American Journal of Environment and Climate (AJEC)

ISSN: 2832-403X (ONLINE)

VOLUME 5 ISSUE 2 (2026)

PUBLISHED BY
E-PALLI PUBLISHERS, DELAWARE, USA

American Journal of Environment and Climate (AJEC)
Volume 5 Issue 2, Year 2026
ISSN: 2832-403X (Online)
DOI: https://doi.org/10.54536/ajec.v5i2.7933
https://journals.e-palli.com/home/index.php/ajec

Hydrology–Water Quality Interactions in a Data-Scarce Tropical River Basin: An Integrated Assessment of Seasonal Dynamics and Water Quality Drivers

Abiodun B Laniyan[1*], Funmilayo M. Alayaki[2], Oladapo S. Abiola[2], Adebola A Adekunle[3], Oluwaseun T. Olurin[4], Akintayo O. Ojo[5]

Article Information

Received: April 02, 2026

Accepted: June 05, 2026

Published: August 06, 2026

Keywords

Cross-Correlation Analysis, Flow Duration Curve (FDC), Hydrology–Water Quality Interactions, Nigeria, Runoff Processes, Tropical River Basin

ABSTRACT

This study presents an integrated assessment of hydrological dynamics and water quality in the Ogbese River Basin, southwestern Nigeria, with the aim of elucidating the processes controlling water quality variability in a data-scarce tropical environment. A three-year dataset (2021–2023) comprising hydrological variables (rainfall and discharge) and water quality parameters (physicochemical, heavy metals, and microbial indicators) was analyzed using a combination of descriptive statistics, non-parametric trend analysis, flow duration curves (FDC), cross-correlation functions (CCF), and principal component analysis (PCA). Results revealed strong seasonal variability, with wet-season conditions characterized by increased discharge, turbidity, and Escherichia coli concentrations, while dry-season conditions showed elevated electrical conductivity and total dissolved solids. Trend analysis indicated increasing tendencies in rainfall, discharge, turbidity, and microbial contamination, although only rainfall exhibited statistically significant change ($p < 0.05$). FDC analysis demonstrated high hydrological variability and relatively limited low-flow persistence, while cross-correlation results showed a rapid water-quality response to rainfall with minimal lag. Exploratory PCA identified three dominant controlling factors: geogenic mineralisation, organic pollution, and runoff-driven metal mobilisation influenced by anthropogenic activities. This study presents a process-based framework by integrating hydrological and water quality analyses using multiple complementary techniques within a short-term dataset, demonstrating the potential of such approaches as early diagnostic tools in data-limited basins. The findings highlight the critical role of rainfall-driven processes in controlling contaminant transport and underscore the need for integrated watershed management strategies to ensure sustainable water resource use.

INTRODUCTION

Access to safe and reliable water resources is a fundamental requirement for human health, ecosystem sustainability, and socio-economic development. Within the framework of Water, Sanitation, and Hygiene (WASH) initiatives and the United Nations Sustainable Development Goal 6 (SDG-6), ensuring the availability and quality of freshwater resources remains a critical global priority. In many developing regions, particularly in sub-Saharan Africa, surface water and shallow groundwater systems serve as primary sources of domestic water supply, yet these resources are increasingly threatened by both natural and anthropogenic pressures.

In many tropical regions, the interaction between rainfall, runoff, and water quality reflects the combined influence of climatic variability and anthropogenic activities. The degradation of water quality and decline in streamflow conditions have been attributed to increased land-use change, agricultural expansion, and urban development. Rural African water sources often exhibit significant microbial contamination, reflecting inadequate sanitation infrastructure and diffuse pollution inputs from surrounding communities (Gao *et al.,* 2023; Njuguna *et al.,* 2024; Adeniji *et al.,* 2019). Such challenges highlight the need for integrated hydrological and water quality assessments capable of linking flow variability with pollutant transport dynamics in tropical basins.

Hydrological processes play a central role in controlling water quality in river systems. Variations in rainfall, discharge, and evapotranspiration influence sediment transport, pollutant mobilization, and dilution capacity. In tropical environments, strong seasonality further amplifies these interactions, with wet-season runoff often associated with increased turbidity, nutrient loading, and microbial contamination. Several studies have demonstrated that rainfall-driven processes significantly affect hydrochemical dynamics and water quality in river basins (Li *et al.,* 2014; Gao *et al.,* 2023). However, the extent to which these processes interact over time, particularly in data-scarce regions, remains insufficiently understood.

In West Africa, rapid population growth, land-use change, and inadequate sanitation infrastructure have intensified pressures on water resources. Agricultural expansion, urbanization, and deforestation contribute to increased surface runoff, sediment yield, and diffuse

[1] Department of Science Laboratory Technology, D.S Adegbenro ICT Polytechnic, Itori-Ewekoro, Nigeria
[2] Department of Civil Engineering, Federal University of Agriculture, Abeokuta, Nigeria
[3] Department of Civil Engineering, Federal University Otuoke. Bayelsa State, Nigeria
[4] Department of Physics, Federal University of Agriculture, Abeokuta, Nigeria
[5] Physics Unit, Directorate of General Studies, Federal University of Allied Health Sciences, Enugu, Nigeria
[*] Corresponding author's e-mail: abiodunlaniyan@gmail.com

pollution, while poor waste management practices exacerbate microbial contamination of water bodies. Previous studies in Nigerian river basins, including the Ogun and Osun systems, have reported elevated levels of turbidity, heavy metals, and microbial indicators linked to anthropogenic activities (Abba *et al.,* 2022; Adeniji *et al.,* 2019). Despite these advances, many studies have focused primarily on static water quality assessments, with limited integration of hydrological dynamics, temporal trends, and multivariate analyses.

