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The impact of wastewater treatment effluent on Crocodile River quality in Ehlanzeni District, Mpumalanga Province, South Africa

Excessive discharge of poorly treated effluent has impacted global water resource systems intensely. The declining state of wastewater treatment plants (WWTPs) is a significant source of pollution in water resources. There is evidence of water resource quality deterioration in natural environments caused by effluent discharges. We assessed the impact of wastewater treatment effluent on the quality of the Crocodile River. For spatial distribution, we collected data from three WWTPs discharging effluent into the Crocodile River and from three points situated downstream of each WWTP. Physicochemical and microbiological parameters such as pH, electrical conductivity, chemical oxygen demand, phosphates, nitrates, ammonia, and *Escherichia coli* were analysed using standard methods of the American Public Health Association. The water quality index was also calculated to give an overall indication of pollution within the catchment. The results show that WWTPs were not complying with the effluent standards set out in their water use licence. The WWTP effluent had a negative impact on downstream water quality, with the water quality index indicating low quality of discharged effluent. It is recommended that a regular and consistent water resource quality monitoring programme be implemented, particularly in areas where effluent discharges are prevalent.

Significance:

In many African nations, water pollution is a serious problem that may be traced to a variety of sources. Surface water pollution has adverse effects on aquatic ecosystems and reduces the availability of clean water. In most semi-arid to dry southern African regions (e.g. South Africa), water scarcity is a significant concern. In these regions, water is a vital resource that must be protected at all times, given that the inadequate infrastructure of wastewater treatment facilities adds to the decline in South Africa's water quality standards.

Introduction

Water is essential for human survival and the long-term development of ecosystems.¹ Globally, population increase, urbanisation, industrialisation, and changes in consumption patterns have resulted in growing demands for freshwater resources.² The declining state of municipal wastewater treatment facilities and infrastructure is one of the largest contributors to pollution in water resources, especially surface water resources. Globally, around 80% of wastewater flows back into the environment as untreated or partially treated, which poses risks to downstream ecosystems and people who rely upon the river as a drinking water source.³ Deterioration of the quality of a water resource, especially South African rivers, has a detrimental impact on socio-economic development because such water cannot be used for bathing, drinking, industry or agriculture. Surface water resources are more susceptible to pollution from various sources because surface water is most easily accessible for general uses.⁴ Municipal wastewater treatment plants' effluent quality is an important factor in determining the best treatment technologies and impact on the ecology of receiving water bodies. Based on the influent wastewater and treated effluent information, the quality of recovered water sources for water reuse can also be evaluated.⁵

Industrial wastewater contamination is a significant issue in South Africa – a fast-growing country with limited freshwater resources. The country is currently designated as water-stressed^{5,6} with just over 1200 m³/person/year of fresh water available for a population of about 58.89 million people⁷. Effluents generated from both industrial and home activities are the second most common source of chemical and microbiological pollution of South Africa's water sources.⁸ Previous research indicates that most municipal wastewater treatment plants (WWTPs) in South Africa rarely treat their wastewater to acceptable standards^{8,9}, while some engaged in the direct discharge of industrial effluents¹⁰, thereby polluting receiving surface water sources. Furthermore, some WWTPs are ill-equipped to remove huge amounts of non-biodegradable trash and heavy metals¹¹, which are subsequently discharged into surface water sources⁷. Effective wastewater management will be required to ensure the long-term sustainability of key water supplies, particularly in urban areas. WWTPs are widely used around the world and are an important stage in improving the quality of wastewater before it is discharged into surface or groundwater and re-enters water systems. Many countries have worked to limit the volume of untreated wastewater discharges to rivers and streams during the last 50 years by closely monitoring and constantly improving municipal and industrial WWTPs.¹²

Although WWTPs are a desirable alternative to unregulated discharges, they do not discharge water of the same quality as that of the receiving water body and also cause physical changes to the receiving system. To avoid public health crises caused by contaminated water sources, efficient pathogen removal from wastewaters is required.¹³ Conventional municipal wastewater treatment without appropriate tertiary treatment such as filtration or disinfection has been documented to pose a risk to public health from enteric pathogens, whether bacterial or otherwise.¹² Despite this, some enteric bacteria have been reported to be more resistant to the activated sludge and trickling filter treatment procedures.¹⁴ Where effluent treatment is effective, the inactivation rates of enteric bacteria by chlorine treatment have been reported to be sufficient¹⁵, but the absence of organic matter reduces the inactivation rates. Water quality monitoring, assessment and evaluation are important for pollution mitigation, control, and water resource management. Water quality monitoring is critical for identifying the major role players and contributors to spatial

and temporal variations in quality, which can be beneficial concerning integrated water resource management.¹⁶ Monitoring is important to ensure that the quality of water resources remains within acceptable limits for sustainable end-use.¹⁷

Given the abovementioned factors, in this study, we aimed to: (1) monitor the quality of the effluent in comparison with the resource quality objectives set for the catchment and/or with the water use licence, (2) determine the concentration of parameters such as ammonia, nitrates, phosphates, chemical oxygen demand, pH, conductivity, and bacteria, and (3) develop a comprehensive water quality index for the water resources sampling sites based on physicochemical and microbiological parameters associated with existing water resource quality standards.

