



Integrating GIS–Based Inverse Distance Weighting and Multivariate Statistical Techniques to Assess Surface Water Quality Within a Sub–Tropical River System

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Abstract Freshwater ecosystems worldwide are facing significant pressures due to the ever-increasing human activities. Land-use intensification has been closely associated with water quality degradation and loss of freshwater biodiversity. In this study, we utilised inverse distance weighted method to assess spatio-temporal concentrations of metals, nutrients and other physicochemical variables in the Komati River, Mpumalanga Province, South Africa. Water quality measurements were taken from nine sampling sites along the Nkomati River and its tributaries –across three seasons i.e, cool-dry (June 2021), hot-wet (December 2021) and hot-dry (February 2024). The results of two-way ANOVA revealed that physicochemical, nutrients and metals variables such as temperature, salinity, potassium, calcium, magnesium, aluminium and sediment phosphorus differed significantly across sites and seasons. Correlation matrix indicated significant relationships between water quality parameters and different land cover types, with pH and temperature exhibiting a strong positive correlation with settlement and agricultural areas. Elevated nitrate concentrations observed in the Nkomati River suggest significant nutrient enrichment, likely linked to adjacent agricultural activities.

The findings of this study offer valuable scientific insight for guiding land use planning and policy development aimed at protecting freshwater resources in sub-tropical river systems. This highlights the need for targeted conservation and management interventions, particularly within the lowveld regions, to mitigate nutrient loading into the river systems.

Keywords Spatio-temporal · Land use patterns · Metals · Nutrients · Water quality · Nkomati River system

1 Introduction

Water is an important natural resource to humans and other organisms, and the ever-growing population, economic development and changes in lifestyle have put more strain on this resource (Duarte et al., 2020; Ram and Irfan, 2021). In addition, the prevalent degradation of water quality in many parts of the world, particularly of surface water, compromises human health, socio-economic activities and threatens aquatic biodiversity (Atangana & Oberholster, 2021; Lin et al., 2022a; Madhav et al., 2021). The underlying causes of decline in water quality in many of these regions is due to climate change, human activities and the intense land use in watershed areas (Shogren et al., 2021; Huang et al., 2023; Qiao et al., 2023; Li et al., 2022). In particular, the discharge of domestic, industrial and mining effluents, as well as the poor use

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of fertilisers, and changes in land use and cover, are some of the major factors influencing surface water quality in many water bodies (Giri, 2021; Mishra et al., 2025; Schreiber et al., 2022; Rafiei–Sardooi et al., 2025; Ameta et al., 2023; Sharma et al., 2024; Teixeira et al., 2024).

Increased agricultural activities, and the consequent surface runoffs, have been positively associated with high concentrations of natural and synthetic loads of heavy metals, fertilisers and pesticides in aquatic systems (Pericherla and Vara, 2023; Soltaninia et al., 2022). In agricultural sectors, to maintain maximum growth rates and yields, a great deal of pesticides and fertilisers are often used. However, these practises impact both the quality and availability of water for the local rivers and the surrounding environment (Craswell, 2021; Liu et al., 2021; Khan et al., 2023; Srivastav et al., 2023). These land use practices can also affect the hydrological cycle (Luo & Moiwo, 2023; Wang et al., 2020). For example, change from native vegetation to human-dominated landscapes (e.g., agricultural crops and deforestation) results in runoff, infiltration and evapotranspiration in the catchment, which have impacts on stream flow dynamics, nutrient, sediment and toxic loads in water bodies (Alam and Dutta, 2021; Bao et al., 2022). In general, the relationships between land use patterns and water quality tends to vary depending on spatiotemporal extent, scale effects of land use patterns, watershed characteristics, landscape composition and configuration and land use intensity (Wang et al., 2014; Cheng et al., 2022).

River ecosystems are also subjected to elevated concentrations of heavy metals emanating from mining and industrial sectors, which pose risks to human health and aquatic ecosystems, due to their potential toxicity (Dalu et al., 2022, 2023; Lin et al., 2022b). Although some heavy metals can occur naturally in rivers, such as when they are released into the river system through weathering of rocks and soils, heavy metal contamination often result from mining and industrial activities (Dalu et al., 2022, 2023; Lin et al., 2022b; Sindern et al., 2016). These elevated heavy metals, along with other pollutants, are then dispersed from point source to different parts of the rivers, thus spreading their impacts along these systems (Qiao et al., 2023; Weideman et al., 2020). Mining has caused heavy metal contamination and thus affect water quality in riverine ecosystems (Minnaar,

2020; Dusengemungu et al., 2022; Dzhanghi & Atangana, 2023; Tibane and Mamba, 2024). The runoff from mining tail dumps contaminated by the toxic metals such as magnesium (Mg), lead (Pb), arsenic (As), cadmium (Cd), mercury (Hg), sodium (Na), boron (B), nickel (Ni) and manganese (Mn) has significantly affected various environmental compartments including river systems, resulting in negative impacts not only to living organisms, but also human health (Isangedighi and David, 2019; Jewel et al., 2020; Khan et al., 2021). The same pattern is observed in the Mpumalanga Province of South Africa, where many rivers and streams are under pressure from human activities such as mining, agriculture and urban pollution (Atangana & Oberholster, 2021; Dzhanghi & Atangana, 2023; Keighley, 2017; Phungela et al., 2022).

The Komati River, in the Mpumalanga Province, is one such system that's being subjected to high pollution as a result of agricultural activities, mining, urbanisation and coal industrial pollutant loads (Keighley, 2017). The river is an important aquatic resource to both the local communities and the surrounding environment (Engelbrecht & Roux, 2006). Within the upper Komati catchment, coal mining and agriculture dominate (Keighley, 2017). The presence of coal mining presents a potential threat of acid mine drainage (AMD), which can severely impact on the river ecosystem through lowered pH and heavy metal contamination, as has been observed for other rivers in South Africa (e.g., Atangana & Oberholster, 2021; Dzhanghi & Atangana, 2023). Similarly, urban and agricultural activities, can also impact negatively on water quality of the Komati River (Engelbrecht & Roux, 2006). It is therefore important that the water quality of this river is monitored, to ensure that the pollution levels are safe for human consumption, and for ecological and environmental sustainability.

