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Reservoir Sedimentation, Water Quality Degradation, and Risk Assessment: Integrated Modelling of Kiri Dam, Nigeria

Gambo A.T; Olaniyan O.S; Adegbola A.A.
Department of Civil Engineering, Ladoke Akintola University of Technology,
Ogbomoso, Nigeria

Abstract
Reservoir sedimentation and water quality degradation remain critical threats to water supply and dam safety in tropical semi-arid regions. This study presents an integrated assessment of hydrological variability, water quality, and sediment contamination at Kiri Dam, Nigeria. Using a 43-year dataset (1982–2024), rainfall and discharge trends were evaluated with the Mann–Kendall test and Sen's slope estimator, while seasonal field sampling in 2024 covered physicochemical, nutrient, microbial, and heavy metal parameters across seven reservoir sites. Risk indices, including the Water Quality Index (WQI), Pollution Load Index (PLI), geo-accumulation index (I_geo), enrichment factor (EF), and irrigation suitability metrics, were applied, supported by principal component analysis (PCA) and regression modelling. Results indicated no significant rainfall trend ($Z = +1.24$, $p = 0.217$; Sen's slope = +1.3 mm yr^{-1}) but a significant increase in discharge (+1,353 $m^3\ s^{-1}\ yr^{-1}$, $p < 0.01$). Wet-season turbidity exceeded WHO/NSDWQ limits by >100-fold (556–573 NTU), coinciding with cadmium (0.018 mg L^{-1}) and lead (0.11 mg L^{-1}) surpassing permissible values (0.003 and 0.01 mg L^{-1}, respectively). Microbial counts exceeded 200 CFU/100 mL at inflow and reservoir-bed zones, confirming faecal contamination. Sediment analysis revealed cadmium enrichment (7–10 mg kg^{-1}), PLI > 1.5, and EF > 10 at inflow and bed sites, classifying them as heavily polluted. PCA grouped turbidity, TSS, Cd, and Pb as co-drivers, while regression confirmed turbidity and Cd as strong predictors of WQI (adjusted $R^2 = 0.72$). Overall, reservoir risks are driven more by sediment–water interactions and operational discharges than by rainfall variability, highlighting the urgent need for adaptive management, including sediment dredging, erosion control, and advanced treatment to safeguard water supply, irrigation, and ecological health.

Keywords: *Kiri Dam; sediment–water interaction; water quality index; pollution load index; ecological risk; tropical reservoirs*

1.0 Introduction
Reservoirs are essential in tropical and semi-arid regions for purposes such as water supply, irrigation, hydropower generation, and supporting ecosystems. However, their sustainability is jeopardized by sedimentation and pollution. Sediment accumulation diminishes capacity and changes flow patterns, whereas pollutants such as nutrients and heavy metals can be remobilized, thereby impairing water quality and damaging ecosystems (Li *et al.*, 2020).
In West Africa, fragile soils, intensive farming, and unregulated land use accelerate erosion and pollutant transfer into reservoirs. Nigerian dams such as Shiroro and Kainji

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face reduced storage capacity and deteriorating water quality due to runoff and urban waste (Ayeni *et al*., 2020; Cecchi *et al*., 2020). Heavy metals, particularly cadmium (Cd) and lead (Pb), present significant concerns, as studies indicate their accumulation in reservoir waters and sediments at levels that exceed established safety standards (Eze *et al*., 2023).

Indices of sediment contamination, such as the geoaccumulation index (Igeo), enrichment factor (EF), and Pollution Load Index (PLI), are extensively employed to evaluate ecological risks according to the thresholds established by the USEPA and the Probable Effect Levels (Long *et al*., 1995). Nonetheless, the majority of Nigerian research concentrates on individual physicochemical or microbial parameters (Bello *et al*., 2021), rather than integrating hydrological variability, sediment quality, and risk indices. Trend analysis techniques, including the Mann–Kendall test and Sen's slope estimator, are effective for correlating long-term hydrological trends with sediment and water quality; however, their application remains limited (Yue *et al*., 2002).

Kiri Dam, constructed in 1982 on the Gongola River within Adamawa State, serves purposes including irrigation, domestic water supply, and fisheries. The dam's catchment area is subject to erosion and land use pressures. Research indicates a decline in capacity, alongside Cadmium (Cd) and Lead (Pb) concentrations surpassing established safety thresholds in water, sediment, and biota (Afolabi *et al* 2021; Ojekunle *et al*., 2022).

This study integrates long-term hydrological analysis (1982–2024) with seasonal field investigations conducted in 2024 to evaluate the interactions between sedimentation and water quality in Kiri Dam. Specifically, it: (i) assesses trends in rainfall and discharge; (ii) investigates seasonal variations in physicochemical, nutrient, microbial, and heavy metal parameters; (iii) examines sediment contamination utilizing indices such as Igeo, EF, and PLI; (iv) identifies ecological hotspots in relation to benchmarks established by the USEPA and FAO; and (v) employs multivariate analyses, including PCA and regression, to determine key drivers and predictive indicators. The results provide valuable insights to support adaptive reservoir management strategies in tropical regions facing issues of sedimentation and contamination.

2. Materials and Methods

2.1 Study area

Kiri Dam (9°40′–9°45′N, 12°00′–12°05′E), situated in Adamawa State, northeastern Nigeria, was constructed in 1982 on the Gongola River for various functions including irrigation, domestic water supply, and fisheries. The basin is characterised by a tropical wet–dry climate, with an average annual precipitation of approximately 950 mm, predominantly occurring from May to October. Significant rates of evapotranspiration influence seasonal variations in water levels. The presence of erodible soils and intensive land utilizations contributes to increased sediment inflows (Mohammed *et al*., 2022).

