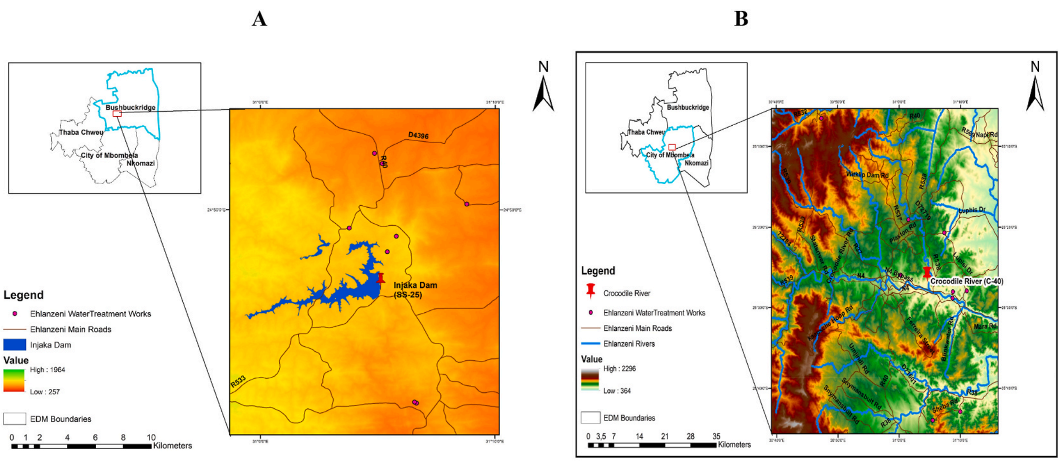

Fig. 1. Maps of the study area, and sampling sites (Esri: https://www.arcgis.com). Fig. 1A shows the Inyaka Dam, and Fig. 1B shows the Crocodile River.

29′18’’S 31° 10′23’’E)

Dense industrial, agricultural, and domestic land use activities surround the Crocodile River, which is used as a discharge point. According to Phungela et al. [16], wastewater treatment systems are problematic for the water quality of the Crocodile River.

2.1.2. Inyaka dam

The Inyaka Dam is an earth-fill Dam constructed along the Marite River in the Bushbuckridge area of Mpumalanga province and was built to store water for irrigation purposes. As of 2014, the dam served as an abstraction point for the Inyaka water treatment plant, which supplied treated water to more than 850,000 people in Bushbuckridge [14]. Given the population supplied by the Inyaka dam, the dam is one of the most critical water resources and is unfortunately under-represented in the literature. Fig. 1A shows the sampling point with coordinates (24°53′26.60’’S 31°04′45.37’’E).

Along the Inyaka Dam, there are noticeable scattered small-scale agricultural activities. This is because the dam was initially intended for irrigation, but most of the water has been repurposed for domestic and drinking use because of the growing population of Bushbuckridge. Moreover, the Maviljan wastewater treatment plant uses the dam as a discharge point (Fig. S2), which is currently under-treating the effluent discharged to the dam.

2.2. Sample collection and handling

Composite water samples were collected in the summer (December to February), autumn (March to May), winter (June to August), and spring (September to November) of 2021 from the Crocodile River and Inyaka Dam. Water samples were collected at nationally established sites designated SS-25 and C-40 in the Department of Water and Sanitation monitoring programme. Water samples were collected from the surface layer in 500 mL sterile bottles directly from the river and dam. A total number of 104 and 102 samples were collected from the Inyaka Dam and Crocodile River, respectively every month of each season. The samples were analysed within 6 h after being transported to the laboratory or stored at $<8^{o}$C overnight when analysis was impossible.

2.3. Experimental methods

Thirteen parameters were selected based on resource quality objectives and risk assessment from surrounding activities. These parameters included *Escherichia coli* (*E. coli*), Total coliforms (TC), Faecal streptococci (FS), Bifidobacteria, pH, Electrical conductivity (EC), Turbidity, Temperature, Average rainfall (AR), Iron (Fe), Manganese (Mn), Nitrate-nitrogen (NO_3-N), and Phosphate (PO_4^{3-}). Only temperature was recorded on site with an infrared thermometer. Average rainfall data were obtained with permission from the South African Weather Services (SAWS).

The concentrations of Fe, Mn, NO_3-N and PO_4 were measured using a Hach DR3900 spectrophotometer (Hach, Loveland, CO) using the powder pillow standard methods. The EC and pH of the samples were analysed with a HACH TitraLab AT1000 Series auto titrator (Hach, Loveland, CO), while turbidity was rapidly determined using a Hach TU5200 spectrophotometer (Hach, Loveland, CO).

E. coli and TC were biochemically determined using IDEXX Colilert-18® (IDEXX, Westbrook, ME) based on the ISO 9308-2 standard method. Briefly, surface water samples were analysed in serial dilutions of 100, 10 and 1 mL. Colilert-18 medium snap packs were dissolved in the samples and incubated for 18–22 h before reading results for TC under visible light and *E. coli* under ultra-violet light.

Bifidobacteria counts were obtained by incubating the pour-plated samples for 72 h at 35°C in a Bifidus Selective Medium (BSM) enriched with BSM supplement (Condalab, Torrenjon de Ardoz, Madrid). All purple-brown colonies were counted and recorded as bifidobacteria.

To determine FS counts, samples were pour-plated and incubated for 48 h at 35°C in a Kenner Faecal (KF) Streptococcus agar base enriched with 1 % TTC supplement (Condalab, Torrenjon de Ardoz, Madrid). All colonies with red to pink colour were counted and recorded as faecal streptococci.

All study area maps throughout this document were created using ArcGIS® software by Esri. ArcGIS® and ArcMap™ are the intellectual property of Esri and are used here under license.

2.4. Statistical analysis

Water quality data were populated using Microsoft Excel 2019. The seasonal parameter means, and standard deviations were computed using IBM SPSS 26. The Pearson correlation matrix at 95 % and 99 % confidence levels determined the relationships between water quality parameters. OriginPro 2024b was used to compute factor analysis (FA) tables and construct principal component analysis (PCA) plots to determine which parameters contributed the most to water quality deterioration.