To date, various water quality monitoring techniques have been employed to assess surface water quality (Ahmed et al., 2020; Zulkifli et al., 2018). Amongst these, GIS and statistical techniques have been used successfully to assess water quality in rivers, lakes, reservoirs and groundwater (Alshehri et al., 2023; Errich et al., 2024; Khouni et al., 2021; Shanmugasundharam et al., 2023; Yasser et al., 2017). Principal component analysis (PCA) is one of the most common statistical analyses used to assess water

quality (e.g., Hammoumi et al., 2024; Phung et al., 2015; Roy et al., 2024; Zeinalzadeh & Rezaei, 2017). It is a multivariate analysis method that reduces the dimensionality and enhances the effectiveness of clustering (He, 2024; Hotelling, 1933). Similarly, the inverse distance weighted (IDW) has also been used widely in water quality assessment studies (e.g., Errich et al., 2024; Javed et al., 2021; Khouni et al., 2021). The IDW is a deterministic spatial interpolation model that has been used widely in hydrology and geoscience (Khadka, 2023; Liu et al., 2020; Lu & Wong, 2008; Xu et al., 2023). Thus, a combination of multivariate statistical approach and IDW can be used complementarily and effectively to assess surface water quality (Yang et al., 2020).

In this study, we used a multivariate statistical analysis and IDW to assess spatio-temporal concentrations of metals, nutrients and other physicochemical variables in the Komati River, Mpumalanga Province, South Africa. The primary objectives were to:

- 1) determine the differences in concentration of metals, nutrients and physicochemical variables across sampling sites;
- 2) identify potential factors that best explain the observed patterns in these concentrations and
- 3) assess the influence of possible pollution sources on Komati River water quality parameters.

We hypothesised that anthropogenic factors, in particular land use patterns, proximity to urban settlements and agricultural activities are the key drivers of water chemistry, primarily due to pollutant being carried by runoff to the river system.

2 Materials and Methods

2.1 Study Area

Sampling for the present study was conducted in the Nkomati River, also known as the Komati River (Fig. 1). The Nkomati River originates in South

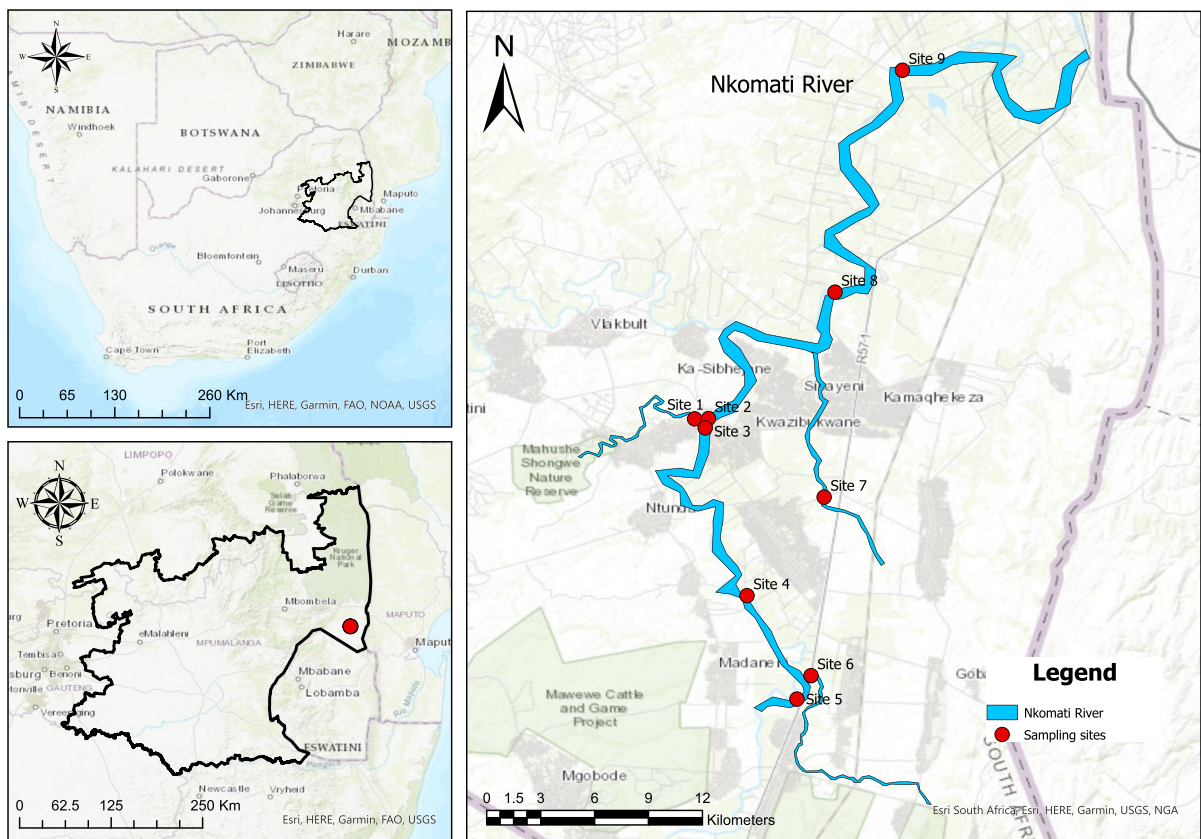


Fig. 1 Study area map showing the sampling sites (i.e., sites 1–9) in the Komati River, Mpumalanga Province, South Africa

Africa and joins the Crocodile River in the Lebombo mountains and flows onwards to enter far south–western Mozambique beneath the border town of Komatiport, where it eventually empties into the Indian Ocean around 24 km northeast of Maputo. The Komati River is 480 km long with a mean annual discharge of $111 \text{ m}^3 \text{ s}^{-1}$. The river is shared between South Africa, Mozambique and Swaziland, and has a total drainage basin area of $50\,000 \text{ km}^2$ of which 63% is in South Africa, 32% Mozambique and 5% Swaziland. The climate of the Komati River Basin varies from hot and muggy in the Transvaal Plateau of South Africa to cold and dry in the coastal plain of Mozambique. The yearly rainfall ranges from 350 mm to 1 200 mm, increasing from east to west, whereas the annual evaporation averages 1 900 mm, decreasing from east to west, with average yearly temperature in the region ranging from 17°C to 40°C (Ndlovu and Shoko, 2023).