2.2 Hydrological Data

Rainfall and discharge data spanning the years 1982 to 2024 were obtained from the Nigerian Meteorological Agency (NiMet) and the Upper Benue River Basin Development Authority (UBRBDA). The datasets comprised monthly and annual series, which were subjected to quality control procedures to address missing values and to conduct homogeneity tests.

2.3 Field Sampling

Seasonal sampling was conducted in 2024 during both the dry (January–March) and wet (July–September) seasons. Water and sediment samples were collected from seven sites representing inflow, outflow, and key

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hydraulic zones: Outflow (9°40′46″N, 12°00′50″E), Inflow (9°47′19″N, 12°01′12″E), Right Bank (9°42′40″N, 12°01′37″E), Middle Surface (9°43′28″N, 12°00′30″E), Left Bank (9°43′09″N, 12°03′16″E), Reservoir Bed (9°43′28″N, 12°00′30″E), and Mid-Reservoir Depth (9°43′28″N, 12°00′30″E). Four replicates were obtained per site to ensure representative sampling.

2.4 Laboratory Analyses

Physicochemical parameters, including turbidity, pH, electrical conductivity (EC), total dissolved solids (TDS), total suspended solids (TSS), dissolved oxygen (DO), biochemical oxygen demand (BOD_5), and chemical oxygen demand (COD), were analysed in accordance with the guidelines established by APHA (2017). Nutrients such as nitrate $(NO_3)^-$, phosphate $(PO_4^3)^-$, and sulfate (SO_4^{2-}) were quantified utilizing UV–Vis spectrophotometry. Major cations-sodium $(Na)^+$, potassium $(K)^+$, calcium $(Ca^2)^+$, magnesium $(Mg^2)^+$- and trace metals-including iron (Fe), manganese (Mn), lead (Pb), cadmium (Cd), chromium (Cr), copper (Cu), zinc (Zn), and nickel (Ni)- were determined through Atomic Absorption Spectrophotometry (AAS) following acid digestion. Detection limits were established at less than 0.001 mg L^{-1} for water samples and less than 0.1 mg kg^{-1} for sediment samples. The microbial quality assessment was conducted using membrane filtration techniques to enumerate total coliforms, Escherichia coli, and enterococci via m-Endo, EMB, and Slanetz–Bartley media.

2.5 Indices and Guidelines

The Water Quality Index (WQI) was calculated using the weighted arithmetic method (Brown *et al.,* 1970). Sediment contamination was assessed with the Pollution Load Index (PLI; Tomlinson *et al.,* 1980), geoaccumulation index (Igeo; Hakanson, 1980), and enrichment factor (EF; Turekian & Wedepohl, 1961). Ecological risks were compared to thresholds set by the US EPA (Long *et al*., 1995). Irrigation indices (Na%, SAR, KR, SSP, PI, MR, RSC) were derived from ionic data following FAO/USSL standards (Richards, 1954; FAO, 2003).

2.6 Statistical Analyses

Descriptive statistics (mean ± SD) were calculated for all variables. Seasonal variations were examined using one-way ANOVA coupled with Tukey’s post-hoc test at an alpha level of 0.05. Hydrological trends were analyzed utilizing the Mann–Kendall test (Mann, 1945) and Sen’s slope estimator (Sen, 1968), with adjustments for autocorrelation as per Yue *et al.* (2002). Correlations between variables were determined using Pearson’s correlation coefficient (r) and Spearman’s rank correlation coefficient (ρ). Principal Component Analysis (PCA) with Varimax rotation was employed to identify key drivers, while multiple linear regression models were developed to predict Water Quality Index (WQI) and sedimentary cadmium concentrations. Diagnostic assessments included Variance Inflation Factor (VIF) (<2), adjusted R-squared values, and residual analyses. All statistical analyses were performed using R software (version 4.2.1) and SPSS (version 26). Figure 2.1 depicts the conceptual model for water and sediment assessment.

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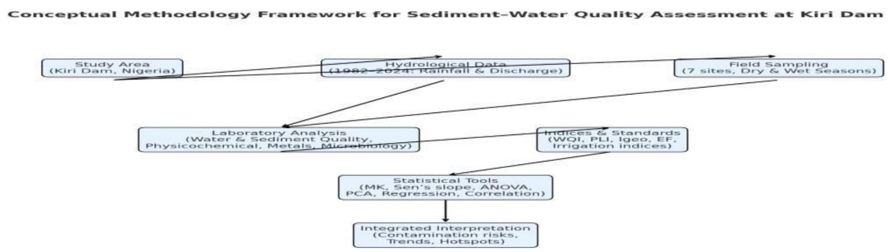

Figure 2.1. Conceptual Methodology Framework for Sediment–Water Quality Assessment at Kiri Dam

3. Results and Discussion

3.1 Hydrological Variability (1982–2024)

Rainfall at Kiri Dam ranged from 656 to 1,260 millimetres annually, with drought periods documented in 1987 and 2002, and peaks observed in 1995 and 2012. The Mann–Kendall test demonstrated no significant long-term trend in rainfall ($Z = +1.24$, $p = 0.217$), although Sen's slope indicated a modest increase of +1.3 millimetres per year. This pattern reflects Sahelian oscillations, previously reported by Oguntunde *et al.* (2014). Conversely, river discharge showed a significant upward trend ($Z = +3.17$, $p = 0.0015$), with Sen's slope corresponding to an increase of +1,353 cubic metres per second per year, thus confirming the influence of operational factors rather than rainfall variation (Ayeni *et al.*, 2020). Seasonal discharge peaks occurred in August–September (>25,000 cubic metres per second) and declined below 200 cubic metres per second in February–March, aligning with West African rainfall cycles and regulated flood releases.