PCA computation procedure.

i. Briefly, the source data from the variables is standardised so that each of the parameters contributes equally to the analysis. Standardisation to a common scale is done using the following equation:

$$z = \frac{x - \overline{x}}{\sigma} \tag{1}$$

Where x is the parameter value; $\overline{x}$ is the mean value of all parameters; and σ is the standard deviation

ii. From this, the covariance matrix is computed to identify correlations of the parameters with each other
iii. From the covariance matrix, the eigenvectors and eigenvalues are generated and ranked from highest (high variance) to lowest (least variance).
iv. Lastly, the eigenvalues with the highest variance are plotted along the principal component axes.

3. Results and discussion

3.1. Water quality properties of the Inyaka Dam

Water quality compliance was evaluated by measuring the critical physical, chemical, and biological properties of the water and comparing them to recommended targets. In this study, selected physicochemical and microbiological parameters of water, such as pH, EC, turbidity, temperature, PO_4^{3-}, NO_3-N, Fe, Mn, *E. coli*, TC, Bifidobacteria, and FS, were measured. The measurements for all four seasons, and the permissible limits, are presented in Table 1.

From Table 1 it is possible to see non-compliance for certain parameters, especially during summer, autumn and winter. The noncomplying parameters included *E. coli* in summer (1,15225 x10^3), autumn (2.7427 x10^2 MPN/100 mL), and Mn in winter (0.19 mg/L). Although variation was observed for other parameters such as pH, EC, Nitrates, and FS, the concentrations remained within the permissible limits.

i Physical parameters

The mean pH of the Inyaka Dam ranged from 7.21 to 7.49 across the observed seasons. The actual seasonal mean pH values were (7.21), (7.31), (7.35), and (7.49) respectively (Table 1). In line with the target water quality guidelines for the Inyaka catchment, the pH was within acceptable ideal limits of 6.5–8.0(15)

The mean EC ranged from 11.27 to 25.16 mS/cm across all four seasons. The lowest mean EC was observed in autumn at 11.27, while the other seasons were consistently in the same range at 21.12, 22.30, and 25.16 mS/cm, respectively (Table 1). This was within the prescribed acceptable limits of $\leq$55 mS/m. Although these values are typical of a lentic system, there is a massive difference between autumn and the other seasons. This trend can only be attributed to seasonal weather variations and yearly rainfall patterns.

The turbidity values ranged from 2.55 to 4.10 NTU for the Inyaka dam. Interestingly, the highest turbidity measures were recorded in winter and spring, when rainfall was minimal. This result was inconsistent with the findings of previous studies [20]. The seasonal mean temperatures regarding their seasonal variations for the surveyed seasons were 24.17^{o}C, 24.4^{o}C, 19.46^{o}C, 21.62^{o}C, respectively (Table 1), these values are conducive to aquatic life and household activities.

In South Africa, temperature is only regulated as an aquatic ecosystem driver [15] It states that temperature variations should occur infrequently and should not vary by more than 2^{o}C. According to Rahman et al. [13], slight variations in water temperature may not be as significant in freshwater because of aquatic life's wide range of temperature tolerance. However, studies by Machender et al. [21] and Ahmed et al. [22] reported that temperature variations play a significant role in highly polluted water because they affect dissolved oxygen concentrations.

Despite the small range in values, high physical parameter variability was observed in the summer season compared to autumn, spring, and winter, with rainfall influencing patterns of variability across all seasons (Fig. 2). However, parameter concentrations were below the permissible ranges. Fig. 2 also provides a comparison of the seasonal variability of the physical parameters in the Inyaka Dam.

ii Chemical parameters

3.1.1. Phosphates and nitrates

Phosphate and Nitrate compounds create significant problems when released into water resources insufficiently treated or without prior treatment. These nutrients are also significant nutrients required by living organisms for their physiological processes. However, these are considered pollutants under heavy loads and above the standard limits. High nutrient loads favour the growth of aquatic plants and accelerate the growth of algal blooms, bad odour and water decolouration [23].

The Inyaka dam receives under-treated effluent discharged from the Maviljan wastewater plant and is surrounded by agricultural activities. It is expected that the concentration of nutrients upstream of the dam will be high. However, there are no visible or reported cases of eutrophication in the Inyaka dam. The mean concentration of PO_4^{3-} throughout the surveyed seasons ranged from 0.02 to 0.07 mg/L. According to the set limits of the Inyaka dam, 50 % of PO_4^{3-} data may not exceed 0.125 mg/L (Table 1). The highest PO_4^{3-} was recorded in the rainy summer months, consistent with other studies [24]. Additionally, Benariba et al. [25], reported fair to low readings of phosphates across all studied seasons.

The nitrate concentration of the Inyaka dam was measured against domestic target water quality set at 6 mg/L. The observed mean values across the seasons ranged from 0.36 to 1.51 mg/L. The highest reading was observed in winter, with less mean rainfall (7.09 mm). The concentrations are within limits set out for the water resource and resonate with other studies [26,27].

3.1.2. Iron and Manganese

Iron is found in freshwater at levels ranging between 0.5 and 50 mg/L [28]. The presence of iron in water promotes the growth of

Table 1
Water quality parameters mean measurements and standard deviations for all observed seasons.

Parameters	Summer			Autumn			Winter			Spring			Limits	
	N (Total)	Mean	SD	N (Total)	Mean	SD	N (Total)	Mean	SD	N (total)	Mean	SD	RQO	TWQG
E. coli	27	1194,07	5042,18	22	274,27	123,24	31	6,52	7,95	24	9,54	13,40	130	130
PO_4	27	0,07	0,07	22	0,04	0,05	31	0,03	0,04	24	0,02	0,03	0,125	0,025
NO_3-N	27	0,57	0,62	22	0,36	0,56	31	1,51	2,43	24	0,95	1,04	6	6
pH	27	7,48	0,44	22	7,21	0,53	31	7,31	0,30	24	7,35	0,41	6.5–8.0	6,5–8,5
EC	27	20,19	19,27	22	11,27	12,78	31	25,16	18,19	24	22,30	19,88	30	40
Aver. Rainfall	27	204,59	135,03	22	66,66	61,48	31	7,09	8,48	24	51,28	61,13	N/A	N/A
Bifidobacteria	27	2,70	2,13	22	5,64	4,86	31	0,58	0,67	24	0,29	0,46	–	–
FS	27	7,22	8,35	22	3,41	4,10	31	2,81	3,11	24	1,75	1,75	–	30
Fe	27	1,09	0,60	22	0,74	0,51	31	0,88	0,29	24	0,76	0,10	–	0,01
Mn	27	0,04	0,01	22	0,08	0,04	31	0,14	0,18	24	0,09	0,03	0,18	
TC	27	16698,59	4834,54	22	11796,18	514,10	31	1933,16	672,21	24	8282,00	960,19	–	–
Temperature	27	25,01	0,95	22	24,45	2,07	31	18,54	2,05	24	21,72	1,23		
Turbidity	27	3,16	1,14	22	3,38	1,26	31	2,99	1,04	24	3,31	1,92	–	–

FS=Faecal streptococci, TC = Total coliforms.