2.2 Water Sample Collection

Water samples ($n=3$) were taken from nine sites along the Nkomati River and its tributaries using 500 mL water containers. Sampling was done in three sessions: cool–dry (June 2021), hot–wet (December 2021) and hot–dry (February 2024). Thus, a total of 27 water samples (nine for each session) were collected and analysed from the study area. At each sampling site, a portable handheld CyberScan Series multiparameter (Eutech Instruments, Singapore) was used to measure basic water parameters such as conductivity ($\mu\text{S cm}^{-1}$), water temperature ($^\circ\text{C}$), salinity (ppt), total dissolved solids (mg L^{-1}) and pH.

2.3 Nutrient and Metal Analysis from Water Samples

Collected water samples were analysed for nutrients (i.e., phosphates (PO_4^{3-}), nitrates (NO_3^-) and ammonium (NH_4^+) at the University of Mpumalanga Laboratory using Hanna Instruments Model HI83300 (Hanna Instruments, Smithfield, RI). Phosphate levels were determined using the HANNA HI717 high-range test kit, which operates within a detection range of $0\text{--}30 \text{ mg L}^{-1}$ and a resolution of 0.1 mg L^{-1} , following a modified ammonia acid method in accordance with the Standard Methods for the Examination of Water and Wastewater (18th edition) (Gawankar

& Masten, 2023). For determination of ammonia, we used ammonia high range test kit (HI3824) with a range of $0\text{--}100 \text{ mg L}^{-1}$ and a resolution of 0.1 mg L^{-1} based on the Nessler method from the American Society for Testing and Materials (ASTM) Manual of Water and Environmental Technology D1426. Nitrate concentration was measured using the nitrate–nitrite reduction method, which is based on the conversion of nitrate ions into nitrite ions, using a reducing agent (typically a mixture of concentrated sulfuric acid and cadmium granules) (Wongniramaikul et al., 2022). The photometer range was $0\text{--}50 \text{ mg L}^{-1} \pm 0.5 \text{ mg L}^{-1}$ accuracy, and the resolution was 0.1 mg L^{-1} .

2.4 Metal Concentration Analysis

Metal analyses were conducted at WaterLab (Pretoria) – a South African National Accreditation System (SANAS) certified laboratory. Analysis of cations (B^{3+} , Ca^{2+} , K^+ , Mg^{2+} and Na^+) and heavy metals i.e., As, Cd, Cr, Cu, Fe, Hg, Mn, Pb, and Zn with detection limit of 0.007 mg L^{-1} , $0.00015 \text{ mg L}^{-1}$, 0.0007 mg L^{-1} , 0.0005 mg L^{-1} , 0.0001 mg L^{-1} , 0.0003 mg L^{-1} , 0.0001 mg L^{-1} , 0.0005 mg L^{-1} , 0.0002 mg L^{-1} were done using Inductively Coupled Plasma–Atomic Emission Spectrometer (ICP–AES, ACTIVA–M; Horiba Advanced Techno, Kisshoin, Japan). Recoveries within 10% of certified values were used as standards (i.e., De Bruyn Spectroscopic Solutions 500 MUL20–50STD2) for analytical accuracy determination. The percentage recoveries for analysed metals ranged between 91.8% and 106.3%. Certified reference material (River Water Reference Material for Trace Metals, NRC Canada, SLRS–4) were used to check accuracy of the instrumental methods using a run–test after every 5 samples. This procedure was maintained throughout the process for consistency.

2.5 Interpolated Water Quality Parameters

The spatial distribution maps of selected nutrients and metals were created using IDW interpolation technique in the ArcGIS environment (ARCMAP Version 10.8) (Hammoumi et al., 2024). The method adopts a linear–weighted combination set of sampling points to determine cell values in each set of data. The extent of local spatial variation is fairly accurate and is based on sampled GPS Co–ordinates versus

concentration of various elements measured in a particular site (Mansood et al., 2022). Consequently, the generated maps were classified using natural breaks method. Although IDW provided a spatial variation of various environmental variables, a limitation for this method is that it does not account for directional flow or upstream–downstream connectivity, which can result in more localized interpolations despite the presence of spatial autocorrelation in the data.

2.6 Data Analysis

The statistical analysis utilized the Statistical Package for the Social Sciences. A two-way analysis of variance (ANOVA) was performed to assess potential differences in physicochemical parameters, metal and nutrient concentrations across the nine sites and seasons. Spatial interpolation of the data was conducted using ArcGIS (version 10.8) employing the IDW technique, a specific geospatial analysis method. In this study we employed correlation matrix to identify correlations among surface water parameters and across various sampling sites. This statistical approach enabled the detection of patterns within complex quantitative data, providing insights into the relationships among different parameters. We further ran correlation analysis to evaluate the association between measured variables. We utilized the simple correlation coefficient to quantify the predictive ability of one variable with the other. This coefficient evaluated the strength of the relationship between two variables, particularly in cases where one variable (*y*, the independent variable) primarily affects the other (*x*, the dependent variable), and vice versa.

