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Tracing Pollution Pathways in the Trichardspruit Catchment, South Africa: Spatio-Temporal Assessment of Water Quality and Wastewater Treatment Impacts

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ABSTRACT

Water quality is fundamental to water security, ecosystem integrity, and public health. This study assessed the impact of wastewater effluent on the Trichardspruit River, which receives effluent from two wastewater treatment works (WWTWs). Over a 12-month period, water samples were collected across six study sites (S1–S6) to evaluate physicochemical and microbiological parameters relative to national Resource Quality Objectives (RQOs) and Water Use Licence (WUL) limits. One-way ANOVA showed significant ($p < 0.05$) spatial differences for all parameters, and Tukey's HSD identified the strongest pairwise contrasts at and below the discharge of WWTW-2 (S5). Orthophosphate peaked at 7.26 mg/L at S5, and remained elevated at 3.6 mg/L at S6. Chemical oxygen demand reached 92 mg/L at S5, and likewise, EC and major ions (Cl^- and SO_4^{2-}) were higher at S5 & S6 than upstream. Microbial contamination exceeded permissible standards throughout the monitoring period, with *E. coli* counts as high as 7230 CFU/100 mL at S6, indicating a severe public health risk. Overall, WWTW-2 (S5) showed a stronger local impact than WWTW-1 (S2), while downstream persistence of salts and microbes indicates that dilution alone is insufficient. The study underscores the need for improved sewer system maintenance, infrastructure upgrades, and stricter enforcement of discharge standards to achieve compliance with Water Use Licenses. Enhanced real-time monitoring and implementation of RQOs are essential to safeguard the Trichardspruit

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River and regional water security.

Keywords: Compliance Monitoring; Contamination; Eutrophication; Trichardspruit; Wastewater Effluent; Water Quality; Water Security

1. Introduction

Freshwater ecosystems such as rivers, lakes, and streams are vital for biodiversity, livelihoods, and climate regulation, yet they face escalating threats from anthropogenic pollution, including industrial effluents, agricultural runoff, and untreated domestic waste. Such sources release numerous pollutants, including heavy metals, excess nutrients, and pathogens that degrade water quality, disrupt aquatic food webs, and pose a significant threat to public health^[1,2].

Globally, the legacy of extensive industrial and agricultural activities has led to the accumulation of persistent contaminants that are a significant threat to aquatic ecosystems^[3]. Contaminants from sources such as industrial activities, mining operations, domestic waste, and wastewater treatment effluent pollute nearby aquatic ecosystems, transforming riverbeds and coastal sediments into long-term toxic reservoirs^[4]. These pollutants do not readily break down and can be reintroduced into the water column by dredging, flooding, or storm events, sustaining chronic exposure risks for downstream ecosystems and communities^[4].

A major water quality concern worldwide is nutrient enrichment, primarily driven by nitrogen and phosphorus from agricultural fertiliser runoff and untreated sewage. This often initiates a cascade of eutrophication, resulting in excessive algal growth, light limitation, submerged vegetation loss, and subsequent hypoxia due to microbial decomposition of dead biomass^[5,6]. These “dead zones,” such as those observed in the Gulf of Mexico, are uninhabitable for most aquatic species^[7].

In water-scarce countries like South Africa, these global pressures are compounded by rapid urbanisation, the proliferation of informal settlements, and the systemic failure of wastewater treatment works (WWTWs)^[8–11]. These challenges are often rooted in rapid urbanisation, overwhelming existing infrastructure, and limited municipal resources. Furthermore, informal settlements, which are frequently located along riverbanks due to land availability, often lack formal sanitation services, and consequently, discharge untreated

household wastewater, comprising both ‘greywater’ from washing and ‘blackwater’ from toilets, directly into adjacent watercourses^[12]. This practice introduces high loads of microbial pathogens, such as *E. coli*, and chemical contaminants, including phosphates from detergents and high concentrations of nitrogenous compounds, further intensifying pollution. As a result, the discharge of partially treated or raw sewage has become a leading driver of aquatic pollution in South Africa, often introducing high loads of nutrients and pathogens into receiving water bodies^[13] and exacerbating public health risks and environmental degradation in communities.

Rivers situated immediately downstream of small to medium-scale wastewater treatment works within rapidly urbanising catchments present a characteristic and often severe signature of anthropogenic impact^[14]. This impact manifests as distinct, yet abrupt increases in chemical and microbial indicators at effluent discharge points, followed by gradual attenuation downstream^[15]. This attenuation is governed by a complex process, such as dilution, microbial degradation, sedimentation, and the river’s natural assimilative capacity, which is frequently compromised during high-flow events^[10,12,14,15].

Rainfall-driven stormwater runoff and combined sewer overflows can further exacerbate pollution levels by allowing untreated or partially treated sewage to bypass the WWTW entirely. Empirical studies in South Africa and other developing contexts have demonstrated the scale of this problem^[10–15]. In response to these challenges, compliance-oriented water quality assessments are increasingly used to evaluate the ecological and public health impacts of WWTWs. These assessments benchmark observed pollutant levels against national regulatory limits such as Receiving Water Quality Objectives (RQOs) and Water Use Licence (WUL) conditions. This approach enables precise, actionable insights for regulators, environmental managers, and wastewater authorities. The present study adopts such a framework to assess the pollution dynamics of the Trichardspruit River, a critical tributary in the Secunda region of South Africa.

This river receives effluent from two municipal wastewater treatment works, as well as diffuse urban runoff and potential industrial discharges. This localised investigation of the Trichardspruit River reflects broader global trends in freshwater degradation due to WWTW discharge and urban expansion. The observed spatial gradients in nutrient, ionic, and microbial parameters in the Trichardspruit River are consistent with patterns documented in similar South African and global studies evaluating the influence of wastewater effluent on receiving rivers^[13–17]. Elevated concentrations of ammonium, nitrates, phosphates, and electrical conductivity at the discharge point and immediate downstream sites align with findings from the Crocodile, Hennops, and Vaal River systems, where chronic discharge from underperforming WWTWs led to eutrophication, oxygen depletion, and microbial contamination^[17–20]. Comparable nutrient-enrichment trends have been reported in peri-urban catchments across Kenya and India, where high chemical oxygen demand (COD) and nutrient loads similarly reflect insufficient tertiary treatment and rapid urban expansion^[20,21].