Materials and methods

Study area

The Crocodile River catchment covers an area of about 10 500 km² and is located roughly 300 km east of Johannesburg in the Mpumalanga Province. It is the largest tributary of the Komati River, which it joins shortly before the border with Mozambique. The Lowveld area has developed rapidly and agricultural activities have greatly increased. These developments abstract large volumes of water from the river, resulting in a decline of the flow, especially during dry seasons. Extensive reeds dominate most of the river's riparian zone. The lowest reaches of the Crocodile River are considered to have poor water quality due to agricultural run-off as well as additional mining activities and poorly treated effluent from WWTPs. Figure 1 shows the study area map with sampling sites located within Mbombela and Nkomazi Local Municipalities, Mpumalanga Province. Ethical clearance to conduct the study was granted by Inkomati Usuthu Catchment Management Agency, and approved by the Cape Peninsula University of Technology's Higher Degree Committee.

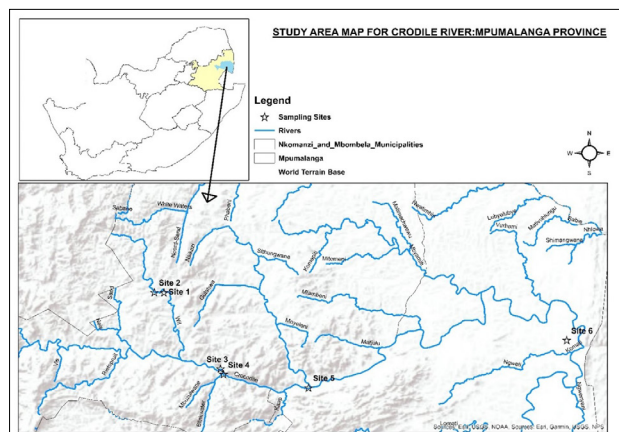


Figure 1: Map of the study area showing the location of sampling points.

Sampling sites

Samples were collected from six sampling sites located in the study area within Mbombela Local Municipality and Nkomazi Local Municipality, which included three WWTPs discharging effluent into the Crocodile River. Within the river, a total of 108 samples were collected between 2017 and 2019. Table 1 lists the sampling sites and their coordinates.

Physicochemical parameters

Wastewater samples used in determining the physicochemical and microbiological characteristics of effluent discharged and of the Crocodile River were collected from six sites between January 2017 and December 2019. Electrical conductivity and pH were determined in situ using a portable Hach Multimeter which was calibrated before use. A UV spectroscopy instrument was used to analyse ammonia, nitrite-nitrate, phosphate and chemical oxygen demand. Ammonia, nitrite-nitrate, phosphate, chemical oxygen demand, total suspended solids, and *Escherichia coli* were analysed at a laboratory accredited by the South African National Accreditation System as per the standard methods of the American Public Health Association.¹⁸

Table 1: Coordinates of the six sampling locations^a across Crocodile River

Sampling sites	Coordinates
White River wastewater treatment plant(Site 1)	S -25.31591; E31.04669
White River – Crocodile River (Site 2)	S -25.31522; E31.02539
Kanyamazane wastewater treatment plant (Site 3)	S -25.48649; E31.17166
Kanyamazane N4 Bridge (Site 4)	S -25.49912; E31.17834
Matsulu wastewater treatment plant (Site 5)	S -25.52907; E31.36631
Downstream Komatipoort wastewater treatment plant (Site 6)	S -25.42271; E31.93726

^aThe sampling points above were selected for the study based on the following factors: Site 1 is the main source of nutrient loading into the White River, which is one of the tributaries of Crocodile River, Site 2 is the point of confluence between White River and Crocodile River, Sites 3 and 5 discharge treated domestic effluent into the Crocodile River and Sites 4 and 6 are situated in a densely populated area with human activities taking place.