3 Results

3.1 Metal and Nutrient Distribution Patterns

The study revealed varying metal concentrations across all the study sites, with metal concentration of the current study relatively low as compared to other studies in the nearby catchment (Table 1). Metals such as iron and aluminium were found to be low in concentration with ranges from 0.10–0.35 mg L⁻¹ and 0.09–0.44 mg L⁻¹, respectively. Manganese (range 0.03–0.17 mg L⁻¹) did not exceed the chronic effect

Table 1 Water quality variables measured within the Nkomati River highlighting selected water quality guidelines. Abbreviation: BDL - below detection limit

Metals	Current study	Umtata River (Fatoki et al., 2002)	Diep River (Jackson et al., 2009)	Plankenburg River (Jackson et al., 2009)	Nyl River (Greenfield et al., 2012)	Dzindi River (Edokpayi et al., 2014)	Mvudi River (Edokpayi et al., 2016)	Target Water Quality Range (TWQR)	TWQR	Chronic effect value (CEV)	Acute effect value (AEV)
Fe (mg L ⁻¹)	0.09–0.44	0.10–4.47	0.2–513	0.3–48	0.0–19.90	0.80–1.70	0.43–5.07	<5	0.005	0.01	0.1
Al (mg L ⁻¹)	0.10–0.35	0.22–0.36	BDL–4	0.3–13.6	0.0–2.09	0.20–0.40	0.39–13.81	<180	0.18	0.37	1.3
Mn (mg L ⁻¹)	0.03–0.17	0.16–2.04	BDL–1.3	BDL–0.4	0.0–5.05	0.05–0.20	0.03–0.68	<2	0.002	0.0036	0.036
Zn (mg L ⁻¹)	BDL	0.07–0.12	0.1–4.4	BDL–1.1	0.0–1.35	0.05–0.23	0.001–0.548	<7	0.007	0.014	0.2
Cr (mg L ⁻¹)	BDL				0.0–3.68	0.03–0.10	0.01–0.59	<0.3	0.0003	0.00053	0.0016
Cu (mg L ⁻¹)	0.01–0.09	0.1–0.53	0.1–0.6	0.3–2.2	0.0–0.87	0.03–0.07	0.01–0.57	<0.5	0.0005	0.001	0.007
Pb (mg L ⁻¹)	BDL	0.24–1.11			0.0–0.18	0.01–0.05	BDL–0.05	<0.15	0.0005	0.001	0.003
Cd (mg L ⁻¹)	0.001–0.008	0.01–0.26			0.0–0.024		0.0002–0.0043		0.00015	0.0003	
As (mg L ⁻¹)	0.001–0.001							<10			
Hg (mg L ⁻¹)	0.001–0.006							<0.04	0.000004	0.000008	0.0017

value (0.18 mg L^{-1}), indicating no potential ecological risks. Zinc and chromium were below detection limits, suggesting minimal contamination. Copper ($0.01\text{--}0.09 \text{ mg L}^{-1}$) exceeded its chronic effect value (CEV) threshold, hence had a potential of posing risk to aquatic life. The Cadmium concentration was found to be $0.001\text{--}0.008 \text{ mg L}^{-1}$ across the study sites which surpassed its CEV threshold, indicating environmental concerns. Cadmium (Cd), arsenic (As), and mercury (Hg) were found in trace levels, with concentrations exceeding chronic guideline limits (Table 1).

Metal and nutrient concentrations within the Nkomati River system varied between sites and across three seasons (Fig. 2 and Table 2). Physicochemical parameters such as pH and temperature varied with distance from upstream to downstream and across different sites. The pH remained alkaline ($\text{pH}=9$) during hot-dry season and relatively slightly acidic to neutral ($\text{pH}=6\text{--}7$) during cool-dry and hot-wet season (Fig. 2a). Water temperature was relatively high ($28 \text{ }^\circ\text{C}$) during the hot-wet season and decreased to $15 \text{ }^\circ\text{C}$ during the cool-dry season (Fig. 2b). Total dissolved solids ranged from $0\text{--}300 \text{ mg L}^{-1}$ from $0\text{--}30 \text{ km}$ upstream to downstream sites, followed by a sharp decline at 70 km to a concentration ranging from $200\text{--}300 \text{ mg L}^{-1}$, across all three seasons (Fig. 2c). Nitrates concentration was found to be high during cool-dry season (range $24\text{--}28 \text{ mg L}^{-1}$), as compared to low concentrations recorded (range $10\text{--}15 \text{ mg L}^{-1}$) during hot-wet and hot-dry seasons (Fig. 2d). High concentrations of potassium and sodium were recorded at 30 km distance from upstream to downstream sites, with significant declines at 70 km distance across all seasons (Fig. 2e, f). Magnesium and aluminium varied across seasons and distance from upstream to downstream sites with high concentration of 80 mg L^{-1} (55 km) and 0.8 mg L^{-1} (15 km), respectively. Calcium varied in concentration with high concentration (75 mg L^{-1}) recorded during the hot-wet season, while total phosphorus did not show any clear pattern across three seasons (Fig. 2i, j).

Two-way ANOVA results showed that most of the physicochemical and metals variables (i.e., temperature, salinity, potassium, calcium, magnesium, aluminium and sediment phosphorus) differed significantly across sites, seasons and sites \times seasons ($p < 0.05$), whereas parameters such as conductivity,

total dissolved solids and sodium showed significant ($p < 0.05$) with sites and seasons (Table 2). Boron ($F=18.143$, $df=8$, $p < 0.001$) and manganese ($F=2.652$, $df=8$, $p < 0.027$) showed significant differences with sites, while pH ($F=14.119$, $df=2$, $p < 0.001$), ammonium ($F=6.080$, $df=2$, $p=0.007$) and Cu ($F=3.646$, $df=2$, $p=0.040$) showed significant differences among seasons. Phosphates, arsenic, cadmium, iron and mercury showed no significant differences ($p > 0.05$) with sites and seasons (Fig. 2; Table 2).

3.2 GIS Based Metal Distribution Patterns

Based on IDW, aluminium concentration was distributed across all sampling sites, however, high concentrations were recorded at sites 7 and 9 at 0.17 mg L^{-1} and 0.18 mg L^{-1} , respectively. This concentration was found to be within the recommended value of less than 1.8 mg L^{-1} based on the Target Water Quality Range (TWQR). During the hot-dry season, the aluminium increased at sites 1, 2 and 3 (Fig. 3b). Calcium varied across seasons, however, increased significantly at downstream sites during cool-dry and hot-dry season while it remained low during the hot-wet season. Generally, potassium and magnesium followed similar patterns across all seasons, with high levels observed at tributary river site 7.

