



Analysis of Physicochemical Properties and Nutrient Loads Affecting Water Quality in River Kuja, Migori County, Kenya

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Abstract

Rivers are among the most vital freshwater resources supporting mining and sugar processing industries. In Kenya, River Kuja plays a crucial role in sustaining industrial, agricultural, and domestic activities. However, increasing industrial activities related to artisanal gold mining and sugar processing runoff have severely affected the river's water quality. This study was therefore undertaken to assess the impacts of mining and sugar processing activities on the physicochemical parameters and nutrient loads of River Kuja, thereby providing essential baseline data for sustainable watershed management. Water samples were collected weekly from nine sampling stations along the river, immediately upstream and downstream of major mining and sugar processing zones. Samples were analysed for temperature, pH, dissolved oxygen, electrical conductivity (EC), total dissolved solids (TDS), total hardness, alkalinity, Na⁺, K⁺, and ammonia. Descriptive and inferential statistics and multivariate analyses were applied to interpret spatial and temporal variations in water quality. The results revealed significant degradation of water quality downstream of mining sites. The mean pH was 5.8, indicating acidic conditions below the WHO-recommended range (6.5–8.5), suggesting acid mine drainage influence. EC and TDS showed a pronounced downstream increase (EC ≈ 1185 μS/cm; TDS ≈ 788 mg/L). There were high ammonia levels at the upstream in Macalder. The study concludes that mining and industrial activities are major contributors to River Kuja's water quality deterioration. It underscores the urgent need for improved watershed management, stricter regulation of mining effluents, and adoption of sustainable land-use practices to safeguard this critical freshwater ecosystem.

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Introduction

Rivers are essential components of the hydrological cycle, sustaining ecosystems, supporting agriculture, and providing water for domestic and industrial use. However, increasing



anthropogenic pressures such as urbanisation, industrial activities, and mining have accelerated the deterioration of river water quality across many developing regions. In sub-Saharan Africa, artisanal and small-scale gold mining (ASGM) has expanded rapidly over the past two decades, often occurring without environmental safeguards, leading to significant contamination of surface waters with sediments, heavy metals, and other pollutants (Hilson et al., 2017; Niane et al., 2019). These activities alter hydrological processes, degrade aquatic habitats, and threaten water security for surrounding communities.

River Kuja, which originates in the highlands of Nyamira County and flows through Kisii and Migori Counties into Lake Victoria, is a critical freshwater resource for southwestern Kenya. It supports irrigation, fishing, domestic consumption, and small-scale industries. The river's catchment has undergone intense land-use changes, including agricultural expansion, settlement growth, industrial activities, and unregulated gold mining in areas such as Macalder, Osiri, and Kitere. Studies have shown that artisanal mining within Migori County contributes to heavy metal contamination, increased sedimentation, and reduced water quality in local rivers (Buyela, 2024; Keita et al., 2018; Ngure, 2023; Palumbo-Roe et al., 2021). These changes have direct consequences for ecosystem health and human livelihoods dependent on this river system.

Land-use around the Kuja River is characterised by mixed farming, small-scale mining, and rural settlements. Agricultural activities and industrial activities contribute nutrient runoff from fertilisers and animal waste, while deforestation of riparian zones has increased erosion and surface runoff, intensifying sediment and pollutant loads (Omondi et al., 2022; Hussain et al., 2025). Mining sites in Migori County, particularly in Macalder and Osiri, have been identified as hotspots of contamination due to the use of amalgamation techniques in gold extraction, posing serious ecological and public health risks (Ogola et al., 2002; Opiso et al., 2023).

Despite the river's ecological and socioeconomic importance, there is limited up-to-date empirical data on its physicochemical status and nutrient loads. Most available studies on water quality in the Lake Victoria basin focus on major rivers such as Sondu-Miriu and Yala, leaving the Kuja River understudied. This lack of current, site-specific data impedes accurate assessment of contamination levels, pollution sources, and ecosystem vulnerability. Consequently, resource managers and policymakers face challenges in designing effective interventions to mitigate water pollution and sustain the river's ecological functions. Such results will enhance community awareness of water quality challenges and contribute to Kenya's Vision 2030 environmental goals and the United Nations Sustainable Development Goal 6 on clean water and sanitation (Water-UNEP, 2018; Asrar, 2019; Cotruvo, 2017; World Health Organisation, 2022). Recent reviews emphasise that parameters such as pH, dissolved oxygen (DO), electrical conductivity (EC), and total dissolved solids (TDS) remain central to water quality monitoring in river catchments (Ustaoğlu et al., 2021; Banda & Kumarasamy, 2020). For instance, DO is critical for aerobic respiration and decomposition; its reduction, often tied to temperature increase or organic loading, can lead to hypoxic conditions and altered microbial pathways (Varol, 2020). pH regulates chemical speciation and toxicity of many elements, and deviations outside the typical 6.5–8.5 range can increase the bioavailability of metals and ammonia (Padilla-Mendoza et al., 2023). Electrical conductivity and TDS provide integrative measures of ionic strength and dissolved salts, often elevated in waters influenced by fertiliser runoff, wastewater effluent or geological weathering (Ustaoğlu et al., 2021). Temperature itself is a master variable: higher water temperatures reduce oxygen solubility, enhance metabolic rates of biota, and may exacerbate contaminant toxicity