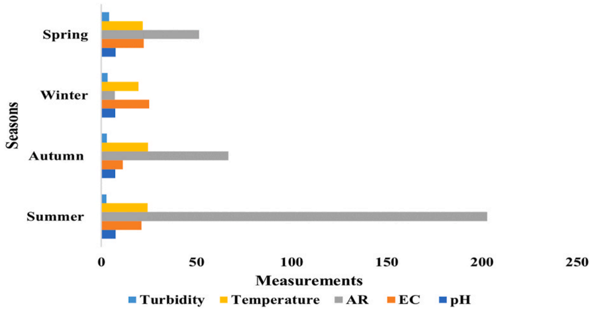

Fig. 2. Variations in the collective physical parameter throughout the different seasons of the Inyaka Dam.

iron bacteria, which combine Iron and Manganese with oxygen to form rust on [29]. The mean Fe measurements ranged from 0.76 to 1.59 mg/L, with the highest level observed in summer. This contrasts with what was reported in Lake Beseka in Ethiopia [24], where Fe concentrations ranged between 0.40 and 3.80 mg/L with the highest concentrations recorded in the dry season.

Deposits of high manganese concentration can be found near the bottoms of deep-fill dams such as the Inyaka Dam. This may be attributed to temperature stratification during the summer months when the warmer water remains in the upper layer of the dam. In winter, the upper layer is cooler and able to mix with the lower layer, thus freeing trapped manganese at the bottom [30]. This process explains the observed mean Mn measurements for all the observed seasons, which were (0.03), (0.07), (0.19), and (0.11), respectively. The highest measurements were observed in winter when the rainfall and temperature were minimal (Table 1). The standard limits for Mn are provided in the South African water quality guidelines for irrigation and domestic use. They were set at 0.18 mg/L and 0,02 mg/L, respectively [31]. Comparatively, the combined chemical parameters showed high concentrations in winter, whereas spring and autumn showed the lowest concentrations (Fig. 3).

iii Microbiological parameters

3.1.3. *Total coliforms and E. coli*

Total coliforms are a group of coliform bacteria found naturally in soil, water, warm-blooded animals, and humans [32]. *E. coli* forms a significant part of this group because it is also used to indicate faecal pollution by mammals in water resources [33]. The standard limit for *E. coli* is set at 1.3×10^2 CFU/100 mL (Table 1) according to the RQOs for the Inyaka Dam. During the surveyed periods, *E. coli* compliance was observed only in winter and spring (6.52; 9.54 MPN/100 mL) when rainfall was minimal (Table 1). This result indicates less sediment run-off and disturbance, leading to cleaner water in the upper layer of the dam. In addition, these observations are congruent with those reportedby Saiful et al. [18] and in both dry and wet seasons. The observed mean TC measurements for all surveyed seasons were ($1.25910 \times 10^3 \pm 388.32$), ($7.5443 \times 10^2$), ($3.59306 \times 10^3$), and ($1.262130 \times 10^4$), respectively (Table 1). The highest mean TC measurements were observed in spring when precipitation and temperature were moderate.

3.1.4. *Faecal streptococci and bifidobacteria*

Very few studies have investigated the effect of these groups of microorganisms on freshwater quality [34,35]. Although these groups are not severe contaminants, their monitoring is significant in environmental and recreational waters [31]. The mean measurement for FS ranged between 1.30 and 4.10 CFU/mL. Although these microorganisms are not regulated in the available RQOs for surface water, the values are well below the 1.3×10^2 CFU/100 mL limit set for *E. coli*. The seasonal mean measurements for FS were (4.10), (2.43), (3.50), and (1.30 CFU/mL), respectively. Higher measurements were observed in summer and winter when climatic conditions differed significantly. On the other hand, Bifidobacteria mean measurements ranged from 0.00 to 3.14 CFU/mL, with the

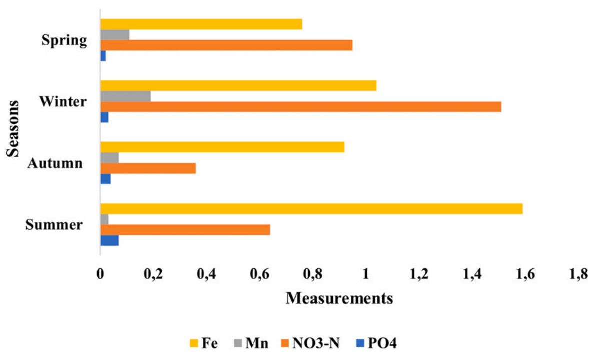

Fig. 3. Collective chemical parameter variations during the observed seasons in the Inyaka Dam.

lowest levels observed in spring and highest in autumn (Table 1). The seasonal mean measurements for Bifidobacteria regarding seasonal variations were (2.1), (3.14), (0.31), and (0.00) respectively. A higher combined microbial variability was also observed in the summer months (Fig. 4). This trend can be attributed to increased temperatures and high rainfall during the summer months.

3.2. Multivariate statistical analysis

i. Correlation Matrix

All-physical parameters, excluding pH, showed a strong and significant linear relationship with either chemical or microbiological parameters during summer. Summer pH was only positively correlated with Mn ($r = 0.469$ and $p < 0.05$). The EC had a strong positive correlation with NO_3-N ($r = 0.960$ and $p < 0.01$), whereas rainfall correlated with *E. coli* ($r = 0.677$ and $p < 0.01$). Temperature and turbidity were the only physical parameters to present significant correlations with more than one parameter. The highest correlation coefficient for temperature was recorded for Fe ($r = -0.660$ and $p < 0.01$). Rainfall greatly influences the turbidity of water, especially in the summer and rainy months, because of sediment disturbance [36]. Rainfall and turbidity had a positive correlation ($r = 0.756$ and $p < 0.01$) in the summer months at the Inyaka Dam. The correlation structure of the microbiological parameters was rather interesting, as the chemical parameters were correlated with the microbiological parameters. Only rainfall and turbidity correlated with *E. coli* significantly ($r = 0.677$ and $p < 0.01$), whereas FS, Bifidobacteria, and TC all positively correlated with *E. coli* ($r = 0.468$ and $p < 0.05$), ($r = 0.507$ and $p = <0.01$), and ($r = 0.413$ and $p < 0.05$), respectively (Fig. 5). This can be attributed to the fact that freshwater sediment contains a variety of microorganisms, and when disturbed by runoff due to heavy rains, microorganisms are released to the surface of the water [37].