Like many urban rivers in the Global South, the Trichardspruit is ecologically sensitive and socio-economically critical, providing water for livestock, irrigation, and downstream domestic use. These pressures mirror

those observed in peri-urban contexts globally, where infrastructure fails to keep pace with population growth. By examining water quality through a regulatory and spatially explicit lens, this study provides a valuable case for understanding the compounded effects of urbanisation and institutional capacity constraints on river systems.

Accordingly, this study investigates the spatio-temporal variability of key physico-chemical and microbial water quality parameters across six sites along the Trichardspruit. It quantifies the influence of WWTW discharges and assesses compliance with national thresholds, including the RQOs for the catchment and the WUL discharge limits. The findings are expected to inform regulatory decision-making, optimise compliance monitoring frameworks, and support improved management of WWTWs in similar urbanising catchments across South Africa.

2. Materials and Methods

2.1. Study Area

The Trichardspruit River is located within the Govan Mbeki Local Municipality, under the Gert Sibande District in Mpumalanga Province, South Africa, and lies between 26°33'6.649" S and 29°4'51.286" E (**Figure 1**).

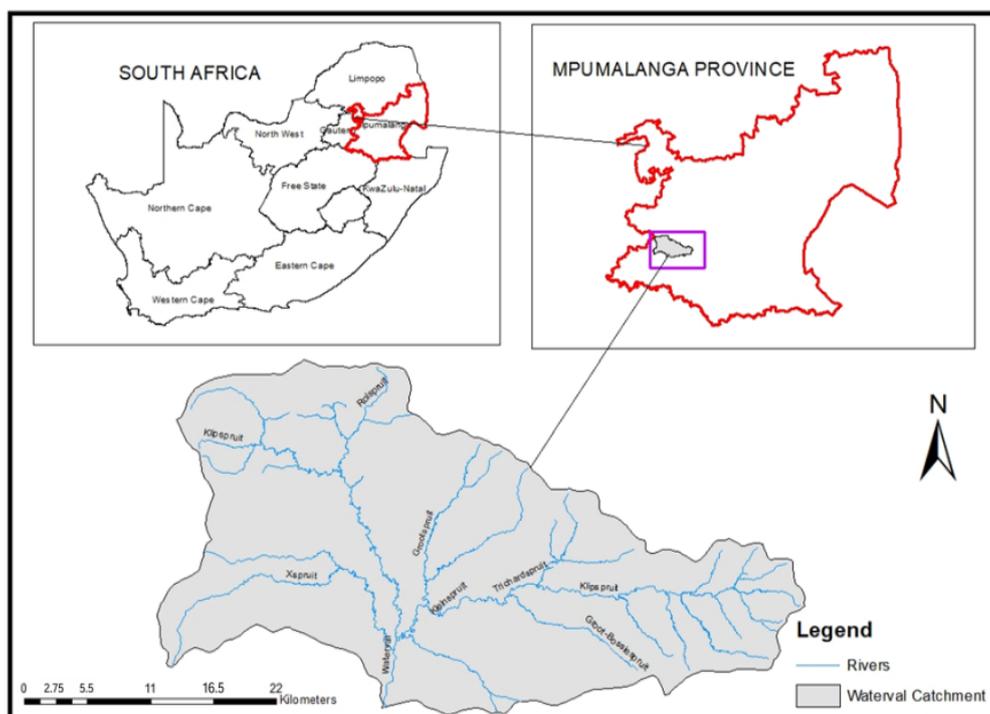


Figure 1. Location of the Trichardspruit Catchment within the broader Waterval sub-catchment.

The Trichardspruit River and its tributaries, the Klipspruit and Groot-spruit, flow through the towns of Secunda, Embalenhle, and Leandra before merging with the Waterval River, which ultimately drains into the Vaal River, as part of the Waterval Catchment^[9,13,16]. The catchment is characterised by warm, dry summers and cold, wet winters, with temperatures ranging from 0.2 °C to 33 °C. This relatively flat area, with elevations between 1540 m and 1692 m, receives approximately 85% of its annual rainfall between October and March^[17]. The Trichardspruit system falls into the seasonal river category typical of South African summer-rainfall catchments, with ~70–85% of annual rainfall occurring between October and March^[17,18].

Streamflow generation is therefore dominated by surface runoff and shallow soil-water during the wet season, while baseflow contributions from deeper groundwater are minimal in the dry season, reducing dilution capacity, allowing pollutants, including nutrients and microbial contaminants, to persist for longer periods^[19].

Conversely, wet-season stormwater surges can mobilise accumulated contaminants from informal settlements, urban surfaces, and industrial zones, and may also trigger hydraulic overloading at wastewater treatment works, leading to intermittent bypasses of untreated effluent^[14–19].

Historically an agricultural area, the region experienced a shift toward mining and petrochemical activity following the establishment of Sasol Secunda in the early 1980s^[13,17]. This rapid industrialisation, coupled with urban growth, has placed increasing pressure on local water resources.

2.2. Sampling Design

To assess the spatio-temporal variability of key physico-chemical and microbiological parameters, water samples were systematically collected at six sampling sites. The six sampling sites were strategically selected to represent a longitudinal profile of the river system with respect to WWTW discharge. Sites 1 and 4 represent upstream reference points, situated beyond the influence of effluent discharge. Sites 2 and 5 are located immediately downstream of the respective WWTW discharge points, thereby capturing peak impact zones. Sites 3 and 6 are further downstream, enabling evaluation of pollutant attenuation and recovery (**Figure 2**). Site selection was also guided by access constraints, observed pollution hotspots, and the need to assess regulatory compliance zones in proximity to WWTW boundaries. Sampling took place during both the high-flow wet season and the low-flow dry season, providing a comprehensive seasonal representation.