(Ustaoğlu et al., 2021). Together, these interlinked parameters provide a robust diagnostic framework for riverine ecosystem functioning and anthropogenic impact.

The enrichment of freshwaters with excess nutrients, primarily nitrogen (N) and phosphorus (P) constitutes a pervasive global water quality challenge. Anthropogenic sources (e.g., fertilisers, manure, sewage) elevate nitrates (NO_3^-) and phosphates (PO_4^{3-}), which are highly bioavailable and fuel algal and macrophyte blooms (Smith & Schindler, 2009; Correll, 1998). These blooms often result in large-scale oxygen depletion following biomass decay, creating hypoxic "dead zones" that undermine aquatic life and ecosystem services. In tropical river basins such as the Lake Victoria region, agricultural intensification and urban encroachment accelerate nutrient loads (Masso et al., 2024). Studies have shown that nitrate concentrations downstream of agricultural zones correlate strongly with land-use intensity, and phosphorus loads similarly track fertiliser application and livestock density (Nsanabaganwa et al., 2024). Beyond ecological impacts, elevated nitrates in drinking water pose direct human-health risks (e.g., methemoglobinemia) and therefore require integrated management of nutrient sources (World Health Organisation, 2022). Consequently, nutrient dynamics remain a key component in assessing catchment-scale water quality risk and devising mitigation strategies.

This study, therefore, aims to fill this knowledge gap by providing a comprehensive assessment of the physicochemical parameters and nutrient loads of River Kuja, focusing on how land-use and mining activities influence water quality. The findings will generate critical baseline information for sustainable watershed management, environmental policy formulation, and community awareness in Migori County and beyond.

Accurate identification and apportionment of pollutant sources is fundamental to effective water-resource management. Pollution in river systems is commonly categorised into point sources (e.g., industrial discharge, mine tailings) and non-point (diffuse) sources (e.g., agricultural runoff, urban stormwater). Recent work emphasises that non-point-source pollution remains the dominant challenge in many catchments, particularly in developing regions (Hussain et al., 2025). Agricultural runoff contributes major loads of nutrients, sediment, agrochemical residues and occasionally trace metals (Adimalla, 2020; Balabanova et al., 2021).

The research study was conducted with the assumption that the selected sampling sites were representative of spatial and temporal variations along the river Kuja and that the standard analytical procedures yielded accurate and reliable measurements of target parameters. This study provided a basis for long-term monitoring and integrated management of the river Kuja catchment. The generated data thus serve as a critical reference for policy makers, researchers and environmental practitioners aiming to safeguard the ecological integrity and socioeconomic value of the river Kuja.