Table 3.1. Hydrological trend statistics for rainfall and discharge at Kiri Dam (1982–2024).

Variable	Mean ± SD	Min–Max	MK Z	*p*-value	Sen's slope
Rainfall (mm)	**943.8 ± 119.5**	**656–1260**	**+1.24**	**0.217**	**+1.3 mm yr^{-1}**
Discharge ($m^3\ s^{-1}$)	**68,214 ± 54,926**	**0–499,746**	**+3.17**	**0.0015**	**+1,353 yr^{-1}**

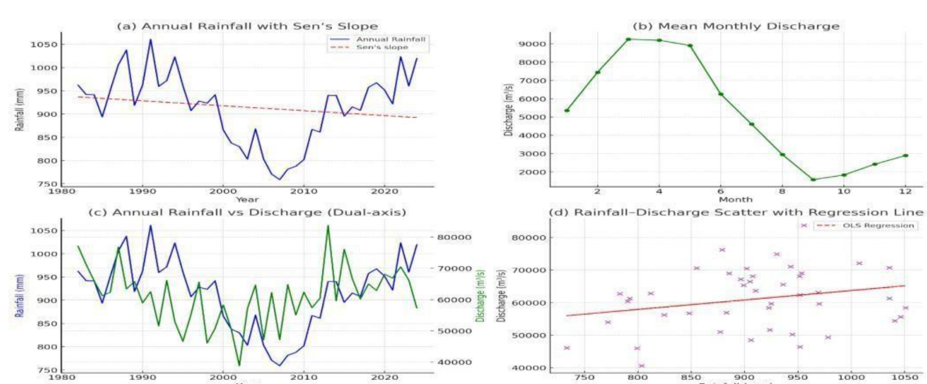

Figure 3.1a–d. Hydrological variability at Kiri Dam: *(a) annual rainfall trend, (b) mean monthly discharge, (c) dual rainfall–discharge lag, (d) rainfall–discharge scatterplot.*

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Increasingdischargesexacerbate downstream flood hazards and sediment transport, even under stable rainfall conditions. A comparable decoupling phenomenon between rainfall and discharge has been documented in regulated rivers within the Sahel region (Awotwi *et al*., 2015).

3.2 Water Quality

3.2.1 Physicochemical Parameters

Reservoir water in Kiri Dam demonstrated notable seasonal variability across key physicochemical parameters (Table 3.2; Figure 3.2a–d). Turbidity increased substantially from 361.9 ± 17.9 NTU during the dry season to 562.7 ± 15.0 NTU in the wet season, surpassing WHO/NSDWQ standards (5 NTU) by more than 100-fold (Figure 3.2a). Dissolved oxygen (DO) levels decreased from 7.0 ± 0.4 to 5.0 ± 0.2 mg L^{-1}, approaching the minimum safe threshold of ≥5 mg L^{-1}, particularly at inflow and bed zones (Figure 3.2b). Electrical conductivity (EC) and total dissolved solids (TDS) exhibited moderate increases during the wet season, from 122.9 ± 22.3 to 164.1 ± 4.3 µS cm^{-1} and from 82.1 ± 15.5 to 118.6 ± 1.7 mg L^{-1}, respectively. Yet, both remained below guideline values (Figure 3.2c). Signals of organic pollution were most pronounced during the wet season, as biochemical oxygen demand (BOD) rose to 3.3 ± 0.2 mg L^{-1}, exceeding the NSDWQ limit of 3 mg L^{-1}, while chemical oxygen demand (COD) increased nearly seven-fold from 3.3 ± 0.5 to 22.9 ± 1.4 mg L^{-1} (Figure 3.2d). These findings suggest runoff-driven inputs of suspended solids and organic matter, a phenomenon also documented in African reservoirs (Cecchi *et al*., 2020; Musa *et al*., 2022).

Table 3.2. Seasonal physicochemical parameters in Kiri Dam compared with WHO/NSDWQ standards.

Parameter	Dry (Mean ± SD)	Wet (Mean ± SD)	Standard	Status
Turbidity (NTU)	361.9 ± 17.9	562.7 ± 15.0	5 (WHO)	✗
pH	7.0–7.4	7.0–7.3	6.5–8.5	✓
EC (µS/cm)	122.9 ± 22.3	164.1 ± 4.3	1000	✓
TDS (mg L^{-1})	82.1 ± 15.5	118.6 ± 1.7	500	✓
DO (mg L^{-1})	7.0 ± 0.4	5.0 ± 0.2	≥5	✓ borderline
BOD (mg L^{-1})	2.5 ± 0.2	3.3 ± 0.2	3	✗ wet
COD (mg L^{-1})	3.3 ± 0.5	22.9 ± 1.4	–	Elevated

Note: ✓ - not exceeded; ✗ - exceeded

3.2.2 Nutrients and Major Ions

Nutrient and ionic chemistry showed seasonal changes (see Table 3.3; Figures 3.2e–h). Nitrate levels stayed stable year-round (24.26 ± 1.30 vs. 23.90 ± 1.57 mg L^{-1}; $p=0.645$), well below the WHO limit of 50 mg L^{-1} (see Figure 3.2e). Phosphate levels remained high (0.82 to 0.85 mg L^{-1}),

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exceeding the FAO irrigation threshold of 0.5 mg L^{-1} (see Figure 3.2f). Sulfate declined significantly during the wet season (106.36 ± 8.43 to 82.65 ± 5.53 mg L^{-1}; p<0.001), due to increased rainfall and inflow (see Figure 3.2g). Major cations (Na^{+}, Ca^{2+}, Mg^{2+}, K^{+}) showed moderate but significant changes (see Figure 3.2h). Sodium slightly increased (6.17 ± 0.17 to 6.39 ± 0.25 mg L^{-1}; p=0.007), while calcium and magnesium decreased; potassium increased in the wet season. All parameters stayed within WHO and FAO limits, but rising phosphate and sodium levels suggest risks of eutrophication and irrigation issues, similar to other tropical reservoirs (Varol *et al*., 2022).