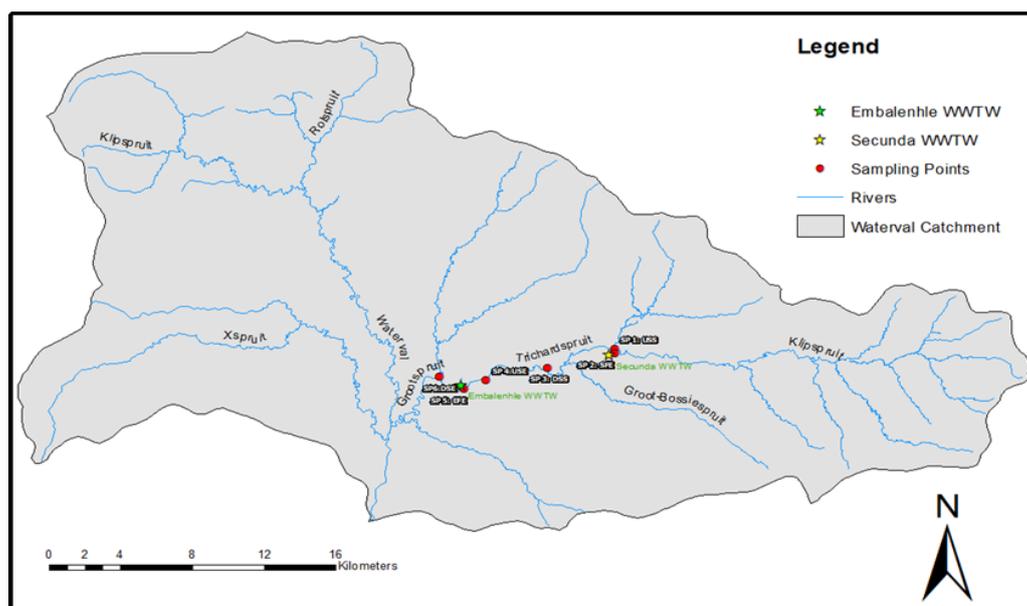


Figure 2. Detailed spatial layout of sampling sites along the Trichardspruit.

At each location, duplicate water samples were collected on the last day of every month throughout 2023. Sam-

ples were then grouped into four meteorological seasons—summer (December–February), autumn (March–May), win-

ter (June–August), and spring (September–November). This resulted in a total of 144 samples across all sites and seasons.

On-site parameters, including pH and electrical conductivity (EC), were measured using a calibrated Hanna HI9828 multiparameter meter. Additional water samples were collected in sterilised polyethylene bottles for laboratory analysis of chemical oxygen demand (COD), ammonium (NH₄⁺), nitrates (NO₃⁻), phosphates (PO₄³⁻), sulphates (SO₄), fluoride (F⁻), chloride (Cl⁻), alkalinity, *Escherichia coli* (*E. coli*), and faecal coliforms.

Water was sampled by submerging bottles 20–30 cm below the surface while facing upstream. Samples were immediately sealed, labelled, and transported on ice in insulated containers. All laboratory analyses were completed within

24 h of collection, in accordance with SANS standards^[18]. Analytical methods included (i) Merck Spectroquant photometry for COD, nitrates, and phosphates; (ii) gravimetric analysis for suspended solids; and (iii) membrane filtration for microbial indicators (*E. coli* and faecal coliforms)^[18,19]. All observed values were compared against the Water Use Licence (WUL) discharge limits and the Resource Quality Objectives (RQOs) defined for the Waterval Catchment, as summarised in **Table 1**.

By monitoring these parameters, the study aimed to assess compliance, identify potential deviations from acceptable water quality levels, and evaluate the cumulative impact of wastewater discharge and other anthropogenic activities on the Trichardspruit River.

Table 1. Water Quality variables in accordance with DWS Water Use License limits and Resource Quality Objectives.

Variables	DWS (WUL and RQO's)			
	Units	WWTW-1	WWTW-2	Trichardspruit River (RQOs)
pH		5.5–9.5	5.5–9.5	6.5–8.5
Conductivity (EC)	mS/m	<70	75–150	<10
Chemical Oxygen Demand		<75	<75	<10
Ammonium (NH ₄ ⁺)		<6	<10	<0.2
Nitrate (NO ₃ ⁻)		<15	<15	<0.1
Orthophosphate (PO ₄)	mg/L	<10	<1	<0.05
Sulphate		NA	NA	<20
Fluoride		NA	NA	<0.05
Chloride		NA	NA	<25
Alkalinity	mg/L as CaCO ₃	NM	NM	<40
Faecal Coliform	CFU/100 mL	0	0	<120
<i>E. coli</i>		0	0	<10

2.3. Data Analysis

Data analysis included descriptive statistics, seasonal trend analysis, correlation assessment, and inferential testing. For each water quality parameter, summary statistics (minimum, maximum, mean, median, and standard deviation) were calculated to evaluate baseline variability and distribution characteristics. Variables exhibiting high right-skewness, such as COD, orthophosphate, ammonium, and microbial counts, were log-transformed to stabilise variance and better meet the assumptions of parametric testing.

One-way Analysis of Variance (ANOVA) was applied to assess whether observed differences in water quality parameters across the six sampling sites were statistically significant. The grouping factor was site location, and ANOVA was performed for all measured parameters.

This test enabled the identification of spatially distinct water quality patterns and confirmed whether differences in mean values were attributable to site-specific influences, such as proximity to wastewater discharge points, rather than random variation. Following ANOVA, Tukey’s Honestly Significant Difference (HSD) post hoc test was calculated for parameters that showed significant differences. This test identifies which specific pairs of sampling sites differ significantly^[19].

Tukey’s *HSD* was computed in R using the studentised range (*q*) distribution for *k* groups and *MSwithin*, using the formula:

$$HSD = q \times \sqrt{\frac{MS_{within}}{n}}$$

Where:

- q is the range statistic value based on the number of groups and degrees of freedom within groups;
- MS_{within} is the Mean Square Within taken from the ANOVA results, which measures the average variation within groups;
- n is the sample size representing the number of observations in each group being compared.

Thus, HSD represents the smallest difference between averages that would be statistically significant ($p < 0.05$).

Time-series visualisation was used to examine seasonal trends and highlight site-specific dynamics. Monthly variations were plotted for four representative sites (S1, S3, S4, and S6), which spanned upstream, midstream (including the WWTW discharge point), and downstream reaches. These plots provided visual evidence of both recurring seasonal trends (wet vs. dry season variability) and persistent site-level anomalies, particularly near the identified discharge zones.