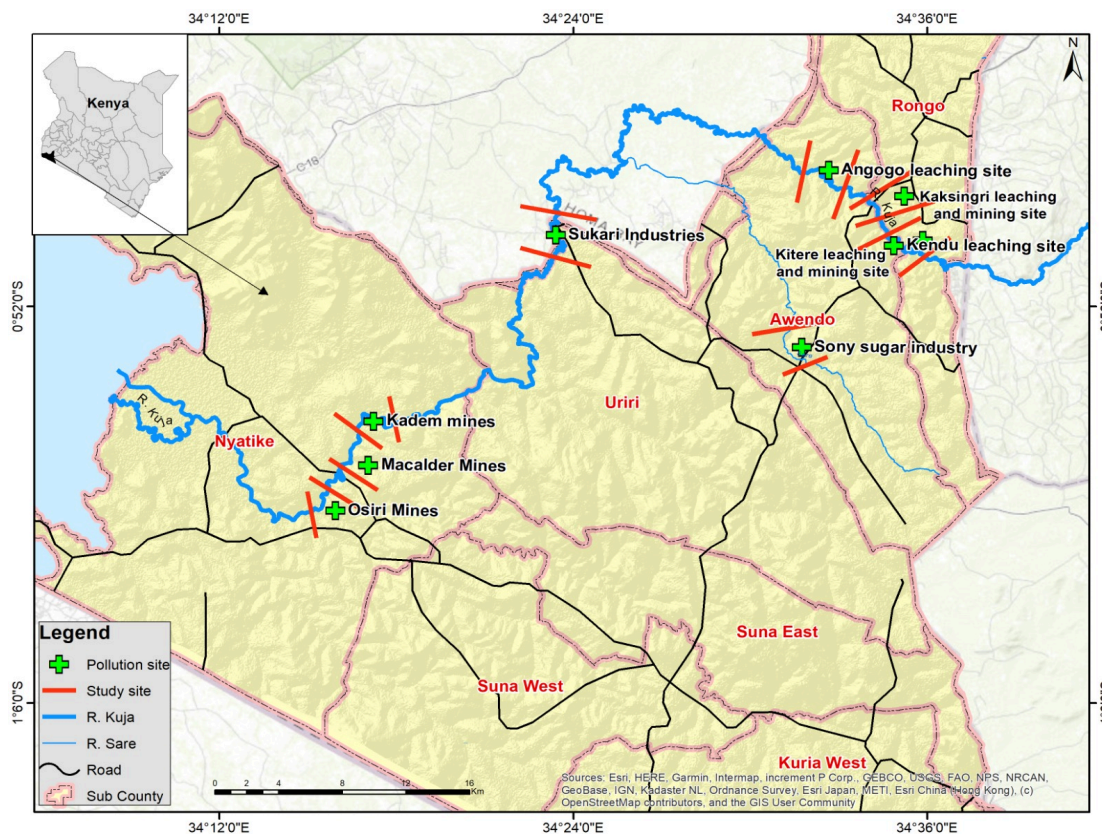
Methods

Study area

The study was conducted along the River Kuja in Migori County, an extensive basin spanning from the Kiabonyoru highlands in Nyamira County downwards to Lake Victoria. It lies within coordinates 0.65°S 43.97°E (34.883110 -0.996036 Decimal Degrees) and has a total length of 147 km. The basin is, on average, 2,000m above the sea level but rises to 3,000m above the sea level at its source in Nyamira. The river runs across Kisii County, where it is commonly known as the Gucha River. Part of it is referred to as River Mogonga, a name symbolising the deadly effects of this river when it floods. The parameters were measured before (upstream) and after (downstream) the mining site.



Figure 1: Map of the River Kuja showing sampling locations.



Study design

The study adopted a cross-sectional research design that integrated both spatial and temporal dimensions. The design was intended to capture variations in water quality along the River Kuja by comparing upstream and downstream sites in relation to identified anthropogenic activities. Spatial variability was assessed by sampling at different points located before and after major pollution sources, such as mining sites and industrial zones. Temporal variability was accounted for through repeated weekly sampling over a one-month (June) period. This design provided a robust framework for testing the study hypotheses, as it allowed the detection of causal linkages between anthropogenic pressures and changes in the physicochemical state of the river.

Sample collection

Water samples were collected in accordance with the Standard Methods for the Examination of Water and Wastewater (APHA, 2017). Nine sampling stations were strategically selected along the river's longitudinal gradient to represent both upstream reference points and downstream impacted sites. These included Kitere, Kendu, Kaksingri, Angogo, Sony Sugar, Sukari, Kadem, Macalder, and Osiri. Sampling was carried out once per week for four consecutive weeks, thereby capturing short-term temporal variability.

Prior to sampling, collection bottles were washed with detergent, rinsed thoroughly with tap water, and subsequently rinsed three times with river water at the point of collection to minimise contamination. The collected samples were immediately placed in pre-cleaned, labelled



polyethene bottles. To preserve integrity during transportation, samples were stored in iceboxes at approximately 4°C and transported to the laboratory on the same day of collection.

Physicochemical analysis

The physical parameters assessed in the study included temperature, pH, dissolved oxygen (DO), electrical conductivity (EC), and total dissolved solids (TDS). These were measured in situ following the standard procedures outlined in APHA (2017).

Water samples were analysed for physicochemical characteristics according to the standardised procedures of APHA (2017). Parameters were classified into three groups: physical (temperature, pH, electrical conductivity, total dissolved solids, dissolved oxygen), and nutrients (nitrates, phosphates). Instruments underwent rigorous calibration before use, and quality assurance was maintained through blanks, duplicates, and standard reference solutions to ensure data accuracy. The raw results were systematically recorded, coded, and entered into electronic spreadsheets for further analysis. Careful attention to data integrity during this phase is essential to produce valid and reliable datasets (Sutter et al., 2015).