Water quality indices

The water quality index (WQI) was used to establish the quality of the water resource and its suitability for supporting aquatic life and social and economic development. The categorisation of water quality based on its quality index is shown in Table 2. Water quality parameters analysed for three different sampling sites (Site 2, Site 4 and Site 6) were used to calculate the WQI. These sites were used for the calculation of the WQI because they are located in the water resource and represent the overall quality of the river at that particular sampling point. The calculation of the WQI was conducted using a weighted arithmetic WQI which was originally proposed by Horton¹⁹ and developed by Brown et al.²⁰ The weighted arithmetic WQI is shown by Equation 1:

$$WQI_A = \sum_{i=1}^n w_i q_i / \sum_{i=1}^n w_i, \quad \text{Equation 1}$$

where n is the number of variables or parameters, w_i is the relative weight of the i^{th} parameter and q_i is the water quality rating of the i^{th} parameter. The unit weight (w_i) of the various water quality parameters is inversely proportional to the recommended standards for the corresponding parameters. According to Brown et al.²⁰, the value q_i is calculated using Equation 2:

$$q_i = 100 \left[\frac{(V_i - V_{id})}{(S_i - V_{id})} \right], \quad \text{Equation 2}$$

where V_i is the observed value of the i^{th} parameter and V_{id} is the ideal value of the i^{th} parameter in the resource quality objectives. All the ideal values (V_{id}) are zero except for pH.²¹ For pH, the ideal value is 7.0 (for natural water) and the permissible value is 8.5 for polluted water. Therefore, the quality rating for pH is calculated from Equation 3:

$$q_{pH} = 100 \left[\frac{(V_{pH} - 7.0)}{(8.5 - 7.0)} \right], \quad \text{Equation 3}$$

where V_{pH} is the observed value for pH.

Table 2: Water quality classification based on the weighted arithmetic water quality index^{20,22}

Water quality index	Water quality status / classification
0–25	Class 1 – Good water quality
26–50	Class 2 – Acceptable water quality
51–75	Class 3 – Regular water quality
76–100	Class 4 – Poor water quality
>100	Class 5 – Very poor water quality

Results and discussion

The heat maps allowed us to explore large data sets and visualise important cases or clusters. Figure 2 depicts changes in water quality indicators analysed per sample location from 2017 to 2019 over two separate seasons (dry and wet). For each parameter studied, data were categorised and compared based on time and season. The actual numerical values are shown in the [supplementary material](#). Water quality data were compared by season (dry and wet) because rainfall run-off has a major influence on the quality of a water resource and the quality of discharged effluent, as well as acting as a diluting factor on the overall concentration of waste.²³

The water body receiving treated effluent from wastewater treatment around the White River WWTP (Site 1) had a wide range of pathogenic microorganisms. In particular, the region got a significant amount of ammonia (NH_3) in 2017 when compared to the other locations (Sites 3 and 5) in the same year. The levels of ammonia were above the legal limit which is set for White River WWTP as per the effluent discharge quality limits for the WWTP water use licence within that area (Table 3). High levels of nitrate (NO_3) and nitrite (NO_2) were observed from Site 1 in the 2019 wet season. WWTP effluent had a considerable impact on ammonium and nitrate concentrations in the water which means that a post-treatment may be required for removal of nitrate,