Spearman's rank correlation was used to explore pairwise relationships between physico-chemical and microbiological variables. This non-parametric approach was chosen for its robustness against non-normal data distributions. Correlation analysis was conducted both globally (all sites combined) and locally (by individual site), enabling a nuanced interpretation of co-occurring pollutant signatures and inferring likely sources. Together, these analyses allowed for the triangulation of spatial and temporal water quality patterns, strengthening the inference that anthropogenic pressures such as effluent from WWTWs are driving measurable changes in the ecological condition of the Trichardspruit River.

3. Results and Discussion

3.1. Descriptive Analysis

Descriptive statistics (Table 2) summarise spatial and temporal variations in key physico-chemical and microbiological parameters across six sampling sites (S1–S6). Most variables showed wide ranges reflecting both seasonal fluctuations and site-specific pollution inputs, driven by upstream and downstream anthropogenic inputs. Chemical Oxygen Demand, ammonium, and orthophosphate concentrations varied substantially between upstream (S1 and S4), discharge

(S2 and S5), and downstream (S3 and S6) locations. These values were benchmarked against the Department of Water and Sanitation's RQOs for in-stream sites (S1, S3, S4, and S6) and Water Use Licence discharge limits for wastewater treatment works (S2 and S5). With the exception of pH at all sites and chloride at S1, all the other parameters exceeded RQOs at one or more in-stream sites (S1, S3, S4, and S6). At the discharge points, concentrations generally met the applicable WULs limits, and FC at both S2 and S5 were non-compliant at both sites (S2 & S5).

Consistent with peri-urban river systems, median COD values often ranged between 20–80 mg/L, indicating significant organic loading, while orthophosphate concentrations typically fell within 0.05–0.5 mg/L, which is sufficient to drive eutrophication^[13–15]. Microbiological indicators were also consistently above acceptable limits, with *E. coli* and FC counts peaking at S6, exceeding 7000 counts/100 mL for *E. coli* and 700 counts/100 mL for FC well above the DWS guideline of <10 counts/100 mL, and exceeding recreational water quality standards set by the World Health Organization (WHO) and national authorities, thus posing severe health risks.

3.2. Spatio-Temporal Variability in Water Quality Parameters

Monthly variability in water quality parameters was visualised using time-series plots across selected monitoring sites (S1, S3, S4, and S6), as shown in Figure 3. These trends revealed distinct temporal patterns and site-specific behaviours, reflecting differential pollution loading and seasonal hydrological changes. Variables such as electrical conductivity, phosphate, ammonium, and fluoride showed higher values at downstream sites (particularly S6), while upstream locations displayed relatively stable, lower concentrations. Seasonal fluctuations were evident for microbial parameters, particularly during warmer months, likely due to increased runoff and microbial survival, while physico-chemical variables such as pH and alkalinity remained relatively stable across sites. Across the 12-month study period, exceedance frequencies (proportion of samples above RQO/WUL) were highest at S5 for COD, NH_4^+ , and PO_4^{3-} (for the majority of the year; ≥ 70 –90%), while S6 retained elevated EC, Cl^- , and SO_4^{2-} for over 6 months, indicating incomplete attenuation downstream.

Table 2. Descriptive Statistics of Water Quality Parameters (Min, Mean, Median, Max, Std Dev) for physico-chemical and Microbiological Indicators.

Parameters	DWS RQO Limit	Sampling Point 1 (Upstream of WWTW-1)					Sampling Point 2 (WWTW-1) Discharge Point					Sampling Point 3 (Downstream of WWTW-1)					
		Min	Mean	Median	Max	Std Dev	WUL	Min	Mean	Median	Max	Std Dev	Min	Mean	Median	Max	Std Dev
pH	6.5–8.5	6.4	7.192	7.35	7.8	0.526	5.5–9.5	7.28	7.462	7.425	7.76	0.134	6.4	7.133	7.25	7.7	0.497
EC (mS/m)	<10	15	32.83	33	40	14.383	70	65.04	68.07	66.375	77	3.797	33	48.5	46.5	65	9.830
COD (mg/L)	<10	25	31.5	27.5	47	7.280	75	28	37.42	34	62	9.394	33	42.5	39	57	9.405
NH4 ⁺ (mg/L)	<0.2	0.24	0.51	0.4	0.98	0.239	6	0.5	1.344	1.03	2.66	0.683	0.56	0.694	0.665	0.87	0.106
NO3 (mg/L)	<0.1	0.21	0.378	0.31	1.09	0.236	15	2.15	3.356	3.15	4.5	0.903	0.28	1.661	1.65	3.3	0.852
PO4 (mg/L)	<0.05	0.01	0.050	0.04	0.1	0.033	10	0.237	0.491	0.5	0.79	0.179	0.11	0.275	0.255	0.54	0.139
Cl (mg/L)	<25	11	17.87	17.95	25	3.826	NM	NM	NM	NM	NM	NM	20	37.916	39	50	9.481
F (mg/L)	<0.05	0.24	0.430	0.34	0.9	0.226	NM	NM	NM	NM	NM	NM	0.36	0.545	0.49	0.81	0.168
Alkalinity	<40	35	60.08	65	85	19.425	NM	NM	NM	NM	NM	NM	63	80	75.5	140	20.613
SO4	<20	22.4	52.33	51.3	79.4	18.63	NM	NM	NM	NM	NM	NM	61.6	73.716	74.85	84.2	8.067
<i>E. coli</i> (counts/100mL)	0	126	261.5	218.5	488	124.90	NM	NM	NM	NM	NM	NM	161	239	211	314	55.144
FC (counts/100mL)	0	41	57.75	52	96	15.92	0	51	113.083	73	313	87.384	45	70.833	75.5	85	12.640