Table 3.3. Nutrients and major ions in Kiri Dam compared with WHO/FAO standards.

Parameter	Dry (Mean ± SD)	Wet (Mean ± SD)	*p*-value	Standard	Status
Nitrate (mg L^{-1})	24.26 ± 1.30	23.90 ± 1.57	0.645	50 (WHO)	✓
Phosphate (mg L^{-1})	0.82 ± 0.09	0.85 ± 0.09	0.535	0.5 (FAO)	✗
Sulfate (mg L^{-1})	106.36 ± 8.43	82.65 ± 5.53	<0.001	250 (WHO)	✓
Sodium (mg L^{-1})	6.17 ± 0.17	6.39 ± 0.25	0.007	200	✓
Calcium (mg L^{-1})	21.50 ± 8.08	18.24 ± 8.19	0.233	75	✓
Magnesium (mg L^{-1})	0.51 ± 0.02	0.52 ± 0.01	0.034	50	✓
Potassium (mg L^{-1})	4.99 ± 0.67	5.41 ± 0.30	0.058	30	✓

Note: ✓ - not exceeded; ✗ - exceeded.

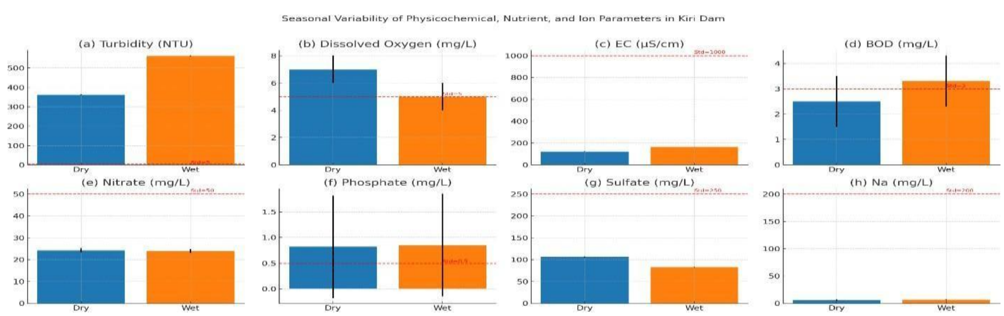

Figure 3.2a–h. Seasonal variability of water quality parameters in Kiri Dam with Standards (dry vs. wet):
(a)Turbidity and TSS – wet-season spikes above NSDWQ/WHO limits; (b)DO decline during wet season; (c) EC and TDS – moderate wet-season enrichment; (d) BOD and COD – wet-season organic loading;(e) Nitrate – stable across seasons, below WHO guideline; (f) Phosphate – persistently high, exceeding FAO irrigation threshold; (g) Sulfate – significant wet-season decline and; (h) Major cations (Na^{+}, Ca^{2+}, Mg^{2+}, K^{+}) – seasonal shifts with irrigation implications.

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The Persistent phosphate enrichment underscores the risks associated with agricultural runoff, in accordance with the observations made by Varol *et al*. (2022).

3.2.3 Heavy Metals

Seasonal variations were pronounced (Table 3.4). Iron (Fe) and Chromium (Cr) exceeded WHO/NSDWQ limits during the dry season (Fe: 523.51 ± 118.40 µg L^{-1} vs. 300 µg L^{-1}; Cr: 128.20 ± 15.22 µg L^{-1} vs. 50 µg L^{-1}), then declined to near-background levels in the rainy season (Fe: 0.05 ± 0.04 µg L^{-1}; Cr: 12.96 ± 1.85 µg L^{-1}; both $p < 0.001$). Copper (Cu) and Zinc (Zn) remained within limits; Zinc decreased significantly during the wet season ($p = 0.005$). Manganese (Mn) was mostly acceptable but showed localized enrichment at inflow/bed sites (Table 3.4). These trends are shown in multi-panel charts—including heavy metals and microbial indicators (panels 3.3a–h): dry-season Fe and Cr peaks (a–b), compliant Cu and Zn with dilution (c–d), and localized Mn rises (e). The correlation confirms peaks during low-flow, followed by dilution during the wet season.

Table 3.4. Seasonal variation of heavy metals compared with standards.

Parameter	Dry (Mean ± SD)	Wet (Mean ± SD)	*p*-value	WHO/NSDWQ	Status
Fe (µg L^{-1})	523.51 ± 118.40	0.05 ± 0.04	<0.001	300	✗ dry
Cr (µg L^{-1})	128.20 ± 15.22	12.96 ± 1.85	<0.001	50	✗ dry
Cu (µg L^{-1})	534.92 ± 84.19	0.00	<0.001	2000	✓
Zn (µg L^{-1})	61.16 ± 10.11	20.55 ± 25.63	0.005	3000	✓
Mn (µg L^{-1})	190.33 ± 47.93	56.87 ± 38.23	<0.001	400	✓ (local ↑)

Note: ✓ - not exceeded; ✗ - exceeded.