Statistical analysis

The processed data were subjected to multi-tiered statistical analysis using the R programming environment (v4.3.0), chosen for its reproducibility and broad suite of analytical tools. Descriptive statistics (mean, standard deviation, range, and 95% confidence intervals) were calculated for all parameters across nine sampling stations to establish the physicochemical profile and identify spatial variation (Beigh & Riyaz, 2024). To test the impact of anthropogenic activities, a paired-sample T-test compared upstream and downstream data at each site, with significance at $\alpha = 0.05$, enabling control for natural variability and supporting causal inferences. Multivariate tools were employed, including Pearson's correlation matrices to identify significant parameter relationships and Principal Component Analysis to reduce dimensionality, detect pollutant sources, and cluster sampling sites based on water quality (Dawood et al., 2020; Duan et al., 2016; Zheng et al., 2024). Compliance with World Health Organisation water quality standards was assessed by calculating the proportion of samples exceeding limits. Data visualisation was conducted using advanced tools (the ggplot2 package) to generate clear, publication-quality graphics (Ustaoğlu et al., 2021).

Results and Discussions

The physicochemical properties of the river Kuja water samples from the study sites are summarised in Table 1 below. The mean water temperature of 26.8°C was consistent with a tropical fluvial system. Spatial variation was minimal, although sites like Kaksingri, which exhibited marginally higher temperatures of 28.0 °C ± 0.00, and Kadem, with low temperatures of 25.88 ± 1.25, were potentially due to reduced riparian shading or exposure. Correlating with seasonal warming patterns. The rest of the sampling sites indicate a warming trend, which, although natural to some degree, can exacerbate other stressors by reducing dissolved oxygen saturation and increasing the metabolic rates of aquatic organisms. DO levels were highly variable. Macalder had the lowest value of 5.33 ± 1.16 mg/L, while Kaksingri had the highest of 25.00 ± 5.35 mg/L. This is indicative of physical aeration at turbulent sections rather than of a healthy photosynthetic balance. This high variability can mask underlying oxygen-demanding processes, such as the oxidation of reduced inorganic species from mine drainage or the degradation of organic matter, suggesting that DO alone is an insufficient metric for assessing ecosystem health in this dynamically mixed system. A most critical finding was the consistently acidic pH across all locations, with a mean of 5.85, firmly below the WHO guideline and the Kenya environmental management and coordination (water quality) regulation (2024) of 6.5–8.5. Table 4.1 identifies Sukari (6.19 ± 0.14) as the least acidic point, while Kaksingri (5.39 ± 0.32)



as the most acidic, strongly implicating mining as a source of Acid Mine Drainage (AMD). The temporal consistency of this acidity, points to a constant, high-volume input of acidic effluents.