Parameters	DWS RQO Limit	Sampling Point 4 (Upstream of WWTW-2)					Sampling Point 5 (WWTW-2) Discharge Point					Sampling Point 6 (Downstream of WWTW-2)					
		Min	Mean	Median	Max	Std Dev	WUL	Min	Mean	Median	Max	Std Dev	Min	Mean	Median	Max	Std Dev
pH	6.5–8.5	7.3	7.758	7.9	8	0.257	5.5–9.5	6.79	7.356	7.4	7.7	0.271	6.79	7.683	7.7	8.5	0.371
EC (mS/m)	<10	44	62.916	62	98	15.43	70–150	77.8	88.144	87	98.7	7.547	51	75.5	76.5	103	15.174
COD (mg/L)	<10	20	28.66	26.5	47	8.00	75	31	70.33	79	92	23.420	25	36.666	32.5	66	12.593
NH4 ⁺ (mg/L)	<0.2	0.83	1.315	1.06	3.2	0.68	10	8.06	14.49	13.5	26.2	6.577	1.57	3.098	3.21	4.39	0.874
NO3 (mg/L)	<0.1	0.89	2.390	2.5	3.4	0.91	15	1.05	2.93	3.21	4.5	1.264	1.75	2.958	2.875	4.2	0.769
PO4 (mg/L)	<0.05	0.2	0.4775	0.33	1.41	0.44	1	1.72	3.637	2.87	7.26	1.965	0.26	1.775	1.725	3.6	0.989
Cl (mg/L)	<25	30	46.333	43	84	14.82	NM	NM	NM	NM	NM	NM	53	73.666	69.5	108	16.837
F (mg/L)	<0.05	0.3	0.916	0.875	1.27	0.30	NM	NM	NM	NM	NM	NM	0.44	1.1733	1.01	2.63	0.693
Alkalinity	<40	65	169.416	151.5	221	57.47	NM	NM	NM	NM	NM	NM	85	169.416	178.5	265	49.667
SO4	<20	55	80.083	83	99	12.41	NM	NM	NM	NM	NM	NM	61.6	90.883	87.5	128	21.002
<i>E. coli</i> (counts/100mL)	0	214	453.25	320	1414	325.7	0	NM	NM	NM	NM	NM	148	324.041	3293.5	7230	2584.86
FC (counts/100mL)	0	44	288.41	204	689	223.5	0	162	543.33	412	1414	428.316	126	311.16	280	740	176.54

Note: NM—Not Measured. Values in red indicate non-compliance.

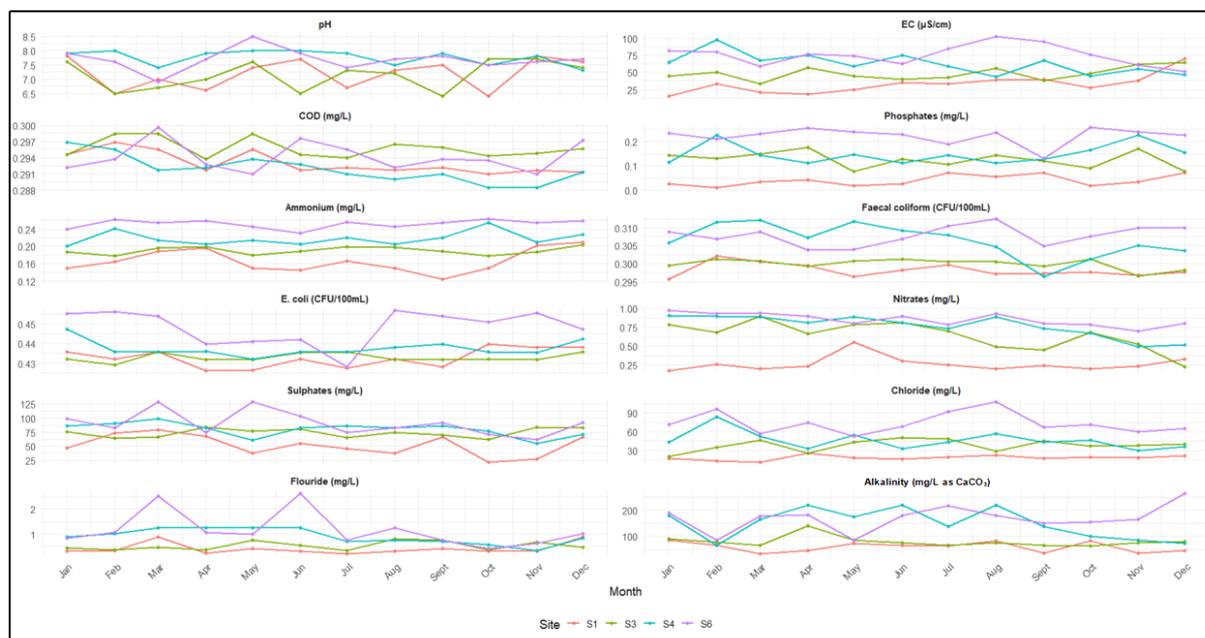


Figure 3. Monthly trends in water quality parameters across selected sites (S1, S3, S4, and S6).

Validation of Spatial Trends

To assess whether the observed differences in water quality parameters across sites were statistically significant, one-way ANOVA was performed for each parameter using site as the grouping factor (Table 3). Results indicated highly significant spatial variation for all tested parameters ($p <$

0.05), with ammonium, chloride, electrical conductivity, and orthophosphates showing the strongest differentiation (F-statistics = 46.9, 42.3, 32.8, and 27.1, respectively). These results confirm that water quality in the Trichardspruit River is strongly influenced by location-specific factors, including potential WWTW effluent discharge, land use, and site-specific hydrological conditions.

Table 3. One-Way ANOVA Results for Spatial Variation of Water Quality Parameters across Sampling Sites in the Trichardspruit River.

Parameter	F-Statistic	p-Value	Tukey's HSD, $p < 0.05$
pH	5.86	0.00015	S4, S6 > S1, S3
Electrical Conductivity	32.85	1.15×10^{-16}	S5 > S1-S4; S4 > S1; S6 > S1 & S3
Chemical Oxygen Demand	21.92	7.25×10^{-13}	S5 > S1-S4; S6 < S5 (\approx S1-S4)
Ammonium (NH ₄ ⁺)	46.90	4.19×10^{-17}	S5 > S1-S3; S6 < S5
Nitrate (NO ₃)	20.99	1.71×10^{-12}	S2, S5, S6 > S1; S5, S6 > S3 (S4 vs. S1 not significant)
Orthophosphate (PO ₄ ³⁻)	27.15	8.22×10^{-15}	S5, S6 > S1-S4; S6 < S5
Sulphate (SO ₄ ²⁻)	12.57	4.56×10^{-6}	S3, S4, S6 > S1
Fluoride (F ⁻)	13.65	4.79×10^{-5}	S4 > S1, S3
Chloride (Cl ⁻)	42.27	5.13×10^{-13}	S3, S4 > S1; S6 > S1, S3, S4
Alkalinity	20.28	2.11×10^{-8}	S4, S6 > S1, S3
Faecal Coliform	10.98	1.03×10^{-7}	S5 > S1-S4; S6 > S1, S3
<i>E. coli</i>	15.12	6.64×10^{-7}	S6 > S1, S3, S4