3.2.4 Microbial Indicators

All microbial metrics exceeded WHO/NSDWQ limits in both seasons (Table 3.5). Total coliforms rose from 713.57 ± 104.87 to 870.73 ± 107.91 CFU/100 mL ($p = 0.017$). Faecal coliforms and enterococci increased non-significantly but peaked at inflow and reservoir-bed sites during the wet season, aligning with runoff and resuspension. Panels f–h of the multi-panel chart—Heavy metals and microbial indicators—show these patterns, with dashed red lines marking WHO thresholds and wet-season bars at hotspots. Together with Table 3.5, these panels reveal a wet-season microbial surge linked to increased turbidity and organic loadings.

Table 3.5. Microbial indicators compared with WHO/NSDWQ standards

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Parameter	Dry (Mean ± SD)	Wet (Mean ± SD)	*p*-value	Standard	Status
Total coliforms	**713.57 ± 104.87**	**870.73 ± 107.91**	**0.017**	**0**	✓
Fecal coliforms	**235.42 ± 80.73**	**316.96 ± 153.70**	**0.245**	**0**	✓
Enterococci	**83.85 ± 21.86**	**100.16 ± 14.16**	**0.128**	**0**	✓

Note: ✓ - present; ✗ - Not present.

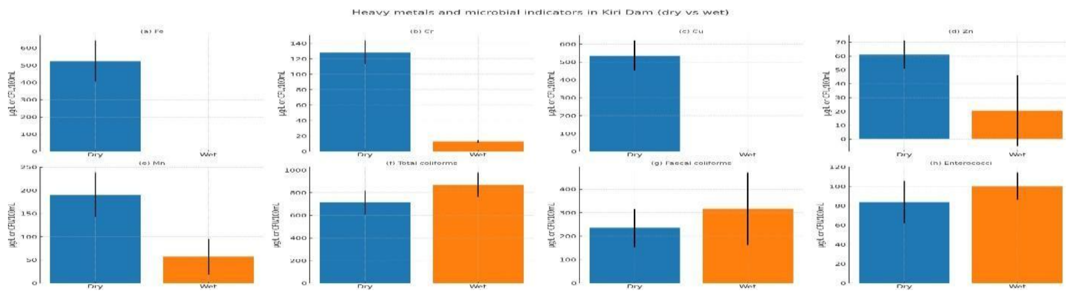

Figure ***3.3a-h. Heavy metals and microbial indicators in Kiri Dam (dry vs wet):***
(a) Fe—Dry-season exceedance; (b) Cr—Dry-season exceedance; (c) Cu—Compliant; (d) Zn—Wet dilution; (e) Mn—Localized at inflow/bed; (f) Total coliforms—Wet season increase; (g) Faecal coliforms—Hotspots at inflow/bed in wet season; (h) Enterococci—Concentrated hotspots in wet season.

3.3 CorrelationofWaterQualityParameters

Correlation analysis identified consistent seasonal associations among physicochemical variables, nutrients, and metals (Tables 3.6a–b). During the dry season, turbidity exhibited a strong correlation with Fe (r = 0.68), Cr (0.71), and Cd (0.74), whereas dissolved oxygen (DO) was negatively correlated with Fe (−0.65) and Cd (−0.69) (Table 3.6a). These —turbidity–metal clusters" are aligned with particle-bound transport mechanisms documented in tropical reservoirs in Ghana and Türkiye (Karikari *et al.*, 2020; Yildiz et al., 2025), as well as with redox-mediated metal release from sediments (Zhang *et al.*, 2021). The wet season demonstrates a similar turbidity–metal pattern (Turbidity–Fe = 0.70; –Cd = 0.76; –Cr = 0.72) and exhibits a more pronounced coupling between nutrients and oxygen demand (NO_3–BOD = 0.63; PO_4–BOD = 0.72; DO–BOD = −0.61). This pattern is characteristic of monsoon-fed reservoirs, where runoff-borne nutrients increase biochemical oxygen demand (BOD) and reduce dissolved oxygen (DO) (Cecchi *et al.*, 2020; Varol *et al.*, 2022). These relationships are illustrated through heatmaps (Figure 3.4a, water-quality sites n = 7).

Table3.6a. Selected Pearson's correlations (dry season, *n* = 7).

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Correlation pair	*r*	*p*-value	Interpretation
Turbidity–Fe	0.68	<0.05	Suspended solids improve Fe transport.
Turbidity–Cr	0.71	<0.05	Cr mobilized with suspended matter
Turbidity–Cd	0.74	<0.01	Strong Cd association with particulates
DO–Fe	−0.65	<0.05	Oxygen depletion mobilizes Fe
DO–Cd	−0.69	<0.05	Low DO increases Cd solubility
Nitrate–BOD	0.61	<0.05	Nutrient enrichment elevates BOD
Phosphate–BOD	0.70	<0.01	P strongly drives organic oxygen demand
DO–BOD	−0.62	<0.05	Organic loading reduces oxygen

Table 3.6b. Selected Pearson's correlations (wet season, *n* = 7).

Correlation pair	*r*	*p*-value	Interpretation
Turbidity–Fe	0.70	<0.05	Turbidity enhances Fe transport
Turbidity–Cd	0.76	<0.01	Cd mobilized with suspended solids
Turbidity–Cr	0.72	<0.01	Cr linked with turbidity
DO–Cd	−0.68	<0.05	Cd increases under oxygen depletion
Nitrate–BOD	0.63	<0.05	Nitrate contributes to oxygen demand
Phosphate–BOD	0.72	<0.01	Phosphorus enrichment drives eutrophication
DO–BOD	−0.61	<0.05	DO reduced as BOD rises

3.4 Spatial Distribution and Hotspots of Risk Indices

The sediment indices underscore pollution hotspots at the inflow regions and the reservoir bed, with Pollution Load Index (PLI) exceeding 1.5 and Enrichment Factor for Cadmium (EF(Cd)) surpassing 10, thereby indicating substantial anthropogenic enrichment (Table 3.7). This pattern aligns with impoundments observed in West Africa and Turkey (Nartey *et al*., 2023; Yildiz *et al.*, 2025; Domínguez-Gálvez & Álvarez-Álvarez, 2025). The TEL/PEL screening methodology (Long *et al*., 1995), as illustrated in Figure 3.4b (based on n = 5 sediment sampling sites), delineates regions susceptible to benthic effects.