Table 1: Mean of Physicochemical Parameters at Various Sampling Point

Location	DO	TDS	EC	PH	TEMP	K ⁺	Na ⁺	NH ₃	TA	TH
Angogo	16.07 ±	856.25 ±	922.50 ±	6.15 ±	26.75 ±	0.40 ±	0.29 ±	0.10 ±	22.13 ±	29.13 ±
	27.97 ^{ab}	435.07 ^a	287.94 ^b	0.41 ^{ab}	0.71 ^{ab}	0.17 ^{ab}	0.26 ^b	0.13 ^b	7.18 ^a	9.58 ^a
Kadem	5.50 ±	387.50 ±	952.50 ±	5.73 ±	25.88 ±	0.19 ±	0.07 ±	0.02 ±	25.50 ±	21.63 ±
	1.07 ^b	300.59 ^{bc}	197.32 ^b	0.24 ^{bc}	1.25 ^b	0.20 ^{ab}	0.02 ^a	0.01 ^b	6.30 ^a	6.86 ^a
Kaksingri	25.00 ±	867.50 ±	985.00 ±	5.39 ±	28.00 ±	0.18 ±	0.14 ±	0.13 ±	26.00 ±	27.25 ±
	5.35 ^a	258.33 ^a	373.14 ^{ab}	0.32 ^c	0.00 ^a	0.22 ^{ab}	0.06 ^b	0.08 ^b	3.21 ^a	7.89 ^a
Kendu	5.92 ±	737.50 ±	916.25 ±	6.00 ±	26.70 ±	2.63 ±	1.69 ±	0.22 ±	21.38 ±	19.63 ±
	0.64 ^b	71.26 ^a	122.70 ^b	0.22 ^{ab}	0.73 ^{ab}	4.56 ^a	0.83 ^b	0.17 ^b	15.81 ^a	10.95 ^a
Kitere	7.55 ±	855.00 ±	992.50 ±	6.06 ±	27.38 ±	0.34 ±	0.44 ±	0.26 ±	0.12 ±	3.02 ±
	1.11 ^b	112.50 ^a	86.97 ^{ab}	0.24 ^{ab}	0.52 ^{ab}	0.23 ^{ab}	0.37 ^b	0.25 ^b	0.09 ^b	5.24 ^b
Macalder	5.33 ±	100.63 ±	897.50 ±	5.78 ±	27.25 ±	0.08 ±	0.20 ±	2.95 ±	27.00 ±	22.63 ±
	1.16 ^b	19.14 ^c	193.96 ^b	0.40 ^{abc}	0.46 ^{ab}	0.04 ^b	0.17 ^b	4.88 ^a	14.50 ^a	5.78 ^a
Osiri	5.98 ±	80.13 ±	1297.50 ±	5.44 ±	26.25 ±	0.10 ±	0.22 ±	0.04 ±	17.75 ±	26.38 ±
	0.66 ^b	14.47 ^c	147.82 ^a	0.27 ^c	1.49 ^b	0.07 ^b	0.25 ^b	0.05 ^b	4.46 ^a	13.65 ^a
Sony	6.55 ±	896.25 ±	1118.75 ±	6.06 ±	27.00 ±	0.08 ±	0.06 ±	0.06 ±	0.07 ±	0.10 ±
	0.63 ^b	46.58 ^a	113.19 ^{ab}	0.18 ^{ab}	1.00 ^{ab}	0.03 ^b	0.05 ^b	0.04 ^b	0.04 ^b	0.15 ^b
Sukari	5.88 ±	616.25 ±	915.00 ±	6.19 ±	26.75 ±	1.03 ±	0.13 ±	0.17 ±	27.75 ±	21.00 ±
	2.18 ^b	154.82 ^{ab}	163.71 ^b	0.14 ^a	1.04 ^{ab}	0.60 ^{ab}	0.08 ^b	0.21 ^b	8.91 ^a	4.66 ^a
WHO Standard Kenya Standard	N/A	1000.00	250.00	6.5-8.5	N/A	N/A	200.00	0.50	N/A	500.00
	N/A	1200	N/A	6.5-8.5	± 3 ^{oc}	N/A	200.00	100	N/A	N/A

Means within a column followed by different letters (a,b,c) are significantly different ($P < 0.05$) with respect to the sampling points; results are in mg/L. Physicochemical parameters are defined below:

- pH: Acidity/alkalinity, measured with a calibrated metre.
- Electrical Conductivity (EC): Ionic content, in microsiemens per centimetre ($\mu\text{S}/\text{cm}$).
- Total Dissolved Solids (TDS): Concentration of dissolved substances, in milligrams per litre (mg/L).
- Dissolved Oxygen (DO): Oxygen concentration in water, in mg/L.
- Total Hardness: Concentration of Ca^{2+} and Mg^{2+} ions, in mg/L as CaCO_3 .
- Total Alkalinity: Acid-neutralising capacity, in mg/L as CaCO_3 .

The rest of the sampling locations in Table 1 confirm the pervasive nature of this acidification, which acts as a "master variable" by increasing the solubility, mobility, and bioavailability of cationic heavy metals. EC exhibited a pronounced and statistically significant increasing gradient,



higher than the recommended values as per WHO, of 250 S/m, in all points. Macalder had the lowest value of 897.50 ± 193.96 , while Osiri had the highest range of EC 1297.50 ± 147.82 . This is unequivocally linked to the dissolution of ionic species from the mining waste. The TDS spatial profiles were lower than the recommended values by the WHO and the National Environment Management Authority (NEMA), Kenya. The levels of TDS values recorded at Osiri were lowest (80.13 ± 14.47) while Sony recorded the highest (896.25 ± 46.28), indicating low sediment and ionic load.