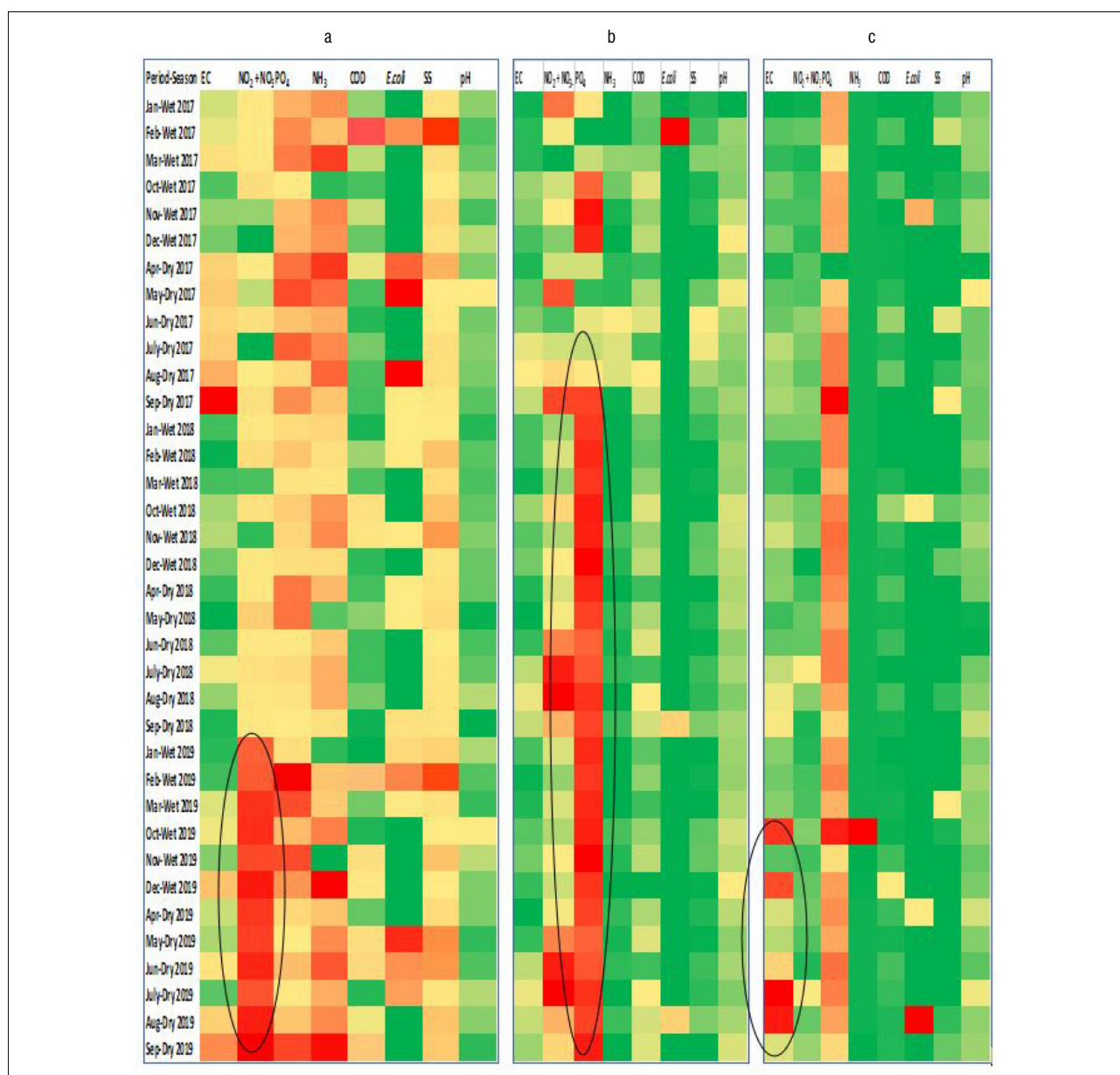


Figure 2: Heat maps showing variations in water quality parameters for (a) White River wastewater treatment plant (WWTP) Site 1, (b) Khanyamazane WWTP Site 3 and (c) Matsulu WWTP Site 5. The higher the intensity of the red colour, the higher the measured parameter. The higher the intensity of the green colour, the lower the measured parameter.

Table 3: Effluent discharge quality limits as per White River wastewater treatment plant (WWTP) water use licence

	pH	Electrical conductivity	$\text{NO}_2 + \text{NO}_3$	<i>E. coli</i>	Suspended solids	PO_4	NH_3	Chemical oxygen demand
White River WWTP	5.5–9.5	70	15	0	25	1	1	75
Khanyamazane WWTP	5.5–9.5	75	15	0	25	1	6	75
Matsulu WWTP	5.5–9.5	70	15	0	25	1	3	75

residual ammonia, and nitrite, depending on the type of procedure used to conduct the anammox conversions and the effluent requirements. Nitrate in waste effluents can come from a variety of sources, including home and agricultural wastes, as well as N-containing fertilisers. Ammonium nitrogen (which is abundant in raw waste) is completely or partially oxidised to nitrate by microbial action, resulting in high nitrate concentrations in treated wastewater. In locations with strong population pressure and agricultural expansion, nitrate pollution of raw drinking water is common. The results above are in line with other studies which were conducted in South African rivers such as the Mhlathuze River, Vaal River and Klip River.^{24,25}

Site 3 had a high level of phosphate from 2017 to 2019; levels were above the required limits as outlined in the water use licence (Table 3). Phosphate concentration was frequently outside the set limit as evidenced in the water quality data during the wet season from 2017 to 2019, with a lower mean concentration in 2017 compared to the same periods in 2018 and 2019. Phosphorus removal in activated sludge systems such as WWTPs (Site 3) relies mainly on phosphorus accumulating organisms for enhanced biological phosphorus removal. Bunce et al.⁵ outline that operating conditions, including prerequisites for metabolism such as carbon, glycogen and electron acceptor requirements, are very important for the growth of such organisms, hence the adjustment of such factors must be undertaken to promote the proliferation of phosphorus accumulating organisms and ultimately remove phosphorus from wastewater. The results from the study conducted by Bunce et al.⁵ show that the plant does enable phosphorus present in wastewater; however, the system is unable to produce an effluent with a phosphate concentration of less than 1 mg/L as per the water use licence limit. The results are in line with a study conducted by Cai et al.²⁶ which revealed that biological nutrient removal systems do not completely remove phosphorus present in wastewater, but remove only around 60% of the total influent phosphorus.