Table 3.7. Sediment indices across sites.

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Site	PLI (Dry)	PLI (Wet)	I_geo (Cd)	EF (Cd)	Risk Category
Inflow	1.32	1.63	Moderate	>10	Polluted–Heavily
Reservoir bed	1.67	1.78	Strong	>10	Heavily polluted
Outflow	1.14	1.51	Low	2–5	Slight–Polluted
Right bank	1.09	1.20	Low	<2	Slight
Left bank	1.18	1.39	Moderate	5–10	Polluted
Mid-surface	0.95	1.02	Background	<2	Near-background

3.5 Ecological Risk Implications

At hotspots, cadmium (Cd) and lead (Pb) levels exceed the Threshold Effect Level (TEL) and near the Probable Effect Level (PEL), risking adverse benthic responses under hypoxic conditions, as seen in Nigerian reservoirs and redox experiments (Olawale *et al*., 2021; Zhang *et al*., 2021). Without intervention, risks could spread to fisheries and food webs, similar to West African systems (Nartey *et al*., 2023).

3.6 Water Quality Index (WQI)

The Water Quality Index (WQI) declines from a poor (dry) classification to poor–unsuitable at more than 60% of sites during the wet season, with the most significant deterioration observed at the inflow and left bank areas (see Table 3.8). The classification panel (Figure 3.4c) illustrates site-by-season transitions in relation to decision thresholds. The deterioration observed during the wet season, associated with turbidity, cadmium (Cd), lead (Pb), and microbial parameters, is consistent with reports from West African reservoirs experiencing storm-driven inflows (Cecchi *et al*., 2020; Bello *et al*., 2021), as well as with documented seasonal oxygen stress in stratifying Nigerian dams (Musa *et al*., 2022).

Table 3.8. WQI across sites and seasons.

Location	WQI (Dry)	WQI (Wet)	Class
Outflow	68.2	55.3	Poor → Poor/Unsuitable
Inflow	72.1	60.5	Poor → Poor
Right bank	65.7	58.4	Poor → Poor
Mid surface	63.4	56.2	Poor → Poor
Left bank	69.5	51.7	Poor → Unsuitable
Reservoir bed	48.6	54.1	Marginal → Poor
Mid depth	66.3	59.8	Poor → Poor

3.7 Suitability for Agriculture and Irrigation

Irrigation indices like Na% and SAR are generally acceptable but indicate marginal sodicity, with KR around 0.9 and RSC over 2.5 meq L^{-1} in some wet-season locations (Table 3.9). Similar wet-season sodicity concerns are noted in tropical reservoirs (Amanambu *et al*., 2022). Threshold

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interpretations follow FAO/USSL guidance (Richards, 1954; FAO, 2003). Panel Figure 3.4d summarizes these constraints and supports recommendations for blending and soil monitoring during peak inflow

Table 3.9. Irrigation suitability indices.

Parameter	Dry	Wet	FAO/USSL Threshold	Status
Na% (%)	35.2 ± 2.1	38.4 ± 3.3	<60	✓
SAR	1.42 ± 0.12	1.68 ± 0.14	<10	✓
KR	0.71 ± 0.09	0.89 ± 0.11	<1	✓ Marginal wet
SSP (%)	37.4 ± 2.2	39.1 ± 2.5	<60	✓
PI	Class II–III	Class II–III	Class I–III	✓ Minor restriction
MR (%)	47.8 ± 3.5	52.4 ± 4.2	>50 restrictive	✗ wet
RSC (meq L^{-1})	2.3 ± 0.4	2.6 ± 0.5	>2.5 unsafe	✗ wet

✗ - unsuitable; ✓ - suitable.

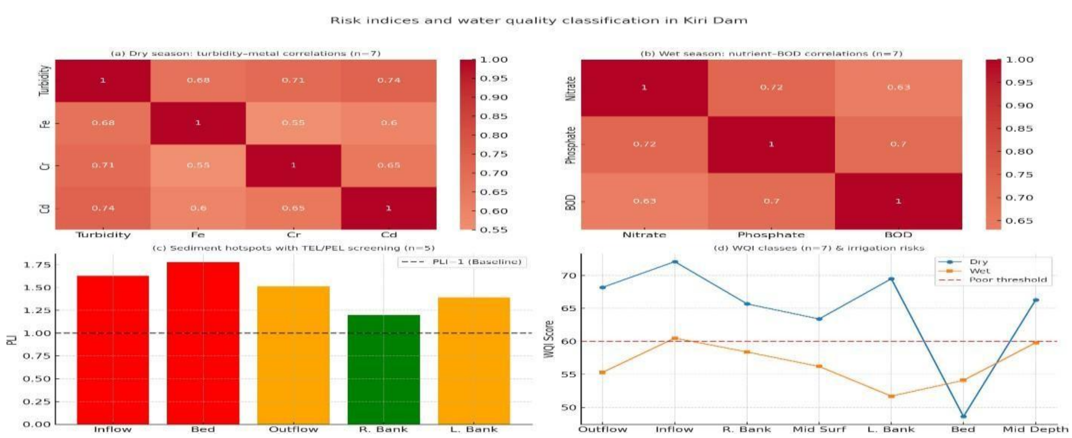

Figure 3.4a-d. Risk indices and water quality classification in Kiri Dam:
(a) Dry season heatmap: turbidity–metal links (n=7); (b) Wet season heatmap: nutrient–BOD links (n=7); (c) Sediment hotspots (PLI, TEL/PEL, n=5); and (d) WQI classes by site/season with irrigation risks (>60% wet-season poor–unsuitable)