In winter, only EC had multiple correlations with Bifidobacteria ($r = -0.450$ and $p < 0.05$), temperature ($r = 0.476$ and $p < 0.01$), Fe ($r = 0.583$ and $p < 0.01$), PO_4 ($r = -0.484$ and $p < 0.01$), and NO_3-N ($r = 0.500$ and $p < 0.01$). In addition, EC showed positive and negative linear relationships, which denotes that any significant change in the EC of the Inyaka Dam may affect other parameters either positively or negatively (Fig. S4). The autumn and spring seasons received almost the same volume of rainfall (66.66 and 51.21). However, in autumn, *E. coli* showed more correlated relationships than any other parameter, whereas in spring, NO_3-N showed more meaningful correlations. *E. coli* showed correlations with PO_4 ($r = 0.612$ and $p < 0.01$), FS ($r = 0.579$ and $p < 0.01$), TC ($r = 1.000$ and $p < 0.01$), and turbidity ($r = 0.467$ and $p < 0.05$). To support these findings, a study conducted in the Turkish lake Imrahor reported that surface runoff due to rainfall causes high microbial counts [37]. In spring, NO_3-N showed correlations with EC ($r = 0.955$ and $p < 0.01$), Bifidobacteria ($r = -0.505$ and $p < 0.05$), TC ($r = 0.538$ and $p < 0.01$), Mn ($r = 0.586$ and $p < 0.01$), and turbidity ($r = 0.516$ and $p < 0.01$) (Figs. S3 and S5). The positive correlation of NO_3-N with the microbiological indicators, Mn, and turbidity indicates a surface drainage, sewage system or animal waste contamination [38]. Fig. 5 presents the Pearson correlation coefficients (r) of all the measured parameters during the summer.

ii Principal Component Analysis (PCA)

PCA is a statistical method that demonstrates the relationship between measured parameters by reducing them to fewer factors [13]. Figs. 6 and 7 present the PCA analyses and the temporal variations in water quality among the observed seasons. Three components (PC1, PC2, PC3) were used to create the 3D plot. In summer, the three components represented 60.4 %, 52.5 % in winter 67.2 % in autumn, and 63.1 % in spring, of the total variation (Tables S1–S4).

The effect of seasonal sampling is illustrated in Fig. 6. In the summer season, *E. coli*, AR, turbidity, Bifidobacteria, and FS correlate more to the component (PC1) and are the most influential in determining water quality. In winter, turbidity, TC, FS, and Mn were the most influential parameters regarding the first component (PC1) largely due to stratification. In addition, the results show that rainfall affects the direction of the linear relationship between Bifidobacteria and the first component in the summer (0.57) and winter (−0.76) (Tables S1 and S2). The autumn and spring PCA biplot comparison presented in Fig. 7 shows different relationships between the parameters.

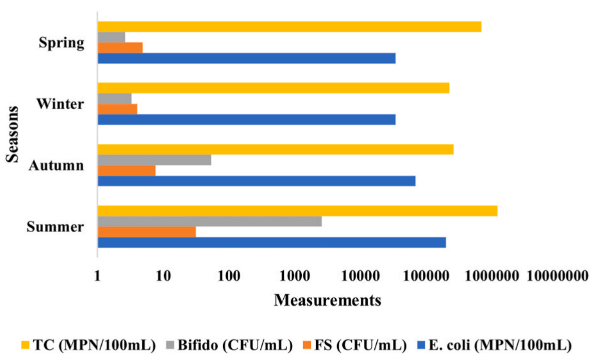

Fig. 4. Comparison of the variations in the collective microbiological parameters during the different seasons in the Inyaka Dam.

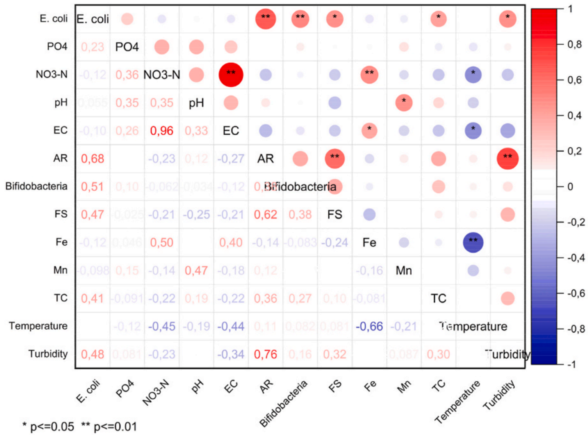

Fig. 5. Correlation matrix for all measured water quality parameters during summer at Inyaka Dam.