Site 5 (Matsulu WWTP) was located downstream of Site 4. This WWTP treats domestic wastewater from Matsulu township and discharges effluent into the Crocodile River. The plant is situated in a residential area that is also dominated by agricultural land-use activities. Although one would have expected high levels of phosphate, nitrate and ammonia (as for Site 1), Site 5 had relatively low rates of these parameters, which shows that there are anthropogenic activities taking place around the area or sewage. Although there were some spikes of *E. coli* around August 2019, low levels of *E. coli* were found throughout the sampling times (2017 to 2018). The same trend can be observed for the phosphate levels from 2017 to 2019. Site 5 had a high rate of electrical conductivity around the 2019 dry season, which was above the effluent quality limits as per Matsulu WWTP's water use licence (Table 3). Other studies have found that, during months of low precipitation such as winter in South Africa, significantly higher electrical conductivity and salinity occur, because enhanced evaporation results in a more concentrated effluent.^{27,28} Water's electrical conductivity is a quick and straightforward way to determine its salinity or total salt content. Domestic sewage effluents can contain high levels of dissolved salts. High salt concentrations in waste effluents can raise the salinity of receiving water, which can have negative ecological consequences for aquatic life. As a result, when combined with other parameters and when the source of dissolved salts is not of natural geological origin, electrical conductivity can be a good salinity indicator.

Physicochemical parameters

Table 4 shows the standard set by the South African Department of Water Affairs as per the Government Gazette no. 39614 issued on 22 January 2016 and issued water use licences. Crocodile River is generally classified as Class C in regard to ecological status, that is, intended to support farming, commercial and sustenance fishing.

Figure 3 shows heat maps depicting changes in water quality parameters analysed per sampling site (Sites 2, 4 and 6) in the Crocodile River. Water quality data were compared according to seasons (dry and wet) because rainfall run-off has a significant impact on the quality of a water resource. For each parameter studied, data were categorised and compared based on time and season. Two parameters – namely chemical oxygen demand and suspended solids – which were analysed

on samples from the effluent of the WWTP were not analysed in samples taken from these sites because they are situated within the water resource (river) and there is no set limit for such parameters on the resource quality objectives.

Table 4: Resource quality objectives set for the Crocodile River water²⁹

Constituents	Limits
Electrical conductivity (ms/m)	70
Nitrite and nitrates (mg/L)	6
Phosphate (mg/L)	0.125
Ammonia-N (mg/L)	6
<i>E. coli</i> (count per mL)	130
pH	6.5–8.5

Figure 3 shows heat maps for Site 2, Site 4 and Site 6 analysed for visualisations of the results obtained in the Crocodile River. Parameters from all three sites were compared to the standard set by the Department of Water Affairs as per Government Gazette no. 39614 and issued water use licences to check if they complied with the set standards. Site 1 is a confluent point between White River and Crocodile River, and the area is mostly dominated by agricultural land-use activities. Data revealed that water resource quality at this site was compliant with the set limits for parameters outlined in the resource quality objectives in most months (Table 4). Although Site 2 was compliant with the set limits, in the 2017 wet season, it recorded values above the legal limits. The site is situated downstream of the White River WWTP, and so it was expected that, as the effluent from the WWTP had high *E. coli* counts during 2017 and 2019 of the same periods, this site would exhibit higher *E. coli* counts during these months; however, higher *E. coli* counts were noted in 2017 only. It was also noted that the area received minimal rainfall of between 100 mm and 200 mm between April and May 2019. These results contradict those of Abia et al.³⁰ who outlined that run-off from the storm influenced the concentration of *E. coli* in the water resource because run-off carries sediments containing microorganisms into the river.

The Kanyamazane N4 Bridge (Site 4) is located downstream of Kanyamazane WWTP (Site 3) which is densely populated, and water resource quality is mostly influenced by anthropogenic activities undertaken within the surrounding informal settlements. In 2017, Site 4 recorded high levels of *E. coli* when compared to those in 2018 and 2019. The recorded levels of *E. coli* were above the standard set by the Department of Water Affairs as per Government Gazette no. 39614 and issued water use licences (Table 4). The overall status of the quality of the water resource reveals that it is not compliant with the set limit. A similar trend was also observed from Site 2, whereby higher *E. coli* counts were observed during the 2017 and 2018 periods and lower counts were noted in samples collected in 2019. This sampling site is situated in a densely populated area in the township called Kanyamazane; the site is also situated approximately 300 m downstream of Kanyamazane WWTP discharge point. The results are in line with the study conducted by Amoah et al.³¹ who outlined that, in addition to the treated effluent discharged into the river, informal settlements situated near the water resources had an impact on the microbial quality of the water resources, as indicated mostly by the presence of *E. coli*. The downstream chemistry and bacterial populations of these rivers were considerably affected by WWTP wastewater. Inorganic nitrogen and phosphorus concentrations were higher downstream of the effluent, similarly to that seen in several habitats.