3.8 Correlation Among Indices

The analysis shows water quality, sediment contamination, and irrigation indices are linked. Sediment enrichment worsens water quality and limits agriculture. Table 3.10 shows significant correlations ($p < 0.05$). The Water Quality Index (WQI) strongly correlates with the Pollution Load Index (PLI; r=0.72), indicating sediment contamination harms water quality, seen in reservoirs in Ghana (Nartey *et al.*, 2023) and Türkiye (Yildiz *et al.*, 2025). Among irrigation factors, sodium percentage (Na%) correlates highly with Kelley's Ratio (KR; r=0.85) and magnesium ratio (MR; r=0.63),

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affecting sodicity risk. Residual sodium carbonate (RSC) correlates with MR (r=0.66), highlighting its role in alkalinity hazards. These results confirm sediment enrichment (PLI) and cation imbalances, especially sodium and magnesium, are key in ecological and agricultural risks. Similar patterns of WQI–PLI and Na%–KR–MR are documented in semi-arid reservoirs in Nigeria (Amanambu *et al*., 2022) and East Africa (Awotwi *et al*., 2015), reinforcing these links.

Table 3.10. Correlation matrix among indices.

Indices	WQI	PLI	Na%	KR	MR	RSC
WQI	1.00	0.72*	0.21	0.18	0.30	0.25
PLI	0.72*	1.00	0.34	0.28	0.42	0.39
Na%	0.21	0.34	1.00	0.85**	0.63*	0.58*
KR	0.18	0.28	0.85**	1.00	0.61*	0.57*
MR	0.30	0.42	0.63*	0.61*	1.00	0.66*
RSC	0.25	0.39	0.58*	0.57*	0.66*	1.00

($p < 0.05$; *$p < 0.01$).

3.9: Principal Component Analysis (PCA) and Regression Modeling

Multivariate analysis identified key factors affecting water and sediment quality. PCA (Table 11) revealed three principal components explaining 73% of the variance. PC1 (42%) was associated with turbidity, TSS, cadmium, lead, and phosphate, indicating sediment-bound metals and nutrients during wet periods. PC2 (20%) was characterised by dissolved oxygen (inverse relationship), iron, and manganese, emphasizing redox-driven mobilization. PC3 (11%) was linked to nitrate and zinc, representing catchment nutrient inputs. Regression analysis (Table 12) identified turbidity and cadmium as key predictors of the Water Quality Index (WQI) (Adjusted R^2=0.72, p < 01), while sedimentary cadmium was best predicted by pH, organic matter, and electrical conductivity (Adjusted R^2=0.74, p < 05). These models confirm sediment chemistry and particles impact water quality. PCA biplot and regression plots (Figures 7 a–b) show seasonal clustering: wet-season samples align with PC1 (sediment drivers), dry-season with PC2 (redox processes). The WQI drops with higher turbidity and cadmium; sedimentary cadmium increases with organic matter and ionic activity. Findings align with studies in Nigeria and Ethiopia, highlighting sediments and redox conditions in contaminant mobilization and reservoir quality.

Table 3.11. PCA loadings (>0.60).

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Component	Variance (%)	Dominant loadings
PC1	**42.1**	**Turbidity, TSS, Cd, Pb, PO_4^{3-}**
PC2	**20.0**	**DO (−), Fe, Mn**
PC3	**11.2**	**NO_3^-, Zn**

Table 3.12. Regression models.

Dependent variable	Predictors	β	*p*	Adj. R^2
WQI	**Turbidity, Cd**	**0.61, 0.55**	**<0.01**	**0.72**
Cd (sediment)	**pH, OM, EC**	**−0.52, 0.57, 0.44**	**<0.05**	**0.74**

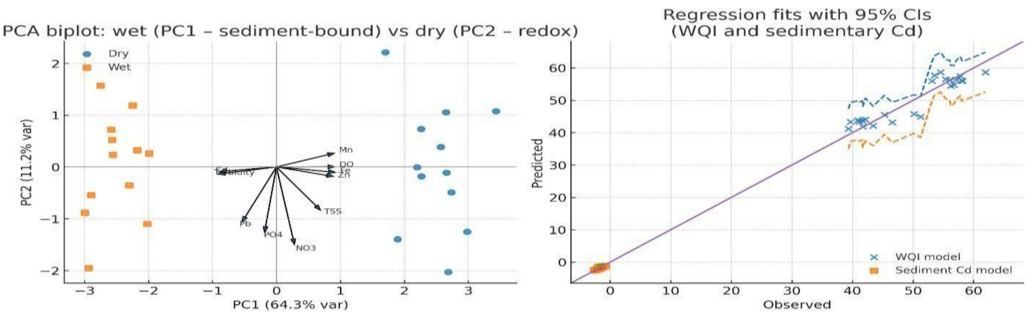

Figure 3.5a–b. PCA and regression results for Kiri Dam:
(a) PCA biplot illustrating wet-season clustering (PC1 – sediment-bound drivers) contrasted with dry-season clustering (PC2 – redox-driven mobilization); (b) Regression scatterplots displaying observed versus predicted Water Quality Index (WQI) and sedimentary cadmium concentrations, accompanied by 95% confidence intervals.

3.10 Limitations

This research covered a single hydrological year (2024), limiting interannual comparisons. It lacked sediment cores or GIS catchment modelling, restricting source attribution. However, by integrating hydrological trends from 1982-2024, seasonal sampling, sediment indices, and multivariate models, a comprehensive risk assessment framework for tropical reservoirs was developed.