Across all parameters, site 7 consistently exhibited high concentrations compared to other sites, particularly during the cool-dry and hot-dry seasons. Conductivity levels were high at site 7 among all seasons, with notably elevated concentrations in the hot-dry season (Fig. 4b) and slightly low concentrations in the hot-wet season (Fig. 4c). Sodium concentrations also peaked at site 7 during the cool-dry and hot-wet seasons (Fig. 4d, f), while a reduction was observed during the hot-dry season (Fig. 4e). Nitrate showed substantial seasonal variation, with high concentrations occurring during the cool-dry season (Fig. 4g), particularly at site 7 and the downstream sections, while concentrations decreased considerably during the hot-dry season (Fig. 4h) before increasing again in the hot-wet period (Fig. 4i). Phosphorus concentrations remained relatively low across all sites but show localized increases at site 7 and some upstream sections, particularly in the hot-dry season (Fig. 4k). Overall, these results indicated that site 7 is a hotspot for elevated ion concentrations, potentially influenced

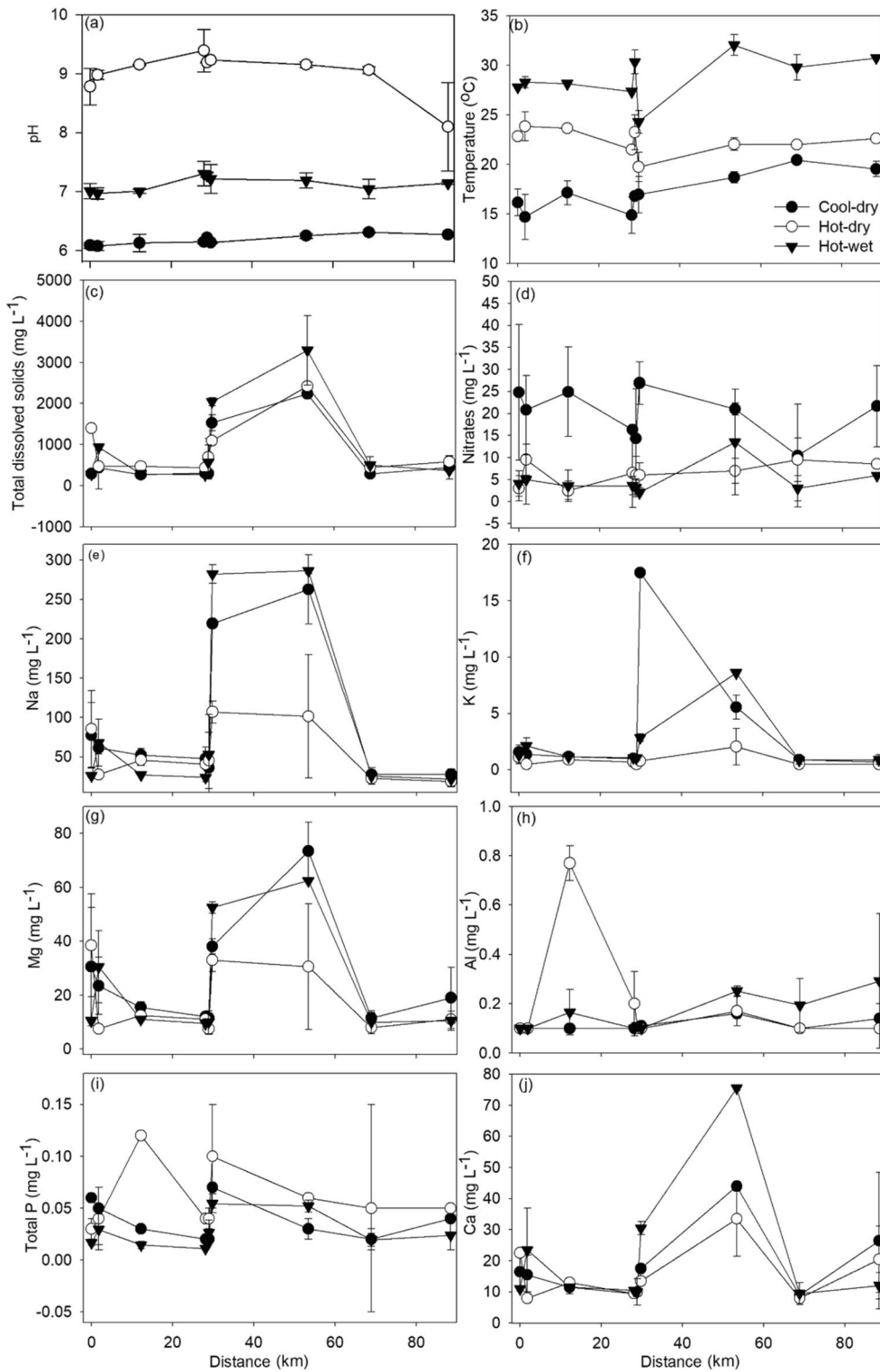


Fig. 2 Variation in metal and nutrient concentration along the Nkomati River system across three seasons at distance (km) from upstream to downstream sites

Table 2 Two-way analysis of variance results for metal and nutrient concentration, along with physicochemical parameters from the Nkomati River

Variable	Site			Season			Site × Season		
	df	F	<i>p</i>	df	F	<i>p</i>	df	F	<i>p</i>
pH	8	0.741	0.655	2	14.119	<0.001	16	0.904	0.573
Temperature	8	9.930	<0.001	2	34.627	<0.001	16	2.786	0.009
Conductivity	8	26.435	<0.001	2	7.709	0.002	16	1.476	0.181
Salinity	8	49.996	<0.001	2	16.382	<0.001	16	4.941	<0.001
Total dissolved solids	8	16.411	<0.001	2	6.197	0.006	16	1.720	0.104
Nitrate	8	0.838	0.578	2	22.245	<0.001	16	0.777	0.696
Phosphate	8	1.205	0.333	2	2.005	0.154	16	0.954	0.527
Ammonium	8	0.289	0.964	2	6.080	0.007	16	1.403	0.212
Na	8	21.462	<0.001	2	3.915	0.032	16	1.876	0.072
K	8	30.549	<0.001	2	32.430	<0.001	16	2.881	0.007
Ca	8	16.548	<0.001	2	1.389	0.267	16	2.049	0.048
Mg	8	18.921	<0.001	2	5.617	0.009	16	2.422	0.021
Al	8	6.794	<0.001	2	4.960	0.015	16	6.052	<0.001
As	8	2.000	0.085	2	0.500	0.612	16	0.500	0.925
B	8	18.143	<0.001	2	0.528	0.596	16	0.654	0.811
Cd	8	0.513	0.836	2	1.831	0.180	16	0.921	0.557
Cu	8	0.969	0.480	2	3.646	0.040	16	0.969	0.513
Fe	8	2.174	0.063	2	0.256	0.776	16	1.676	0.115
Mn	8	2.652	0.027	2	0.600	0.556	16	1.230	0.308
Hg	8	1.572	0.180	2	2.020	0.152	16	1.572	0.146
Sed phosphorus	8	7.772	<0.001	2	20.198	<0.001	16	4.147	0.001

by tributary inflows or localized sources, while seasonal shifts significantly impact the distribution of these concentrations along the river.