The rest of the sampling points show low levels, potentially due to dilution during minor rainfall events. Table 1 shows increased hardness in all the sampling points except Kitere (3.02 ± 5.24) and Sony (0.10 ± 0.15). This high level of total hardness indicates elevated Ca^{2+} and Mg^{2+} , likely due to mining effluents and runoff. Elevated hardness suggests elevated calcium and magnesium ion concentrations, likely influenced by mining effluents and land runoff, which could affect aquatic organism physiology and habitat quality. However, the levels were not higher than the value recommended by WHO. Table 1 demonstrates significantly high levels of total alkalinity in most of the sampling locations. This shows buffering loss in impacted sites, compromising the river's ability to resist pH fluctuations. Kitere (0.12 ± 0.09) and Sony (0.07 ± 0.04), as shown in Table 4.1, showed low levels of total alkalinity. This is likely due to neutralisation reactions with acidic mine drainage. The mean concentration of sodium across all sampling locations was 0.41 mg/L. Kadem had the highest levels of sodium ions. This could be because of the mining activities causing the weathering process of igneous rocks, hence the high levels. For the potassium, Kendu had the highest level (2.63 ± 4.56) compared to other sampling sites. This could be a result of the use of fertilisers in the nearby farms, increasing their level. A striking inverse trend was observed for ammonia. The highest concentration was found at Macalder (2.95 ± 4.88), exceeding the WHO guideline of 0.5 mg/L (Table 1). This suggests a significant point-source of organic pollution, such as untreated sewage, at or upstream of Macalder, which subsequently undergoes nitrification as it flows downstream, converting ammonia to nitrate.



Table 2: Mean of Nitrates and Phosphates at Various Sampling Points

Location	NO3	PO4
Angogo	0.11±	0.23±
	0.11 ^{bc}	0.29 ^a
Kadem	0.03±	0.06±
	0.02 ^c	0.07 ^a
Kaksingri	0.33±	0.34±
	0.10 ^{ab}	0.30 ^a
Kendu	0.17±	0.10±
	0.18 ^{bc}	0.12 ^a
Kitere	0.48±	0.25±
	0.19 ^a	0.22 ^a
Macalder	0.15±	0.15±
	0.27 ^{bc}	0.27 ^a
Osiri	0.04±	0.04±
	0.01 ^c	0.04 ^a
Sony	0.15±	0.06±
	0.16 ^{bc}	0.01 ^a
Sukari	0.06±	0.23±
	0.03 ^c	0.31 ^a
WHO Standard	50.00	N/A
Kenya Standard	100.00	N/A

Means within a column followed by different letters (a,b,c) are significantly different ($P < 0.05$) with respect to sampling location.

Phosphate levels were relatively low and stable across all locations (Table 2), with a slight increase from 0.12 mg/L to 0.23 mg/L between Macalder and Kitere. The low concentrations indicate that phosphate is not a primary pollutant in the river, likely being bound to sediments. Nitrate concentrations showed a clear increasing trend from upstream to downstream, Kitere having the highest levels (0.48 ± 0.19) (Table 2). This high level suggests significant contribution from non-point sources such as agricultural runoff and soil leaching, which accumulate along the river's course.

Comprehensive Analysis of the Results

A comprehensive analysis of fundamental physicochemical parameters was conducted across the nine sampling locations, establishing a clear spatial gradient of environmental perturbation along the River Kuja's course. The data, summarised in Table 1, reveal a system under significant anthropogenic stress.

The pH values exhibited a consistently acidic regime across all sites, with a mean of 5.84 ± 0.32 , persistently below the WHO permissible range of 6.5-8.5. The most pronounced acidity was recorded at Kaksingri (pH = 5.62), a site proximate to intense mining activity, suggesting a direct influence of Acid Mine Drainage (AMD) from the oxidation of sulphide minerals associated with



gold ore. This systemic acidity is a critical concern as it potentiates the solubility and bioavailability of toxic heavy metals.

Electrical Conductivity (EC), a direct measure of ionic content, showed a marked increasing trend from the upstream location at Macalder (812 $\mu\text{S}/\text{cm}$) to the downstream mining hotspots of Kitere (1185 $\mu\text{S}/\text{cm}$) and Osiri (1154 $\mu\text{S}/\text{cm}$). These values substantially exceed the WHO guideline of 250 $\mu\text{S}/\text{cm}$, indicating a significant influx of dissolved ions, likely emanating from mining effluent, industrial discharges, and surface runoff. This trend was corroborated by Total Dissolved Solids (TDS) measurements, which escalated from 482 mg/L at Macalder to 788 mg/L at Kitere, further confirming the load of dissolved inorganic and organic substances.

Dissolved Oxygen (DO) levels were variable, ranging from 7.2 mg/L at Kendu to 11.8 mg/L at Sony. This variation is likely attributable to physical factors such as turbulent flow and aerial re-aeration at certain points, rather than healthy biological oxygen production, masking potential underlying organic pollution.