Site 6 is located approximately 50 m downstream of Komatipoort WWTP, which primarily treats domestic wastewater from Komatipoort Town. The area is mostly dominated by agricultural land-use activities (sugar cane, maize). The overall status of the quality of the water resource reveals that it is not compliant with the set limit (Table 4). This sampling site is also situated in a populated area in the town of Komatipoort and is approximately 200 m downstream of Komatipoort WWTP discharge

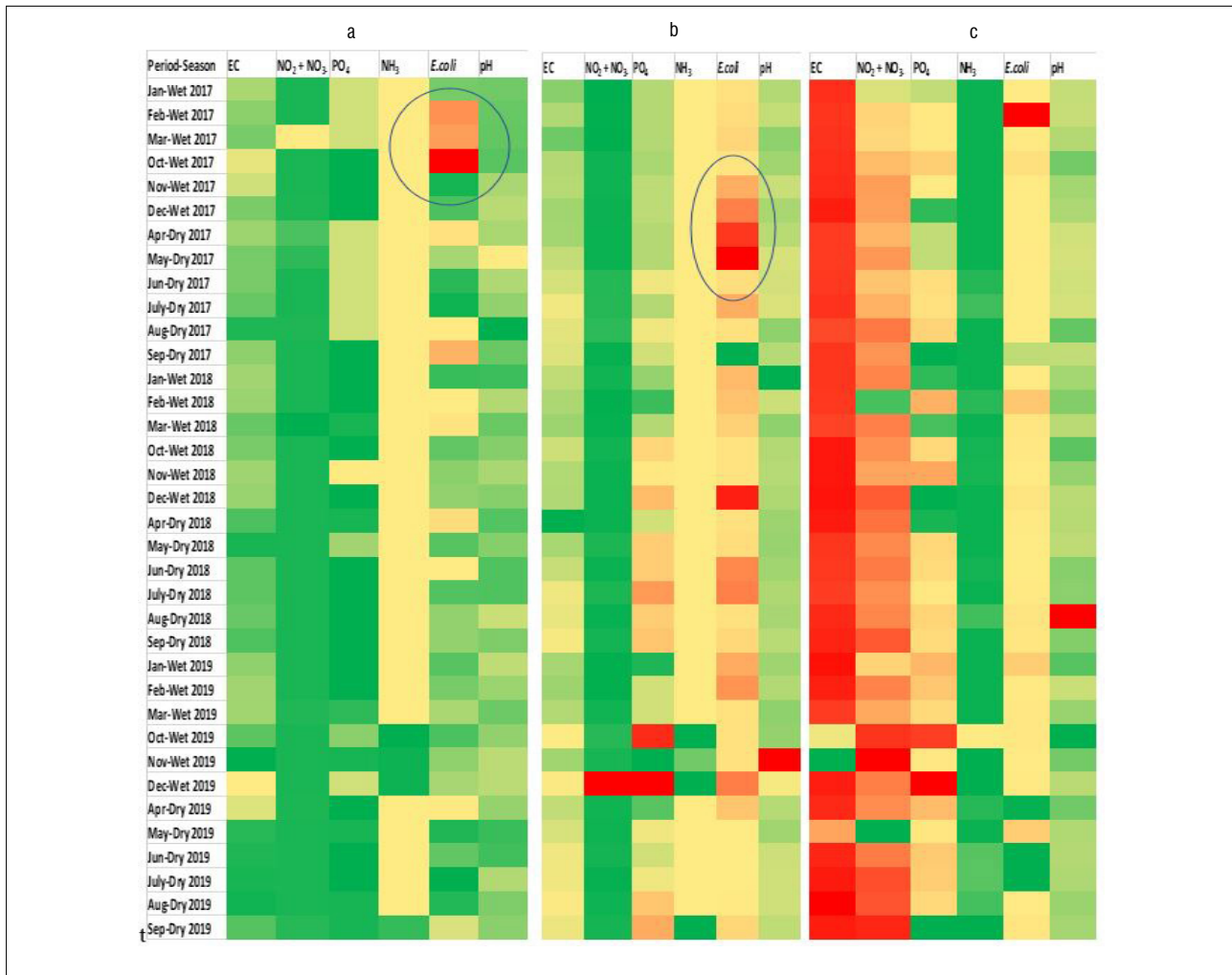


Figure 3: Heat maps showing variations in water quality parameters for (a) White River – Crocodile River (Site 2), (b) Kanyamazane N4 Bridge (Site 4) and (c) downstream Komatipoort wastewater treatment plant (Site 6). The higher the intensity of the red colour, the higher the measured parameter. The higher the intensity of the green colour, the lower the measured parameter.