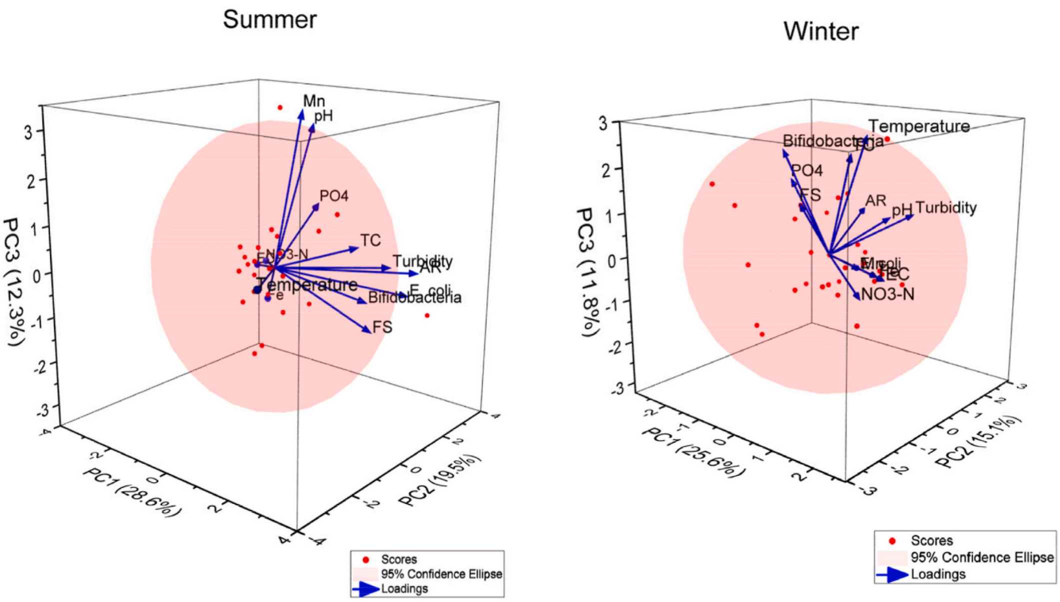

Fig. 6. A comparison of 3D PCA plots for analysed parameters in the summer and winter seasons for the Inyaka Dam.

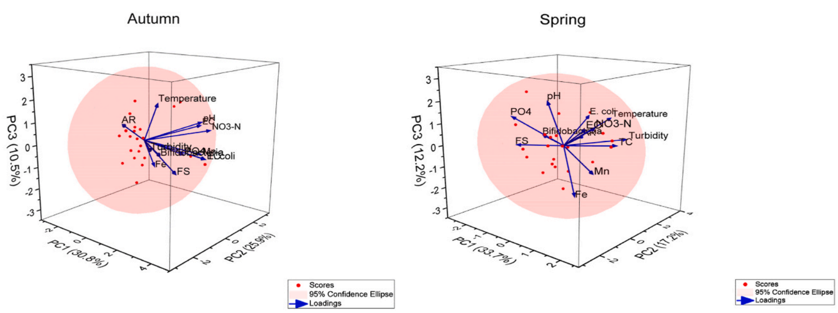

Fig. 7. PCA biplots presentation for the analysed parameters in autumn and springs for the Inyaka Dam.

The autumn and spring seasons received almost the same average rainfall (66.66 and 51.21 mm). This denotes that rainfall was not responsible for the parametric variations between the two seasons. However, the Inyaka Dam is a lentic system that is influenced by stratification. As such, during spring low temperatures, Mn, NO_3-N, EC, turbidity, and TC concentrations were high, a phenomenon also observed in winter. The autumn season displayed the opposite of what was observed in the winter and spring seasons, with lower concentrations of NO_3-N, Mn, EC, turbidity, and TC. Notwithstanding, PCA showed that the water quality in spring was influenced by turbidity, TC, FS, and Mn, while autumn was influenced by TC, *E. coli*, PO_4, FS, and turbidity.

3.3. Water quality properties of the Crocodile River

Similar water quality properties were compared at the Crocodile River to those at the Inyaka Dam. The results for all four seasons are presented in Table 2. The parameters were measured against the Crocodile River RQOs and TWQG, where RQOs were unavailable. Table 2 demonstrates several non-compliances during summer for EC, PO_4^{3-}, *E. coli*, Mn, Iron, and FS. This is due to the greater amount of rainfall (120.10 mm) received in summer compared to autumn, winter, and spring (Table 2). Moreover, parameter values decrease with the decreasing rainfall received in subsequent seasons.

i Physical parameters

The mean pH measured across the observed seasons ranged from 7.59 to 7.82, with the highest value recorded in spring. The seasonal mean pH regarding seasonal variation for all observed seasons was (7.68), (7.79), (7.59) and (7.82), respectively (Table 2). These pH measurements were well within the set limits for the Crocodile River (Table 2). In addition, the pH range reported in this study is consistent with recent studies conducted in the Crocodile River [16,39].

The electrical conductivity of a river is greatly influenced by river flow, run-off of sediments due to heavy rainfall, and anthropogenic activities that disturb settled sediments. The highest EC measured across the observed seasons was in summer (204.75 mS/m) when the rainfall was also highest (120.10 mm). The lowest (90.47 mS/m) was measured in winter when rainfall was minimal (7.89 mm) compared to the other seasons (Table 2). This is consistent with studies conducted in River Rwizi, Uganda [40]. According to the Crocodile River standard limits, the observed EC measurements across all seasons denote that the water is unsuitable for contact recreation and inconducive for aquatic ecosystems. The EC of water is strongly related to turbidity in a manner of direct proportion. When turbidity is high, the EC also increases because of the disturbance of settled salts.

Rainfall is another parameter that significantly influences turbidity and EC because it is responsible for the run-off of salts and disturbance of settled sediments, especially in river systems [37]. The highest measured rainfall was observed in the summer months, which is typical in the region. The mean rainfall for all seasons was (120.10), (51.23), (7.89), and (43.89 mm), respectively (Table 2). The lowest mean rainfall was observed in the winter, which is typically a dry season.

The seasonal mean temperatures ranged between 16.49°C and 23.11°C. The lowest mean temperature was measured in winter, whereas the highest was measured in summer. The temperature measurements in the spring and autumn months were almost similar (22.31°C and 22.40°C), which means that temperature did not play a significant role in influencing meaningful variation in spring and autumn. To support the foregoing observations, the collective physical parameters showed greater variability in the summer months, with EC and rainfall being influential across all seasons (Fig. 8).

ii Chemical parameters

3.3.1. Phosphate and Nitrate

Flowing systems such as rivers are supposed to have the least risk of eutrophication compared to lakes, ponds, and dams. Although a wastewater treatment plant discharges effluent into the Crocodile River, there are no reported incidences of eutrophication in the area. Nonetheless, the phosphate measurements for the observed seasons ranged between 0.22 and 0.39 mg/L (Table 2), which is well above the specified limits for the Crocodile River. A similar study [16] also reported high measurements of phosphates at the exact location and attributed this to the nearby wastewater treatment plant. The highest tolerable limit for phosphate is 0.125 mg/L (Table 2). The seasonal mean concentrations of nitrate were (4.20), (1.75), (1.79), (3.10). The highest nitrate measurements were obtained in summer (4.20 mg/L) and spring (3.10 mg/L) (Table 2), where rainfall measurements were higher compared to winter and autumn. These measurements were well below the limit of 6 mg/L for nitrate in the Crocodile River.