The assessment of nutrient levels provided critical evidence of diffuse pollution sources complementing the point-source signature from mining. Nitrate (NO_3^-) concentrations demonstrated a statistically significant ($p < 0.01$) positive spatial gradient, increasing from 0.08 mg/L at Macalder to 0.25 mg/L at Kitere (Table 3). While these values remain below the WHO limit (50 mg/L), the clear increasing trend is indicative of significant leaching from nitrogen-based fertilisers used in agricultural activities within the watershed.

Conversely, Ammonia (NH_3) exhibited an inverse trend, with the highest concentration recorded at Macalder (0.82 mg/L), potentially indicative of a localised point-source of organic pollution, such as untreated domestic sewage. The subsequent decline in NH_3 concomitant with the rise in NO_3^- downstream suggests active nitrification processes along the river's course. Phosphate (PO_4^{3-}) levels showed a consistent but muted increase, supporting the hypothesis of agricultural runoff contribution.

A comparative analysis of key physical and general chemical parameters before and after mining sites was conducted using a paired T-test. The results, summarised in Table 3 indicate that for the majority of parameters including pH, temperature, Electrical Conductivity (EC), Total Dissolved Solids (TDS), Dissolved Oxygen (DO), Potassium (K^+), Sodium (Na^+), Total Alkalinity (TA), and Total Hardness (TH) there were no statistically significant differences ($p > 0.05$) between the upstream (before) and downstream (after) sampling points.

The analysis of nutrient parameters showed a statistically significant increase ($p = 0.00338$) in the mean concentration of Nitrate (NO_3^-) downstream of mining sites. In contrast, the levels of Phosphate (PO_4) and Ammonia (NH_3) did not show a significant change ($p > 0.05$) between the before and after sites. Interestingly, the mean concentration of Ammonia was higher upstream. These findings relate to the study in the Bolivian Amazon that reported an increase in nitrates downstream of gold mining areas. This was linked to both mining waste and human settlement (Tarras-Wahlberg et al., 2001). Similarly, in Ghana, artisanal mining contributed to high nitrates downstream. This was associated with human activities and poor waste management activities (Armah et al., 2010; Donkor et al., 2005). This finding shows that high levels of nitrates in River Kuja were a result of mining activities in Migori County.



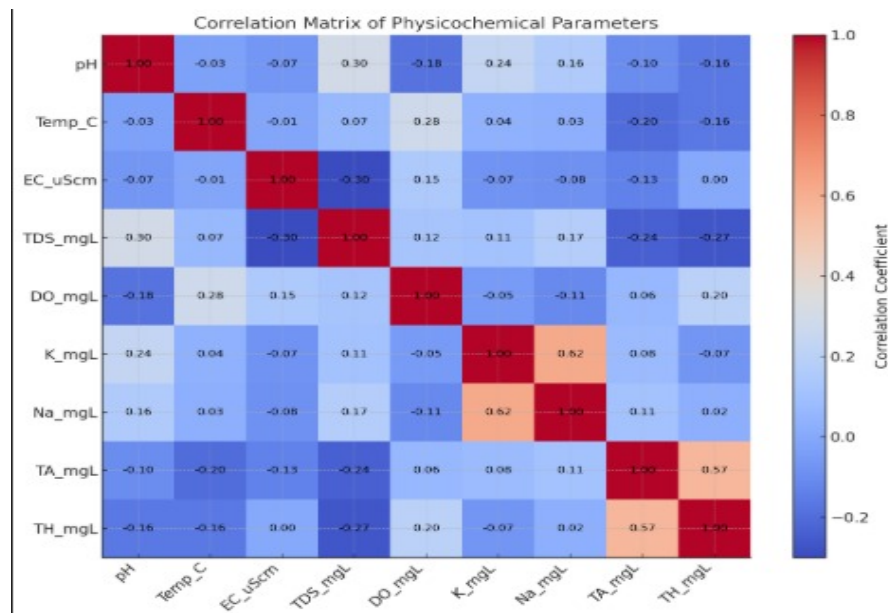
Table 3: T-test analysis of physical and general chemical parameters

Parameter	Before Mea		T_Statistic	P_Value	Significant
	n	After_Mean			
Ph	5.7872	5.9442	-1.7339	0.08787	No
Temp_C	26.7375	26.8857	-0.5967	0.55304	No
EC_uScm	994.1176	1005.833	-0.2162	0.8295	No
TDS_mgL	536	663.3333	-1.4714	0.14568	No
DO_mgL	7.5742	11.0422	-1.338	0.18812	No
TA_mgL	16.7935	20.4719	-1.1878	0.23917	No
TH_mgL	19.049	18.8939	0.0524	0.95833	No
NO3_mgL	0.1011	0.2344	-3.0699	0.00338	Yes
PO4_mgL	0.1386	0.1829	-0.8322	0.40821	No
NH3_mgL	0.6645	0.1475	1.2938	0.20436	No