point. Site 6 recorded high levels of electrical conductivity, irrespective of year or season, which were above the required levels as set by the Department of Water Affairs as per Government Gazette no. 39614 and issued water use licences (Table 4). This limit was exceeded in river water samples, and the parameter is alarming, while the effluent discharge has remained consistent when looking at the WWTP (Site 5). But electrical conductivity in the river was higher (relative to measurements at the reference location), indicating a significant impact. Within the same site, levels of nitrate and nitrite were high during the years 2018 and 2019, rendering the river non-compliant with the set limits (Table 4). Site 6 showed a trend distinct from those of Sites 2 and 4 as it recorded high electrical conductivity, nitrate and nitrite, irrespective of the season during which the samples were collected. Because of the presence of chloride and phosphate, a failed sewage system would increase conductivity. But because the Crocodile River is classified as Class C ecological status, intended to support farming, commercial and sustenance fishing, the concentration of nitrates in river water is not thought to be a hazard for residential usage. However, eutrophication makes nitrate an issue for other applications. Therefore, non-point sources are said to account for almost two thirds of contaminant loading in surface waterways, with nitrate being the most common pollutant. Excess NO₃ and NO₂ can cause eutrophication – a growing concern in many developing countries.

Water quality Index

Classification of the water quality of the water resource relating to the weighted arithmetic WQI is shown in Table 2 and the computed WQI for

different sites (Sites 2, 4, 6) is shown in Tables 5–7. The present index is based on the desirable and permissible limits of *E. coli*, pH, electrical conductivity, phosphate, nitrite-nitrate and ammonia as defined by the resource quality objectives of Crocodile River.

White River – Crocodile River confluence (Site 2)

Table 5 shows the calculation of the WQI of Crocodile River at Site 2 and the standard values of the selected six water quality parameters according to the resource quality objective of the catchment (see Table 2). Based on the classification of the water quality concerning the weighted arithmetic WQI method as shown in Table 4, the WQI for Site 2 was 31.27, which indicates acceptable water quality. These results are in line with a study conducted by Şener et al.³² to evaluate the water quality of Aksu River using a WQI. The study included 21 sampling sites located within the river and it was observed that the WQI of sampling sites located mostly in the middle region ranged between 37.6 and 62.9 during both dry and wet seasons, showing water of good quality.

Kanyamazane N4 bridge (Site 4)

Table 5 shows the calculation of the WQI of Crocodile River at Site 2. Based on the classification of the water quality shown in Table 6, the WQI value of Site 4 was 101.18, which indicates very poor water quality. It can be observed that the poor water quality can be attributed to high *E. coli* counts present in the water. These results are in line with the study conducted by Ewaid et al.³³ who outlined that WQI values showing

Table 5: Calculation of the water quality index (WQI) of the Crocodile River at Site 2

Parameter	Standard value (Sn)	1/Sn	$\Sigma 1/Sn$	$K=1/(\Sigma 1/Sn)$	$Wi=K/Sn$	Ideal value (Vo)	Mean conc. value (Vn)	Vn/Sn	$Qn=Vn/Sn*100$	WnQn
<i>E. coli</i>	130	0.0076	8.472	0.1180	0.0009	0	314.03	2.415	241.56	0.2193
pH	8.5	0.1176	8.472	0.1180	0.0138	7	7.64	0.42	42	0.5831
Electrical conductivity	70	0.0142	8.472	0.1180	0.0016	0	30.83	0.440	44.04	0.0742
Phosphates	0.125	8	8.472	0.1180	0.9441	0	0.0401	0.3208	32.08	30.289
Nitrate + nitrite	6	0.1666	8.472	0.1180	0.0196	0	0.1331	0.0221	2.218	0.0436
Ammonia	6	0.1666	8.472	0.1180	0.0196	0	0.1803	0.0300	3.005	0.0591
Sum (Σ)					1					WQI=31.27

Table 6: Calculation of the water quality index (WQI) of the Crocodile River at Site 4

Parameter	Standard value (Sn)	1/Sn	$\Sigma 1/Sn$	$K=1/(\Sigma 1/Sn)$	$Wi=K/Sn$	Ideal value (Vo)	Mean conc. value (Vn)	Vn/Sn	$Qn=Vn/Sn*100$	WnQn
<i>E. coli</i>	130	0.0076	8.472	0.1180	0.00090	0	2404	18.49	1849.23	1.68
pH	8.5	0.1176	8.472	0.1180	0.01389	7	7.82	0.53	53	0.74
Electrical conductivity	70	0.0142	8.472	0.1180	0.00169	0	25.48	0.364	36.4	0.061
Phosphates	0.125	8	8.472	0.1180	0.94418	0	0.13	1.04	104	98.19
Nitrate + nitrite	6	0.1666	8.472	0.1180	0.01967	0	1.38	0.23	23	0.452
Ammonia	6	0.1666	8.472	0.1180	0.01967	0	0.18	0.03	3	0.059
Sum (Σ)					1					WQI=101.18