All tested parameters show significant spatial variation across the sampled sites. These results strongly suggest that water quality differs across locations, likely due to site-specific pollution pressures. One-way ANOVA and Tukey HSD post hoc tests revealed significant ($p < 0.05$) spatial variation in nearly all measured parameters across the Trichardspruit River. Physico-chemical variables and microbial indicators consistently displayed elevated concentrations at Sites 4 and 5, which correspond to the WWTW effluent discharge zone and its immediate downstream section. Nutrients, on the other hand, are split by behaviour, where orthophosphate exhibits a sharp step-increase at S5 with partial, but incomplete attenuation at SP6, nitrate is uniformly higher than S1 across the mid to lower reaches, and ammonium shows an extreme spike at SP5 followed by rapid recovery to near-upstream levels at S6.

Organic loading (COD) peaks strongly at SP5 and drops significantly by S6, evidencing short-reach dilution. Microbial indicators diverge from COD; where *E. coli* and faecal coliforms are highest downstream at S6, exceeding S1/S3/S4 and pointing to cumulative inputs and limited attenuation between the discharge point and the downstream site. A partial recovery trend was observed at Site 6, suggesting natural attenuation through dilution, microbial degradation, and sedimentation processes.

3.3. Association between Water Quality Parameters

Spearman's rank correlations were computed both globally and by site to examine associations among water-quality

variables (**Figure 4**). At the upstream reference point (S1), relationships were generally weak to moderate. In contrast, sites proximal to discharge points (S3 and S5) showed strong positive correlations among key nutrients (ammonium, nitrate, orthophosphate) and between COD and microbial indicators, indicating co-loading of reduced/oxidised nitrogen, bioavailable phosphorus, and organic matter typical of wastewater inputs. Downstream sites (S4 and S6) also exhibited moderate to strong correlations among EC, nitrate, orthophosphate, and sulphate, consistent with the persistence and mixing of effluent-derived ions and nutrients along the flow path.

Electrical conductivity varied markedly among sites, reflecting ionic enrichment from wastewater and peri-urban runoff; whereas COD indicated heterogeneous organic loading, and alkalinity (with modest but significant pH shifts), suggesting site-specific buffering linked to effluent chemistry and in-channel processing. Microbial indicators (*E. coli* and faecal coliforms) were elevated at sampling points downstream of the discharge points (S2 and S5), signalling a public-health concern and pronounced spatial heterogeneity in faecal contamination. Taken together, the correlation structure and spatial contrasts point to a discharge-centred impact gradient, with partial downstream attenuation for some parameters but continued influence of upstream effluent and ancillary urban inputs in the lower reach.

These results reveal significant spatial and seasonal variations in water quality, with WWTW discharge points (S2 and S5) having a marked influence on downstream conditions, highlighting the role of wastewater effluent as a major pollution source^[20].



Figure 4. Correlation matrix showing the association between water quality parameters.

Note: The asterisks indicate the statistical significance of correlations: * $p < 0.05$, ** $p < 0.01$, and *** $p < 0.001$.

3.4. Influence of Wastewater Treatment Works on River Water Quality

Similar to urban rivers across northern Europe, the pH levels across the study sites fluctuated within an acceptable, predominantly neutral to slightly alkaline range (7–8.5), which is often influenced by urban pollution^[21] and represents conditions conducive to the survival of many macroinvertebrates^[22]. The highest pH values were recorded at S4 and S6, potentially influenced by the introduction of acid-forming substances such as phosphates, nitrates, and sulphates^[21]. Although no significant deviations from regulatory standards were observed, minor fluctuations suggest

the influence of both natural processes and anthropogenic activities^[5,17,23].

Electrical conductivity, a key indicator of dissolved ions in water, showed pronounced spatial differences, with the highest values recorded at S5, particularly during wet seasons. Similar observations were made in the Akaki Catchment in Ethiopia^[18], as well as in the Turag River in Bangladesh^[23], where EC fluctuated as a result of increased runoff and effluent discharge^[24]. EC levels at SP6 exceeded RQO limits, suggesting cumulative impacts of WWTW effluent^[25] in the Trichardspruit River. Similarly, chemical oxygen demand values varied significantly across sites, with SP5 showing consistently elevated levels. COD concen-

trations exceeded acceptable limits during specific months, particularly in summer, likely due to increased organic matter decomposition and runoff^[26,27]. The significant difference in COD between S4 and S6 (mean difference: 41.67 mg/L) reinforces the conclusion that effluent from S5 introduces high organic loads, impacting downstream water quality^[18,23,26]. Consequently, measuring the Chemical Oxygen Demand is an essential method for evaluating the performance of these treatment facilities, as COD indicates the level of organic pollution being discharged into the environment^[23,26].

3.5. Nutrient Enrichment and Eutrophication Risk

The elevated concentrations of ammonium, nitrates, and phosphates at WWTW outlets and downstream sites indicate substantial nutrient loading, consistent with findings from local studies in the Crocodile^[28–30], and Limpopo^[31], catchments, Nandoni Dam^[32], the Vaal River^[13,15], as well as other international studies in Bangladesh^[23], Brazil^[33], Ethiopia^[18], as well as the United Kingdom^[34] and northern Europe^[19]. Similarly, ammonium concentrations were noticeably elevated at S5, with a peak of 26.2 mg/L in January, far exceeding the WUL discharge limit of 10 mg/L.

The significant differences in ammonium levels between S1 and S3 (mean difference: 0.184 mg/L) and between S4 and S6 (mean difference: 1.783 mg/L) confirm that WWTW discharge, as well as other anthropogenic activities, are major contributors to nitrogen pollution in the river^[18,23,26,29–34]. In contrast, S1 and S4 had relatively low average concentrations (0.51 mg/L and 1.315 mg/L), while S3 and S6 recorded 0.694 mg/L and 3.098 mg/L of ammonium, respectively. The notable high ammonium concentrations at S5 exceeded the WUL discharge limit of 10 mg/L, confirming wastewater effluent as a significant pollution source^[35].