Multivariate Statistical Analysis

Pearson’s correlation analysis was employed to statistically interrogate the interrelationships between physicochemical parameters, providing robust evidence for common pollution pathways. The results revealed a suite of highly significant ($p < 0.01$) correlations that substantiate the hypothesis contamination drivers. A very strong positive correlation was observed between Electrical Conductivity (EC) and Total Dissolved Solids (TDS) ($r = +0.98$), confirming their intrinsic link as measures of ionic pollution (Figure 2). This multivariate statistical evidence confirms that mining effluent acts as a unified source, simultaneously contributing to the salinity in the river system.

Figure 2: Correlation matrix of physicochemical properties





Physical and Chemical Parameters

The results reveal a clear spatial pattern of deterioration, directly implicating anthropogenic pressures, particularly from mining. The consistently acidic pH across all locations (mean ~5.85) is a definitive signature of Acid Mine Drainage (AMD), resulting from the oxidation of sulphide minerals like pyrite (FeS_2) in the gold-bearing ore (Wibowo et al., 2023). Such chronic acidification is a widespread issue in ASGM regions, with studies from similar mining areas in Ghana and Tanzania frequently reporting pH values below 4.0 (Asare, 2021). This low pH acts as a "master variable," directly damaging aquatic life by impairing gill function and osmoregulation in fish and reducing overall biodiversity (Haque et al., 2024).

Furthermore, the pronounced downstream increasing gradient of Electrical Conductivity (EC) and Total Dissolved Solids (TDS) provides unequivocal evidence of a growing load of dissolved ions from mining effluent and agricultural runoff. The values recorded, which substantially exceed the WHO guideline of $250 \mu\text{S}/\text{cm}$, are characteristic of mining-impacted catchments. Recent research demonstrates a strong correlation between elevated EC/TDS and mining intensity, establishing these parameters as reliable proxies for the total ionic pollution burden from such activities (Kastury et al., 2024). This spatial degradation of core physical and chemical parameters establishes a foundational understanding of the system's compromised state.

Nitrates and Phosphates

The nutrient data enabled a clear differentiation between pollution sources, effectively separating mining impacts from agricultural and domestic inputs. The inverse relationship observed between Ammonia (NH_3) and Nitrate (NO_3^-) is indicative of active in-stream nitrification. The high ammonia levels at the upstream Macalder site suggest a significant point-source of organic pollution, most likely untreated domestic sewage from the rapid, unplanned settlements typical of mining areas, a common issue in the developing world (Nanle, 2025).

Subsequently, the decline in NH_3 and the concomitant, statistically significant increase in NO_3^- downstream is a pattern characteristic of non-point-source pollution from agricultural fertilisers. This trend is well-documented in watershed studies focusing on agro-industrial pollution, where fertiliser leaching leads to a cumulative increase in nitrate load along a river's course (Masso et al., 2024; Nsanzabaganwa et al., 2024). The clear statistical separation of these sources – point-source sewage versus diffuse agricultural runoff – is a critical outcome for designing targeted, cost-effective mitigation strategies.

Conclusion

The ecological integrity and water portability of the Kuja River system are compromised by human activities, predominantly artisanal and small-scale gold mining, sugar processing, and agriculture. The evidence robustly confirms that the compounding pressures of mining, inadequate sanitation, and agricultural runoff have led to severe degradation, posing a direct threat to aquatic ecosystems and the communities dependent on this vital water resource.

The study confirmed severe spatial degradation of the river's physical condition. The consistently acidic pH (mean ~5.85) is a definitive signature of Acid Mine Drainage, while the pronounced downstream increase in Electrical Conductivity (EC) and Total Dissolved Solids (TDS) signals a heavy burden of dissolved ionic pollutants from mining and agricultural runoff



The nutrient dynamics revealed a clear separation of pollution sources. A point-source of organic pollution, indicated by high upstream ammonia, is likely untreated sewage from mining settlements, while the significant downstream increase in nitrate is characteristic of non-point-source pollution from agricultural fertilisers

In essence, the River Kuja exemplifies the devastating environmental cost of unregulated resource extraction and inadequate waste management. The study provides a scientifically robust baseline that necessitates immediate and coordinated action to avert a long-term public health disaster and ecological collapse.

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