3.3 Relation Between Water Quality and Land Cover Types

There were significant relationships between water quality parameters and different land cover types (Table 3). Temperature ($r=0.75$, $p<0.001$) and pH ($r=0.88$, $p<0.001$) exhibited strong positive correlations with settlement and agricultural areas but were negatively correlated with forest and bareland (Table 3). Nitrate concentrations were inversely related to settlement and agriculture ($r=-0.63$, $p<0.001$) while showing a positive correlation with forest and bareland ($r=0.63$, $p<0.001$). Similarly, parameters such as ammonium, potassium, and magnesium displayed negative correlations with settlement and agriculture but positive correlations with forest and bareland (see Table 3). Total phosphorus shows a weak positive correlation with settlement and agriculture ($r=0.34$, $p=0.045$) and a negative

correlation with forest and bareland ($r=-0.34$, $p=0.045$). These findings suggest that anthropogenic activities influence water chemistry, with agricultural and settlement areas contributing to higher nutrient loads while forested regions maintain lower concentrations.

4 Discussion

Clear spatial and temporal variations in the concentrations of metals, nutrients and key physicochemical parameters were observed across the sampling sites. This demonstrates heterogeneity in water quality along the Nkomati River. Secondly, we identified a combination of natural and anthropogenic factors, in particularly land use patterns, proximity to urban settlements and agricultural activities as key drivers shaping the observed variability in water chemistry (Wang et al., 2014). Lastly, this study provides evidence of site-specific pollution inputs, especially near urban and industrial zones whereby these activities are the ones that have the influence of point and

Fig. 3 Variation in aluminium (Al), calcium (Ca), potassium (K) and magnesium (Mg) along the Nkomati River system across three seasons

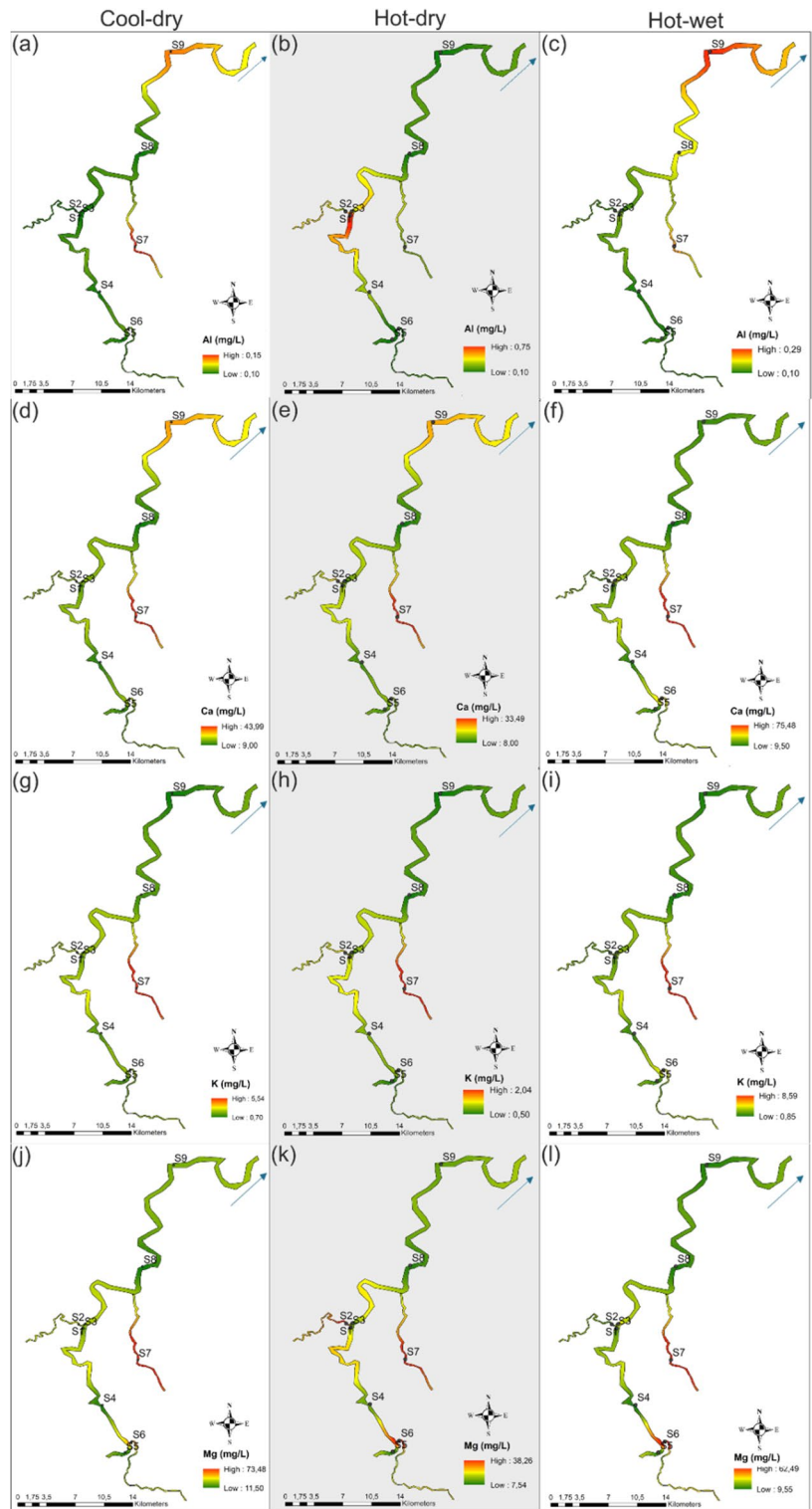


Fig. 4 Variation in conductivity, sodium (Na), nitrate and phosphorous along the Nkomati River system across three seasons