3.3.2. Iron and Manganese

Fe and Mn concentrations in the eastern part of the Crocodile River are considered risky parameters that require frequent monitoring. This is due to the manganese processing company upstream of this study location. Sources of manganese in surface water can originate from both natural and anthropogenic activities [41] The seasonal mean Mn for all observed seasons was (0.65), (0.19), (0.18), and (0.23) respectively (Table 2). In contrast to the Inyaka Dam, only the winter season in the Crocodile River complied with the aquatic ecosystem standard limit of 0.18 mg/L (Table 2). The Crocodile River experienced high manganese concentrations during the summer rainy seasons (0.65 mg/L). This is in congruence with previous studies reporting a range between 0.22 and 0.34 mg/L [39].

The Fe concentrations ranged from 0.39 to 2.14 mg/L. The limit for domestic use is set at 0.01 mg/L [42]; thus, the water is not suitable for domestic use. The highest measurements were obtained in summer when rainfall was highest in the Crocodile River, while the lowest concentration was measured in the winter. This is similar to the observations made by Ojok et al. [39] in River Rwizi, Uganda, where Fe concentrations exceeded permissible limits. Consistent with the foregoing observations, the summer months with high rainfall were responsible for the highest variability (Fig. 9).

Table 2
Mean and standard deviation values of the physicochemical and microbiological properties of the Crocodile River for four seasons.

	Summer			Autumn			Winter			Spring			Limits	
	N (Total)	Mean	SD	N (Total)	Mean	SD	N (Total)	Mean	SD	N (total)	Mean	SD	RQOs	TWQG
E. coli	22	201858.00	5293.13	18	69388.72	1165.83	37	34440.73	112.65	25	45598.84	771.92	130	130
PO_4	22	0.39	0.32	18	0.22	0.10	37	0.24	0.23	25	0.38	0.61	0.125	0.025
NO_3-N	22	4.20	5.92	18	1.75	1.32	37	1.79	0.74	25	3.10	3.31	6	6
pH	22	7.68	0.28	18	7.79	0.39	37	7.59	0.31	25	7.82	0.22	6.5–8.0	6.5–8.5
EC	22	204.75	58.71	18	91.66	64.86	37	90.47	123.03	25	140.34	102.51	55	40
Aver. Rainfall	22	120.10	62.11	18	51.23	32.79	37	7.89	9.12	25	43.89	35.38	N/A	N/A
Bifidobacteria	22	2595.05	6154.44	18	53.67	111.18	37	3.30	2.47	25	2.64	3.67	–	–
FS	22	31.64	13.93	18	7.67	6.49	37	4.03	5.97	25	4.88	4.13	–	30
Fe	22	2.14	2.37	18	0.65	0.17	37	0.39	0.18	25	0.73	0.18	–	0.01
Mn	22	0.65	0.72	18	0.19	0.06	37	0.18	0.07	25	0.23	0.08	0.18	
Coliforms	22	1220190.14	2257.93	18	261620.39	251.63	37	224903.16	550.35	25	696279.12	1787.05	–	–
Temperature	22	23.11	1.24	18	22.40	1.07	37	16.49	4.05	25	22.31	1.36		
Turbidity	22	52.32	52.45	18	13.66	10.87	37	4.52	1.70	25	18.02	8.46	–	–

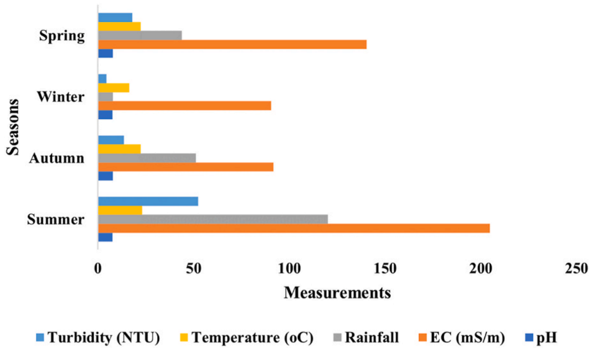

Fig. 8. Comparison of the variations in the collective physical parameters during different seasons in the Crocodile River.

i Microbiological parameters

3.3.3. *Total coliforms and E. coli*

Total coliforms are used to evaluate the treatment efficiency in water treatment plants and only indicate gaps for improvement in the treatment process. *E. coli.* on the other hand, is used as the preferred indicator of pollution of water resources [33]. The general limit for *E. coli* in the Crocodile River is 1.3×10^2 CFU/100 mL (Table 2), and for the current investigation, the mean *E. coli* measurements ranged between 3.444×10^4 and 2.01858×10^5 MPN/100 mL (Table 2). Microbial growth variability is high in lotic systems such as rivers as illustrated in Fig. 10. This variation pattern is typical of bacterial communities, especially in the dry and wet seasons [43]. The lowest measurement was observed in winter (3.444073×10^4), while the highest was observed in the summer (2.01858×10^5). All measurements exceeded the prescribed limits, as detailed in Table 2.

3.3.4. *Faecal streptococci and bifidobacteria*

Faecal streptococci (FS) are used to indicate the presence of pollution of animal faecal origin [20] and are preferred indicators of pollution in recreational waters such as marine environments, because they can survive longer than coliform bacteria in water. The maximum limit for FS in recreational waters is at most 30 CFU/mL (Table 2). The results obtained from the different seasons in the current observation (31.64, 7.67, 4.03, and 4.88 CFU/mL) show only non-compliance in the summer. Interestingly, summer is usually the season when recreational activities increase. Bifidobacteria measurements ranged between 2.64 and 2595 CFU/mL, with the highest measurement obtained in the summer and the lowest in winter. The limit for Bifidobacteria is not set for any water resource in South Africa because it is considered an unsuitable indicator of pollution [44].