The presence of excessive ammonium in surface water contributes to oxygen depletion, toxicity to aquatic life, and overall water quality deterioration in the Trichardspruit River^[18,26,30,33,36]. These nutrients are key drivers of eutrophication^[23,37], with potential consequences including excessive algal growth, oxygen depletion, and loss of biodiversity^[33,34,36,37]. The persistent exceedance of regulatory thresholds at multiple sites points to chronic nutrient enrichment from WWTW discharges, particularly from sur-

rounding informal settlements and farmlands^[33,34,36–38]. Nitrate concentrations, on the other hand, exceeded the recommended threshold at multiple sites, with the highest levels recorded downstream at S6. Elevated nitrate concentrations can lead to excessive algal growth^[39], eutrophication, as well as reduced dissolved oxygen levels, which often lead to a decline in aquatic biodiversity^[30,39,40]. In addition to elevated nitrate concentrations, phosphate concentrations followed a similar trend, with S5 showing the highest recorded levels (7.26 mg/L), far exceeding the recommended limit of 1 mg/L. These findings align with other studies, which found that wastewater treatment plants frequently fail to effectively remove phosphorus^[32–34,37]. The significant differences in phosphate levels between S1 and S3 (mean difference: 0.226 mg/L) and between S4 and S6 (mean difference: 1.30 mg/L) reinforce the conclusion that S5 is a major contributor to nutrient pollution. Moreover, the significant differences in nutrient concentrations between S1 and S3 and between S1 and S6 suggest that both wastewater discharge and diffuse pollution sources contributed to nutrient enrichment^[41,42] in the Trichardspruit River. Given that nitrate and phosphate are key contributors to eutrophication^[37], effective nutrient monitoring is therefore critical to protecting aquatic ecosystems and preventing excessive nutrient loading^[43].

3.6. Microbial Contamination and Public Health Risks

Microbial contamination was notably high across all sites, with *E. coli* and faecal coliform levels frequently exceeding permissible limits. Both WWTW discharge sites recorded faecal coliform levels far exceeding the recommended limit (0 CFU/100 mL), with values ranging from 41 to 741 counts/100 mL. Upstream faecal coliform counts averaged 57.75 CFU/100 mL, increasing to 288.42 CFU/100 mL, while downstream values ranged from 70.83 CFU/100 mL to 311.16 CFU/100 mL.

Likewise, the presence of *E. coli* also exceeded permissible limits, with upstream levels ranging between 126 CFU/100 mL and 1414 CFU/100 mL, and downstream values soaring to 7230 CFU/100 mL at certain times of the year. The highest recorded value of 7230 CFU/100 mL at S6 is indicative of the discharge of raw or poorly treated sewage^[32–34] at S5, rendering the water unsafe for irrigation^[37,39,41], recreation, and domestic use^[42,44–46]. In addi-

tion to sewage contamination, the microbial contamination could also be attributed to direct pollution by informal settlements situated near water resources^[47–50].

3.7. Spatial Distribution and Pollution Hotspots

Upstream sites (S1, and for several parameters S4) generally reflected better water quality, while downstream sites (S3 and S6) showed cumulative pollution signals, especially in parameters like EC, COD, chloride, and sulphate. The persistent elevation of these indicators downstream suggests that the river's assimilative capacity is being exceeded^[45,50], and dilution alone is insufficient to mitigate pollution^[29–33]. S5 emerged as a statistically significant pollution hotspot, with the highest concentrations of COD and faecal coliform. Taken together, the spatial footprint and co-occurrence of multiple indicators show that impairment is not confined to a single point source, but arises from a myriad of sources which include regulated point discharges from the WWTWs which are amplified by multiple diffuse inputs from leaking sewers and pump-station overflows, greywater outfalls, informal sanitation, stormwater inflow/infiltration, and intermittent industrial releases^[34,51]. This blend of point and non-point sources explains why improvements at one works may not, on their own, restore compliance downstream, and underscores the need for an integrated catchment response alongside plant-level process optimisation.

Consistent with this interpretation, chloride, often associated with irrigation return flows, sewage, and industrial processes^[52], varied across the study sites. S1 recorded 11 mg/L (well within the 70 mg/L guideline), whereas S3 exceeded regulatory thresholds in February (97 mg/L), July (92 mg/L), and August (108 mg/L), suggesting seasonal hydrological controls and episodic inputs. The observed increase in chloride concentrations at S6 likely reflects a combination of partially treated wastewater from S5, pump-station overflows, and additional domestic/industrial effluent^[52]. The substantial differences in chloride concentrations between S4 and S6 further indicate possible new inputs between these points rather than conservative transport alone. By contrast, alkalinity levels ranged from 35 mg/L to 221 mg/L upstream and increased to 63–265 mg/L downstream, consistent with higher dissolved carbonate/bicarbonate from sewage and industrial waste^[53]. This elevated buffering capacity helps

stabilise pH and moderates acidification potential within the catchment^[54].

3.8. Patterns of Pollution Linkages across Sampling Sites

The correlation analysis across sampling sites (**Figure 4**) revealed distinct patterns of co-occurrence among physico-chemical and microbial water quality parameters, reflecting underlying pollution processes and spatial gradients in anthropogenic impact. These patterns, captured in the correlation matrix and density plots, underscore the presence of compound pollution loads where multiple stressors appear simultaneously, particularly in areas influenced by wastewater discharge^[34,37–39]. Strong positive correlations were observed between ammonium, nitrates, and phosphates at the two discharge points (S3 and S5). This co-loading of nutrients is consistent with effluent-derived pollution^[43–47], where treatment inefficiencies or partial treatment allow a suite of interrelated contaminants to enter the receiving environment^[51–53].