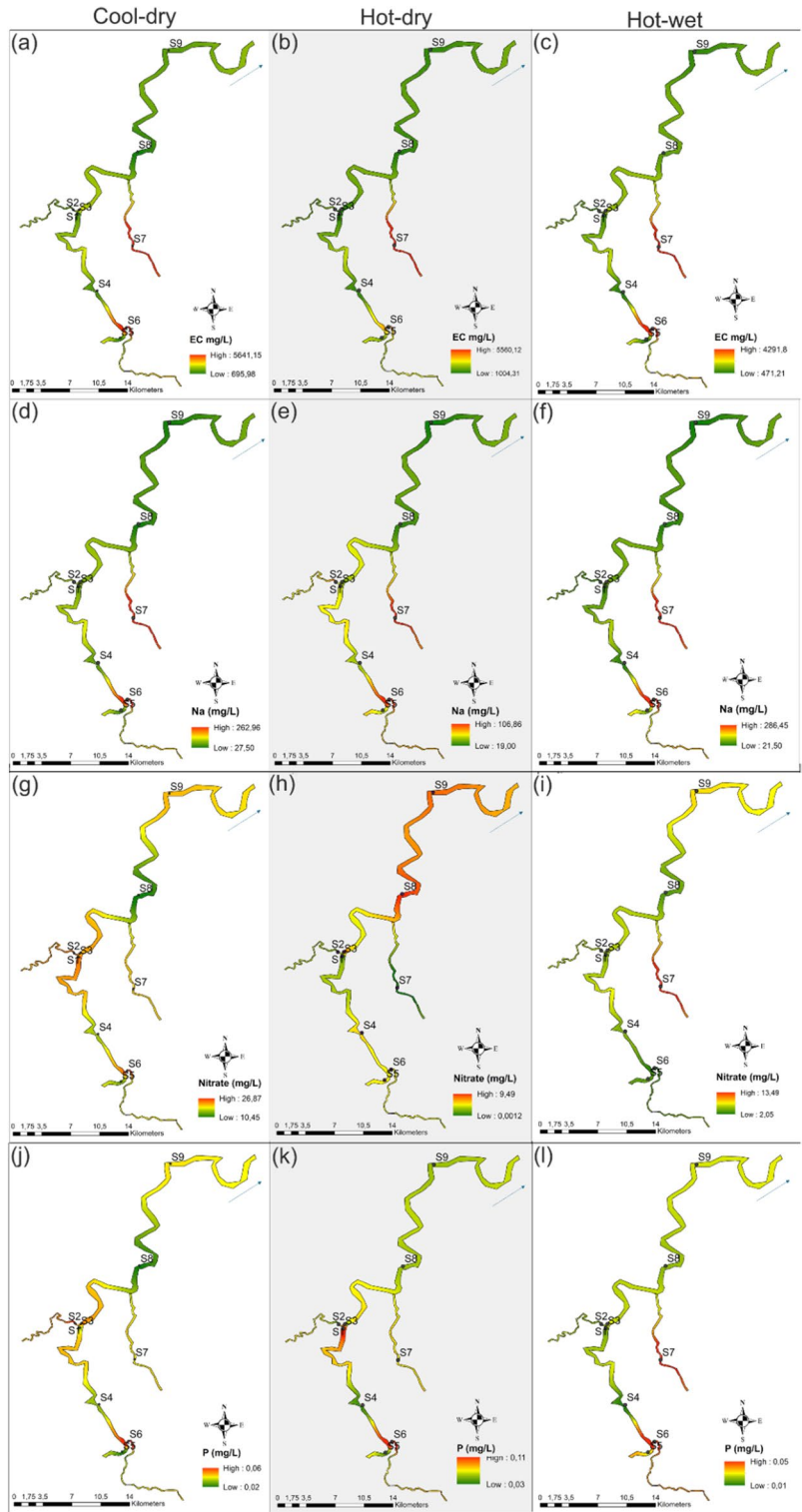


Table 3 Correlation variables between water quality and land cover types highlighting only significant variables. The values in parentheses are *p*-values

Variables	Settlement	Agriculture	Forest	Bareland
pH	0.88 (<0.001)	0.88 (<0.001)	-0.88 (<0.001)	-0.88 (<0.001)
Temperature	0.75 (<0.001)	0.75 (<0.001)	-0.75 (<0.001)	-0.75 (<0.001)
Nitrate	-0.63 (<0.001)	-0.63 (<0.001)	0.63 (<0.001)	0.63 (<0.001)
Ammonium	-0.42 (0.011)	-0.42 (0.011)	0.42 (0.011)	0.42 (0.011)
K	-0.45 (0.006)	-0.45 (0.006)	0.45 (0.006)	0.45 (0.006)
Mg	-0.38 (0.024)	-0.38 (0.024)	0.38 (0.024)	0.38 (0.024)
Total phosphorus	0.34 (0.045)	0.34 (0.045)	-0.34 (0.045)	-0.34 (0.045)

non-point pollution sources on the river's water quality. Thus, these results suggest that the study aims were met and thus the results offer a comprehensive understanding of spatial and seasonal water quality dynamics and their underlying causes within the Nkomati River system.

In this study, the spatial distribution of environmental variables across the sampled sites revealed distinct seasonal patterns under varying climatic conditions (see Figs. 2 and 3). From all the sites (upstream to downstream), the hot-wet season exhibited high variability in physicochemical and metal variables compared to the cool-dry and hot-dry seasons, suggesting heightened water quality changes during periods of increased precipitation and temperature. This pattern is particularly evident in the middle and farthest distances from the upstream sites, where peaks in ecological responses possibly related to productivity, community composition for nutrient and metal availability were more pronounced. During the cool-dry season, most measured variables remained relatively stable across the spatial gradient, reflecting the comparatively low-energy, low-productivity state of the system during this period and was expected as it has been similarly observed in several studies (Alam et al., 2024; Munyai et al., 2025; Netshiongolwe et al., 2020). In contrast, the hot-dry season showed moderate values, with occasional site-specific peaks and this suggest minor but water quality variables responses to the warming trend even in the sites with low water flow.