3.11 ConceptualSynthesisand Implications

Long-term hydrology, water quality, and sediment indices provide a comprehensive framework for understanding sediment–water interactions at Kiri Dam. Precipitation, land utilizations, and erosion processes influence sediment inflows that introduce cadmium and lead into the reservoir. These metals settle at the bed and are remobilized during wet periods under fluctuating redox conditions, forming hotspots. Nutrients such as phosphate and nitrate elevate biochemical oxygen demand, thereby accelerating eutrophication and microbial contamination. Over 60% of samples collected during the wet season are classified as poor or unsuitable, surpassing

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thresholds established by WHO/NSDWQ. Sediment indices, including PLI, Igeo, and EF, indicate enrichment of cadmium, thereby highlighting ecological risks. The implications of these findings include compromised water supply, restrictions on irrigation due to elevated magnesium and sodium levels, and contamination downstream. Sustainable management strategies advocate for sediment control, improved treatment procedures, and erosion mitigation measures (Cecchi et al., 2020; Amanambu *et al.*, 2022; Yildiz *et al.*, 2025).

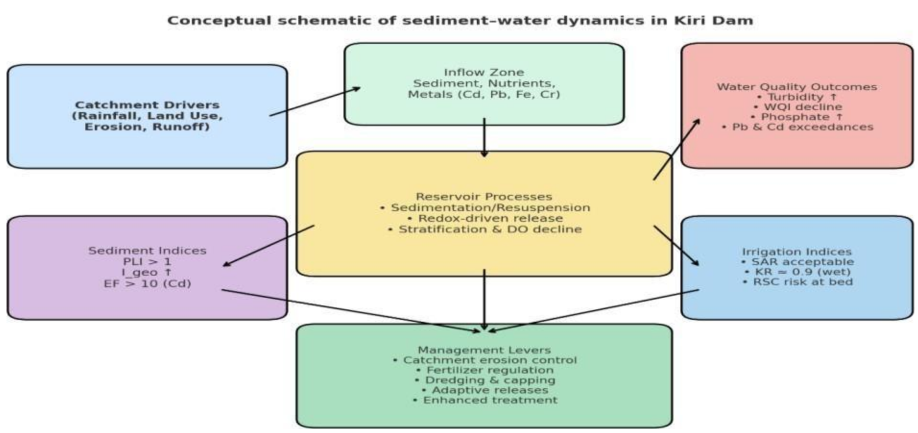

Figure 3.6 Conceptual schematic of sediment–water dynamics in Kiri Dam

4. Conclusions and Recommendations

4.1 Conclusions

Reservoir safety at Kiri Dam depends more on sediment–water interactions and operational discharges than rainfall variability. Rainfall showed no significant trend, but discharges increased significantly (+1353 m^3/s annually). Wet-season inflows raised turbidity (>500 NTU), phosphate (>0.5 mg/L), Cd (>0.003 mg/L), Pb (>0.01 mg/L), and microbial contamination (>200 CFU/100 mL). Sediment analysis confirmed Cd enrichment (7–10 mg/kg), PLI >1.5, and EF >10 at inflow and bed hotspots. WQI classified over 60% of wet-season sites as poor–unsuitable, while irrigation risk was marginal for sodicity. PCA and regression identified turbidity and Cd as key indicators of water quality decline.

4.2 Recommendations

- ✶ Optimize dam releases to minimize sediment resuspension.
- ✶ Dredge/cap inflow and bed hotspots to reduce Cd/Pb remobilization.
- ✶ Implement erosion buffers and regulate upstream fertilizer/mining.
- ✶ Upgrade treatment plants (coagulation–filtration–disinfection) with real-time turbidity and Cd monitoring.
- ✶ Adopt blending strategies for irrigation and monitor soils for sodicity and Cd.
- ✶ Institutionalize seasonal WQI–PLI monitoring dashboards for adaptive management.

4.3 Closing Remark

Kiri Dam underscores vulnerabilities of tropical reservoirs where sediment–water interactions, not rainfall alone, determine safety and sustainability. Adaptive

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management strategies are essential for balancing water supply, irrigation, and ecological integrity.

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Author Contributions

Conceptualization: A.T. Gambo, O.S. Olaniyan
Methodology: A.T. Gambo
Investigation: A.T. Gambo
Formal Analysis: A.T. Gambo, O.S. Olaniyan
Writing – Original Draft: A.T. Gambo
Writing – Review & Editing: O.S. Olaniyan, A.A. Adegbola
Supervision: O.S. Olaniyan

Conflicts of Interest

The authors declare no conflicts of interest, financial or personal, that could have influenced the outcomes or interpretation of this study.

Data Availability

The datasets and analysis scripts that support the findings of this research are available from the corresponding author upon reasonable request.

Highlights

- ✶ Rainfall at Kiri Dam (1982–2024) showed no significant long-term trend.
- ✶ Reservoir discharge increased significantly (+1,353 m^3/s per year), reflecting operational regulation.
- ✶ Wet-season inflows (>550 NTU turbidity; phosphate >0.5 mg L^{-1}; Cd and Pb above WHO/NSDWQ limits) drive water quality deterioration.
- ✶ Sediment analysis revealed cadmium enrichment (7–10 mg kg^{-1}), PLI >1.5, and EF >10 at inflow and reservoir bed hotspots.
- ✶ WQI classified >60% of wet-season sites as poor–unsuitable for drinking, while irrigation indices showed marginal sodicity risks.
- ✶ PCA and regression confirmed turbidity and Cd as strong predictors of WQI, supporting their use as early-warning indicators.

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