3.4. *Multivariate statistical analysis*

i Correlation Matrix

All the studied parameters except temperature showed a correlation with one or more parameters in the summer. NO_3-N and EC showed more meaningful and significant linear relationships with other parameters. However, NO_3-N showed no correlation with any of the microbiological parameters, whereas EC only showed a correlation with FS ($r = 0.568$ and $p < 0.01$). Rainfall also showed a positive correlation with Fe ($r = 0.485$ and $p < 0.05$), Mn ($r = 0.520$ and $p < 0.05$), and turbidity ($r = 0.548$ and $p < 0.01$). The pH measurement presented a negative correlation with EC ($r = -0.675$ and $p < 0.01$), Fe ($r = -0.687$ and $p < 0.01$), Mn ($r = -0.634$ and $p < 0.01$), and turbidity ($r = -0.694$ and $p < 0.01$) (Fig. 11). Congruent with these findings, a study by Kothari et al. [37] reported

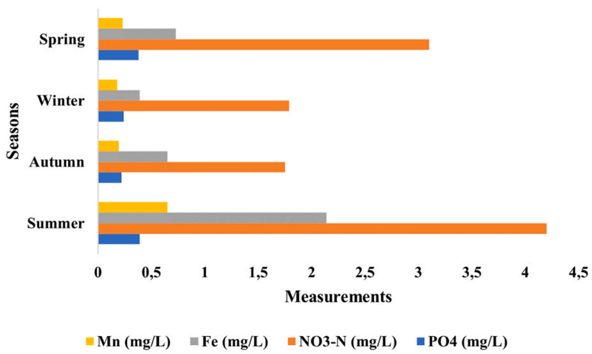

Fig. 9. Comparison of variations in the collective chemical parameters during different seasons in the Crocodile River.

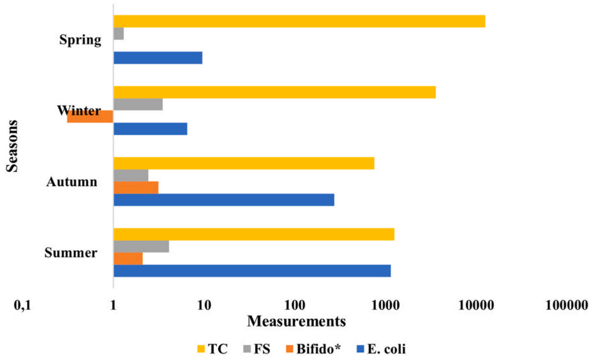

Fig. 10. Comparison of the variations in the collective microbiological parameters during the observed seasons in the Crocodile River.

negative Fe (r = - 0.3), and low correlation values EC ($r = 0.2$) and turbidity ($r = 0.01$).

In winter, *E. coli* had the most meaningful linear relationships with other parameters, while rainfall did not correlate with all the parameters. *E. coli* correlated with PO_4 ($r = 0.907$ and $p < 0.01$), NO_3-N ($r = -0.609$ and $p < 0.01$), TC ($r = 0.807$ and $p < 0.01$), Bifidobacteria ($r = 0.470$ and $p < 0.01$), and EC ($r = -0.337$ and $p < 0.05$), NO_3-N presented a correlation with EC ($r = 0.669$ and $p < 0.01$), Bifidobacteria ($r = -0.404$ and $p < 0.05$), FS ($r = 0.361$ and $p < 0.05$), and TC ($r = -0.622$ and $p < 0.01$) while the correlation of NO_3-N with microbiological parameters in winter was negative (Fig. S8). The recorded winter rainfall was low for the Crocodile River (7.89 mm). As such, this correlation pattern can be attributed to possible contamination from sewage systems. agricultural activities, or animal wastes [38].

Like the Inyaka Dam, the spring and autumn seasons in the Crocodile River showed less difference in the amount of rainfall received (43.89 and 51.23 mm). Rainfall only showed a correlation in the spring season with Mn ($r = -0.691$ and $p < 0.01$), while there was no correlation with any of the parameters in autumn. Only *E. coli* showed more than one meaningful linear relationship with PO_4^{3-} ($r = 0.554$ and $p < 0.05$) and turbidity ($r = 0.658$ and $p < 0.01$) in the autumn season. In spring, *E. coli* showed correlations with EC ($r = -0.431$ and $p < 0.05$), Bifidobacteria ($r = 0.587$ and $p < 0.01$), and TC ($r = 0.647$ and $p < 0.01$) (Figs. S6 and S7). These observations are consistent with those reported by Solaiman et al. [45] where *E. coli* correlated with EC ($r = 0.25$ and $p < 0.001$).

ii Principal Component Analysis (PCA)

The first, second, and third components (PC1, PC2, PC3) were used to compute the PCA plots for all observed seasons, with summer explaining 74.7 %, winter 64.2 %, autumn 58.2 %, and spring 58.8 % of the total variance (Table S2). In addition, Figs. 12 and 13 illustrate the parametric variance and influence across the four seasons. The longer the arrow, the higher the correlation and subsequent influence on water quality.

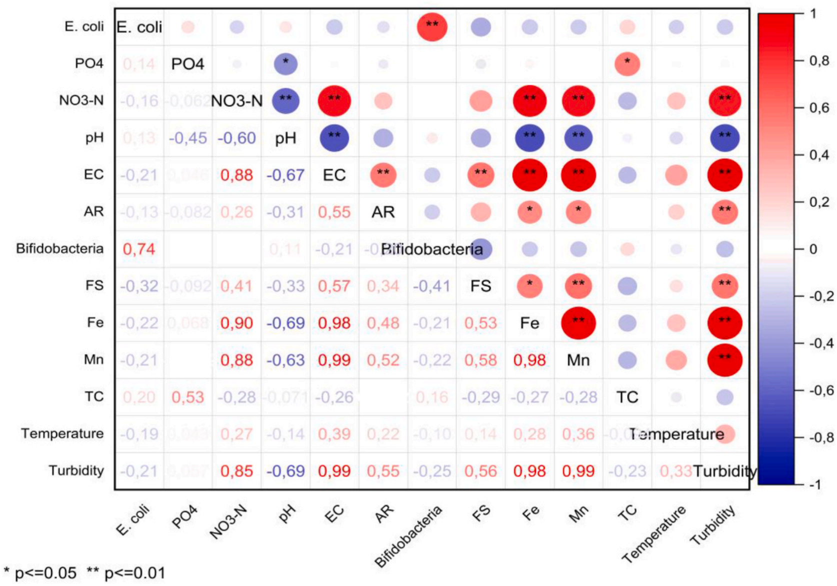

Fig. 11. Correlation matrix for all observed water quality parameters in summer in the Crocodile River.