Table 7: Calculation of the water quality index (WQI) of the Crocodile River at Site 6

Parameter	Standard value (Sn)	1/Sn	$\Sigma 1/Sn$	$K=1/(\Sigma 1/Sn)$	$Wi=K/Sn$	Ideal value (Vo)	Mean conc. value (Vn)	Vn/Sn	$Qn=Vn/Sn*100$	Wn Qn
<i>E. coli</i>	130	0.0077	8.472	0.1180	0.00091	0	2144	16.49	1649.23	1.50
pH	8.5	0.1176	8.472	0.1180	0.01388	7	8.1	0.73	73	1.013
Electrical conductivity	70	0.0142	8.472	0.1180	0.00168	0	125.3	1.79	179	0.301
Phosphates	0.125	8	8.472	0.1180	0.94418	0	0.67	5.36	536	506.08
Nitrate + nitrite	6	0.1667	8.472	0.1180	0.01967	0	9.14	1.52	152.3	2.99
Ammonia	6	0.1667	8.472	0.1180	0.01967	0	0.488	0.081	8.13	0.160
Sum (Σ)					1					WQI=512.05

poor water quality as observed from Site 3 can be attributed to natural phenomena and anthropogenic activities such as wastewater discharge occurring along the river. Medeiros et al.³⁴ also conducted a similar study on the quality index of surface water of Amazonian rivers and noted that WQIs determined for the water resources flowing through or located near urban centres or populated areas were impacted by domestic and industrial untreated effluents; they highlighted that lack of adequate sanitation services and treatment processes has been the main reason for water quality deterioration in these water resources.

Downstream Komatipoort WWTP (Site 6)

Table 7 shows the calculation of the WQI of Crocodile River at Site 6. The WQI of Site 6 was 512.05. Based on the classification of the water quality (Table 2), it was observed that the quality of the water was very poor. This site is situated approximately 50 m downstream of Komatipoort WWTP. These results are also in line with a study conducted by Şener et al.³² who evaluated the water quality of Aksu

River using a WQI and observed that the WQI value for certain sampling sites located in the upper regions of Aksu River reached a maximum of 304.51 during the dry season and 304.33 during the wet season, which indicates extremely poor water quality. From tributaries data, they outlined that the reason for such poor water quality was the input of municipal and industrial wastewater discharged at the banks of the river³², which also supports the high effluent noted at Site 5.

Conclusion and future research

The assessment of the impact of wastewater treatment effluent on water quality of the Crocodile River based on the physicochemical and microbiological parameters and indices indicates the quality of the water resources is impacted due to poorly treated discharged effluent, evidenced by higher WQIs of 101.18 and 512.05 observed at Site 4 and Site 6, respectively, which is mostly attributed to high *E. coli* counts frequently recorded during the study. These results obtained in the current study suggest there is a WWTP effluent related pollution in the Crocodile

River. Based on the results of our study, the pollution of the Crocodile River can be attributed to, amongst other non-point sources, poor quality effluent discharged into the water resource. Poorly treated effluent from WWTPs discharged into the water resources has a significant impact on the functioning, integrity, and quality of the water resource and associated ecosystem. Several studies were also conducted on the impact of wastewater effluent on the receiving environment and they confirm that there is still a lot of work that needs to be undertaken in regard to improving effluent quality to protect our water resources.

Recommendations

- A call to vigilance and aggression by responsible authorities with regard to compliance monitoring and enforcement of effluent discharge laws and regulations to ensure minimal pollution in rivers and streams.
- A comprehensive and detailed study including all WWTPs located within the Crocodile River catchment, covering a wide period of water quality data (15 to 20 years) should be undertaken to successfully assess the overall impact.
- A public awareness and education programme, especially in densely populated areas situated next to a water resource, is needed to educate the public on the importance of water resources and measures that can be taken by settlers to reduce non-source pollution.
- A scheduled continuous operations and maintenance programme for wastewater treatment works and related infrastructure must be put in place to ensure effective operation.
- The local government should conduct a feasibility study, and assess and invest in post-treatment technologies that can be integrated into current process technology to enhance the operation and ensure compliance of discharged effluent with set standards.

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Data availability

Raw data from Inkomati Usuthu Catchment Management Agency (IUCMA) were used in the study. The information can be requested from IUCMA <https://www.iucma.co.za>

Competing interests

We have no competing interests to declare.

Authors' contributions

T.T.P. conducted the study and the collection of data was relevant for the writing of the article. All authors contributed to conceptualisation, structuring and writing the article.

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