Similarly, faecal indicators (*E. coli*, faecal coliforms) showed strong positive associations with chemical oxygen demand, pointing to the co-release of microbial and organic pollutants^[5,9,11,12,18] in untreated or inadequately treated sewage^[30,32–34]. These correlations validate prior results and reinforce the utility of multi-parameter monitoring in detecting wastewater signals. In contrast, upstream sites (S1 and S4), which were less affected by direct effluent discharges, displayed weaker or more sporadic correlations between variables. This suggests a less synchronized pollution profile and reflects the influence of more diffuse or background processes. Downstream sites (S4 and S6), however, retained several moderate to strong associations, particularly among electrical conductivity, sulphates, and nutrient parameters^[54–56]. These downstream linkages highlight the cumulative effect of upstream discharges and the persistence of pollutants in the water column.

Notably, the strength and consistency of pollutant linkages increased at sites with known anthropogenic pressure, confirming that wastewater effluent not only elevates pollutant concentrations but also alters the structural relationships between variables^[57–59]. The repeated appearance of strongly correlated nutrient and microbial parameters at discharge and downstream locations provides a reliable finger-

print of wastewater impact and a practical framework for identifying priority pollutants in compliance monitoring. The downstream decline in pollutant concentrations observed at Site 6 supports evidence from the Rietvlei and Apies Rivers that natural attenuation through dilution, adsorption, and microbial degradation can reduce effluent signatures over short distances^[60–63]. Collectively, these parallels confirm that the Trichardspruit system mirrors widespread regional and global challenges of balancing effluent assimilation capacity with escalating urban wastewater volumes.

3.9. Implications for Wastewater Infrastructure and Governance

The results indicate that wastewater treatment failures at the two wastewater treatment plants along the Trichardspruit are causing both acute local contamination and broader catchment-scale degradation that threatens ecosystem health, public safety, and water security. The discharge point at S5 is a statistically significant pollution hotspot with the highest COD and solids; however, elevated COD and other contaminants at multiple sites indicate that the problem is not limited to a single point source, showing that contaminants are transported downstream and compounded by other diffuse sources.

Downstream sites (S3, S4, and S6) show cumulative pollution, indicating that the river's natural capacity to recover is overwhelmed, resulting in persistent contamination along the catchment. The persistent contamination of the Trichardspruit River suggests that high levels of pollution are due to raw sewage discharges^[32–34,36], infrastructure failures^[36–40], and ineffective wastewater treatment^[42,44,45], attributing elevated faecal coliform levels to untreated and poorly treated sewage effluent^[47,48,52,55]. The issue of poorly treated effluent (discharged by WWTWs) that does not meet regulatory standards is a result of challenges such as mechanical breakdowns, power outages, poor maintenance, and unskilled personnel^[61,63–65].

WWTW-2, in particular, appeared to be non-functional or poorly managed, as indicated by extreme phosphate and microbial concentrations observed at the discharge point (S5), as well as downstream (S6). The results, therefore, reveal widespread non-compliance with discharge limits and water quality guidelines, pointing to operational failures. This situation is consistent with research highlighting the deteri-

orating state of sewage infrastructure in Africa^[45,46,55,58,59]. Therefore, informal settlements and downstream users reliant on river water for domestic, agricultural, or livestock use are also disproportionately exposed to acute and chronic health risks from microbial and chemical contaminants^[65,66]. The persistence of elevated nutrient and microbial indicators downstream underscores the need for improved process optimisation and compliance monitoring within the local WWTW infrastructure to prevent long-term ecological degradation. Furthermore, these findings highlight the importance of moving beyond single-parameter assessments and towards integrated, multivariate analyses that capture the interactive nature of pollution in impacted catchments. Moreover, without urgent improvements, continued exposure to contaminated water will compromise human health, aquatic ecosystem functioning, and downstream drinking water supplies. Degraded raw water quality increases treatment complexity and cost for drinking water supplies, thus undermining resource reliability for dependent communities, resulting in instances such as Cape Town's Day Zero, as well as the unfortunate 2023 fatalities that occurred because of contaminated drinking water supplies in Hammanskraal, South Africa.

4. Conclusion and Recommendations

This study assessed the spatio-temporal variability of water quality in the Trichardspruit River, South Africa, focusing on the impacts of effluent discharged from two wastewater treatment plants within the catchment. The results revealed significant pollution loading at WWTW discharge points and downstream sites, with elevated levels of chemical oxygen demand, ammonium, phosphate, and microbial contaminants far exceeding regulatory thresholds. Seasonal and spatial trends highlighted the persistence of nutrient enrichment and faecal contamination, particularly during warmer months. The analysis confirmed that existing wastewater infrastructure, particularly at WWTW-2 (S5), is failing to adequately treat effluent, contributing to widespread non-compliance with discharge limits and RQOs.

Downstream cumulative impacts indicate that the catchment's assimilative capacity is being exceeded, with far-reaching negative implications for aquatic ecosystem health, human exposure risks, and long-term water security. To ad-

dress the water quality degradation observed in the Trichard-spruit River, a suite of coordinated interventions is recommended. First, urgent rehabilitation and retrofitting of infrastructure at WWTW-1 and WWTW-2 are needed, including the installation of enhanced nutrient removal and microbial disinfection technologies. Operational optimisation should follow, focusing on improved process control, real-time monitoring, and capacity-building for plant operators. In parallel, regulatory oversight should be strengthened through routine compliance monitoring and integration with national performance audit frameworks, such as the Green Drop programme.

At the community level, targeted interventions are needed to reduce pollution from informal settlements, including improved sanitation access and decentralised wastewater solutions. These efforts should be supported by a catchment-based management approach that brings together municipalities, industries, farmers, and civil society to promote shared accountability. Furthermore, public participation and citizen science initiatives could help extend monitoring coverage and foster environmental stewardship. Finally, further research should explore microbial source tracking and ecosystem responses to better understand the long-term impacts of wastewater discharge and inform adaptive management strategies.

Author Contributions

Conceptualization, N.T. and M.D.M.; methodology, N.T.; investigation (field & lab), N.T.; data analysis, M.D.M.; software (R scripts), M.D.M.; visualization, M.D.M. and N.T.; writing—original draft, N.T.; writing—review and editing, M.D.M.; project administration, N.T.; funding acquisition, N.T. Both authors have read and agreed to the published version of the manuscript.

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mittee of the University of South Africa on 10 March 2023.

Informed Consent Statement

Not applicable.

Data Availability Statement

All processed data, as well as raw monthly site-level measurements, are available from the corresponding author upon reasonable request.

Conflicts of Interest

The authors declare no conflict of interest.

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