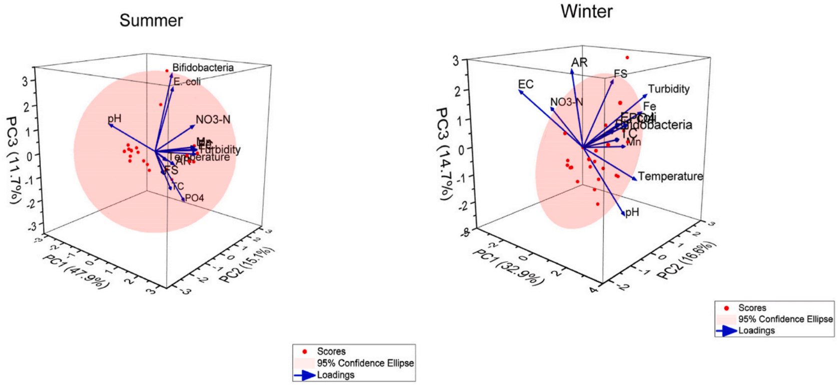

Fig. 12. PCA plots for analysed parameters for the summer and winter seasons in the Crocodile River.

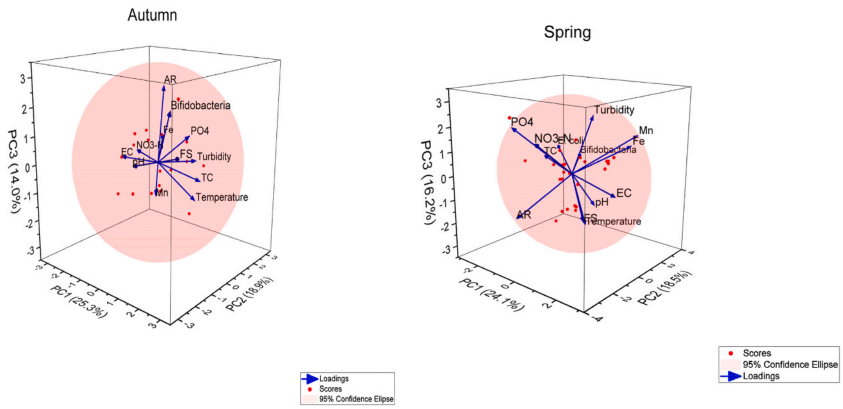

Fig. 13. PCA plots for analysed parameters for the summer and winter seasons in the Crocodile River.

The Crocodile River presented a different parametric variance and influence compared to the pattern observed in the Inyaka Dam. In the summer season. eight (turbidity, EC, Fe, Mn, NO_3-N, pH, FS, and AR) essential parameters influenced water quality compared to five in the Inyaka Dam.

Differences in the number of influential parameters can be attributed to other factors, such as ecosystem dynamics. The winter season revealed five parameters (*E. coli*, PO_4^{3-}, TC, NO_3-N, and Bifidobacteria) with the greatest influence on water quality.

The autumn and spring seasons in the Crocodile River differed significantly from those observed in the Inyaka Dam. Fig. 13 illustrates the comparison of the two seasons in the Crocodile River.

In autumn, turbidity, *E. coli*, and PO_4 levels were responsible for water quality deterioration. Despite receiving almost similar volumes of rainfall (51.23 and 43.89 mm), the water quality in spring was highly influenced by different parameters such as Mn, Fe, and rainfall. According to Che et al. [39], Mn levels in the Crocodile River vary during the wet seasons. This explains why Mn contributes to water quality degradation. These observations are also consistent with other studies [46] that reported significant changes in physicochemical and heavy metal concentrations in South African rivers.

4. Conclusions

This study examined the impact of weather variations on water quality in the Inyaka Dam and Crocodile River, South Africa, highlighting the threat to water security intensified by anthropogenic activities and climate change. Water quality is affected by temperature and rainfall, which are key contributors to climate variability. The study found that water pollution in these aquatic systems stems from both natural processes, such as stratification, and human activities like wastewater treatment and agriculture.

In the Inyaka Dam, summer rainfall significantly increased microbial counts, including *E. coli*, and turbidity. Pearson correlation analysis showed strong positive correlations between rainfall and *E. coli* (0.68) and turbidity (0.76) (Fig. 5). Conversely, an increase in temperature led to a decrease in pollutants like Fe, EC, and NO_3-N due to negative correlations. In contrast, the Crocodile River's summer season was marked by high levels of EC, turbidity, Fe, Mn, and NO_3-N, which negatively correlated with pH.

Winter conditions in both water bodies featured low rainfall and temperatures, with continued water quality deterioration in the Crocodile River due to reduced water flow. In winter, the Crocodile River showed high levels of *E. coli*, total coliforms, Bifidobacteria, and PO_4^{3-}, while in the Inyaka Dam, PO_4^{3-} and Bifidobacteria levels decreased as Fe, EC, and NO_3-N increased.

The study concludes that water quality degradation, particularly in summer, is driven by rainfall and effluent discharges, with pollution levels often exceeding permissible limits. The findings underscore the need for tailored water quality management strategies that consider the unique characteristics of lentic (Inyaka Dam) and lotic (Crocodile River) systems. It advocates for ecosystem-specific, climate-resilient approaches to effectively mitigate water pollution and enhance water security. This research emphasizes the importance of distinguishing between different aquatic ecosystems when designing water pollution control strategies and policies.

5. Future directions

Despite the availability of well-defined local water quality monitoring guidelines and standard limits, certain water quality parameters are crucial to the overall quality of surface waters. This is particularly important because most surface water resources serve as discharge points or receiving sources for effluent discharges and agricultural runoff. Therefore, parameters such as dissolved oxygen (DO), 5-day biological oxygen demand (BOD5), and chemical oxygen demand (COD) should be included in any study related to surface water pollution. This study did not assess these parameters, which is considered a major limitation of the findings. Consequently, future studies should emphasise these parameters in addition to those outlined in local water quality monitoring programs.

Data availability

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

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CRediT authorship contribution statement

Lazarus Katlego Mogane: Writing – review & editing, Writing – original draft, Visualization, Validation, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Esper J. Ncube:** Writing – review & editing, Supervision, Conceptualization. **Titus A.M. Msagati:** Writing – review & editing, Supervision, Formal analysis, Conceptualization. **Tracy M. Masebe:** Writing – review & editing, Supervision, Resources, Project administration, Funding acquisition, Formal analysis, Conceptualization.

Declaration of competing interest

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

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.heliyon.2024.e38246.

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