The divergence in trends among the three seasons highlights the interaction between hydrological regimes and pollution input to the river system, indicating that wet season influxes play an important role in structuring abiotic variables (i.e., physicochemical, nutrients and metals) across various landscapes. Furthermore, the observed peaks in measured

variables during the hot-wet season could be linked to increased organic matter input, enhanced chemical spillages from nearby industrial sites, application of fertilizers by subsistence farmers who grow crops near the riverbanks (typically stimulated by water availability) and higher soil moisture in the area. This is supported by previous research indicating that seasonal inundation and hydrological dynamics are key drivers of spatial heterogeneity in aquatic systems (Huang et al., 2023; Stoffers et al., 2022; Wang et al., 2024). The strong responses observed at longer distances (distance from upstream to downstream sites) may suggest that these sites are more hydrologically dynamic or that they receive more diverse or episodic inputs than locations closer to the origin, possibly due to geomorphological or catchment characteristics.

Seasonal contrasts also highlight the vulnerability of such systems to climate variability and potential future shifts in rainfall and temperature regimes. Thus, if hot-dry conditions become more prolonged under changing climatic conditions, as projected in many semi-arid and subtropical regions by several studies (e.g., Adom et al., 2022; Matimolane et al., 2024; Soti & Thomas, 2022), the homogenization of spatial patterns observed in the cool-dry season may become more common. This could potentially reduce the quality of water in the Nkomati River system and its tributaries and thereby negatively affecting the quality of water in the river system. Similarly, extreme wet periods could promote ecosystem processes such as nutrient cycling and biological interactions.

Based on analysis of variance, the results of this study further revealed significant spatial and seasonal variability in key water quality parameters, with conductivity, total dissolved solids, sodium, potassium, and soil phosphorus emerging as the most responsive indicators of water quality. These parameters displayed highly significant differences across sites and seasons,

as well as strong site and season interaction effects. This suggests that the observed water chemistry patterns are influenced not only by individual factors such as site or rainfall, but by their combined effects. For example, conductivity and total dissolved solids were significantly higher during the hot–wet season, indicating elevated mineral input likely due to surface runoff and increased leaching during periods of intense rainfall. Furthermore, extreme events, such as floods and droughts, can intensify pollution levels by altering pollutant transport, concentration of various nutrients and metals and their distribution in river systems (Biswas et al., 2018; Ciszewski & Grygar, 2016). Moreover, the seasonal enrichment of nutrients and metals constituents has important ecological implications, as they may influence osmoregulation in aquatic biota and alter species composition, especially among sensitive macroinvertebrates and fish (Dong et al., 2021; Li et al., 2022; Oliveira et al., 2024).

The strong spatial variation in sodium and potassium concentrations points to localized geological or land–use influences, potentially linked to upstream soil types or anthropogenic inputs. These ions are essential for biological processes, but their elevated concentrations, particularly during the hot–wet season, could contribute to ecological stress if water guidelines for aquatic ecosystems are exceeded (Ubuoh et al., 2023). The significance of sediment phosphorus, especially its strong seasonal signal and interaction with site effects, further highlights nutrient mobility under varying hydrological regimes. High phosphorus concentrations during wet periods may lead to eutrophication risks (Duan et al., 2023; Rozemeijer et al., 2021), especially in downstream sites, by stimulating excessive algal and microbial productivity. Furthermore, ammonium exhibited significant interaction effects, suggesting that localized environmental conditions such as redox potential and microbial activity vary temporally across sites, and further influencing nutrient availability and transformation. The limited seasonal variation in pH and temperature indicates relative changes within the system, yet slight interaction effects for pH suggest that episodic acidification may still occur across the sampled sites over a period of time.

The metal concentration data from the current study reveal relatively low levels of contamination across most sites when compared to other South African rivers and water quality guidelines. Iron, aluminium, manganese, copper, cadmium, arsenic, and mercury

were detected within the target water quality range for aquatic ecosystems, indicating limited ecological risk. Notably, metals such as zinc, chromium, and lead were below detection limits, suggesting minimal anthropogenic input and effective natural river attenuation. All detected metals remained well below CEV and AEV, suggesting that current metal levels are unlikely to pose a threat to aquatic life. These results provide a strong rationale for long–term monitoring and the inclusion of temporal replication in aquatic ecological studies, particularly in climate–sensitive regions such as the Nkomati River catchment. The result from this study further illustrates how integrating spatial gradients with seasonal dynamics can yield insights into water quality status and ecosystem functioning while also offering valuable guidance for management and conservation efforts aimed at sustaining ecological integrity under shifting environmental scenarios. Overall, these findings provide the importance of considering both spatial and seasonal dimensions in aquatic ecosystem assessments.

5 Conclusion

In this study, we present multivariate statistical analysis coupled with geographic information system (IDW) approach that offers valuable insights into the spatial and seasonal variations in water quality parameters within a river system. This approach highlights the significance of these variations and explores the interrelationships that exist among various water quality parameters, thereby enhancing our understanding of the complex chemical elements (specifically physicochemical and metals variables) dynamics influencing the health of aquatic ecosystems. From this, the influence of environmental variables on river water quality can be deduced and visualized. Also, we can differentiate by this method areas with high concentrations and areas with low concentrations of various constituents along the river system while also associating various anthropogenic activities with the water quality. The information mapped using IDW provide a solid basis for river water quality management and land use planning. This approach will enable the implementation of targeted and effective management strategies, including planned urban development, the regulation of direct pollutant discharges and the enforcement of proper treatment protocols for urban wastewater.

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Data Availability All data generated or analyzed during this study are included in this published article.

Declarations

Ethical Approval This article does not contain any studies involving animals performed by any authors, nor does it contain any studies involving human participants performed by authors.

Consent to Participate All Authors agree to participate in the published version of the manuscript.

Consent for Publication All authors agree to publish this work.

Competing Interests The author declares that there is no conflict of interest.

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