The Ogbese River Basin represents a typical tropical watershed experiencing increasing environmental pressures, yet comprehensive studies linking hydrology and water quality in this basin remain scarce. Existing research has largely emphasized hydrochemical characterization without fully exploring the temporal dynamics, hydrological controls, and underlying processes governing water quality variability. In particular, there is a lack of integrated studies that combine seasonal analysis, trend detection, flow regime characterization, and advanced statistical techniques to provide a holistic understanding of system behavior. To address these gaps, this study presents an integrated assessment of hydrological variability and water quality dynamics in the Ogbese River Basin over a three-year period (2021–2023). The study combines descriptive statistics, non-parametric trend analysis, flow duration curve (FDC) analysis, cross-correlation techniques, and principal component analysis (PCA) to identify key controlling processes and pollution sources. To the authors' knowledge, this is among the first studies in the Ogbese River Basin to integrate trend detection, flow-duration analysis, cross-correlation functions, and multivariate statistics within a unified framework for evaluating hydrology-water quality interactions. Unlike studies that rely primarily on static water quality assessment, this work adopts a process-based approach to examine temporal dynamics and interactions between hydrology and water quality. The study also demonstrates how short-term datasets can serve as early diagnostic tools for identifying emerging hydrological and environmental changes in poorly monitored basins.

The specific objectives of the study are to:

(i) Evaluate seasonal variations in hydrological and water quality parameters;

(ii) Assess temporal trends and variability using non-parametric statistical methods;

(iii) Characterize flow regime behavior using flow duration curves;

(iv) Examine lag relationships between rainfall and water quality parameters; and

(v) Identify dominant hydrochemical processes and pollution sources using multivariate analysis.

By integrating hydrological and water quality analyses, this study provides new insights into the processes controlling water quality in tropical river systems. The findings contribute to a better understanding of hydrology–water quality interactions in data-limited environments and offer a framework for supporting sustainable water resource management and policy development in similar basins across sub-Saharan Africa.

LITERATURE REVIEW

Hydrology–Water Quality Interactions in River Systems

River water quality is strongly influenced by hydrological processes that regulate the transport, dilution, transformation, and retention of pollutants within catchments. Variations in precipitation, streamflow, runoff generation, and watershed characteristics determine the movement of sediments, nutrients, organic matter, and other contaminants into aquatic environments. During periods of high discharge, increased surface runoff can mobilize pollutants from agricultural lands, urban surfaces, and disturbed catchments, whereas low-flow conditions often concentrate dissolved constituents because of reduced dilution capacity (Khatri & Tyagi, 2015). Consequently, hydrological variability plays a critical role in determining the spatial and temporal dynamics of river water quality.

Previous studies have consistently demonstrated significant relationships between hydrological conditions and water quality parameters. Seasonal fluctuations in river discharge influence turbidity, suspended solids, nutrient concentrations, dissolved oxygen, electrical conductivity, and other indicators of aquatic ecosystem health (Yidana *et al.,* 2020; Gizaw *et al.,* 2019). These interactions are particularly important in tropical environments where pronounced wet and dry seasons generate substantial variability in flow regimes. Understanding hydrology–water quality interactions is therefore essential for sustainable water resources management, pollution control, and environmental protection. Despite their importance, hydrological and water quality assessments are frequently conducted independently, particularly in developing countries where monitoring resources are limited. This separation often restricts understanding of the mechanisms through which hydrological processes influence water quality conditions. Integrated assessments that simultaneously examine hydrological variability and water quality dynamics are therefore increasingly recommended for effective watershed management and evidence-based decision-making.

Water Quality Dynamics in Tropical River Basins

Water quality degradation has become a major environmental challenge in many tropical river basins due to rapid urbanization, agricultural intensification, industrial development, and population growth. These pressures contribute to increased sediment loads, nutrient enrichment, organic pollution, and microbial contamination, thereby reducing the ecological integrity and usability of freshwater resources (Edokpayi *et al.,* 2019; Adeyemo *et al.,* 2020). The effects of these anthropogenic activities are often intensified by seasonal hydrological variability, which influences pollutant transport pathways and dilution processes. Studies across sub-Saharan Africa have reported significant seasonal variations in river water quality. Wet-season conditions are commonly associated with elevated turbidity, suspended solids, and nutrient concentrations due to enhanced runoff and erosion, while dry-season conditions frequently exhibit increased concentrations of dissolved ions resulting from reduced streamflow and increased evaporation (Mureithi *et al.,* 2021; Yidana *et al.,* 2020). Such seasonal patterns highlight the importance of incorporating hydrological information into water quality monitoring and management programmes.

Evidence from Nigeria similarly demonstrates the influence of both environmental and anthropogenic factors on river water quality. Ebuete *et al.* (2023), using the National Sanitation Foundation Water Quality Index (NSFWQI), reported substantial variations in the water quality of the River Nun in Bayelsa State and emphasized the need for continuous monitoring of freshwater systems subjected to human activities. Likewise, Laniyan *et al.* (2025) found that seasonal hydrological variability significantly influenced hydrochemical characteristics in the Ogun and Oshun Rivers of southwestern Nigeria, with phosphate, turbidity, sodium, and total dissolved solids identified as important indicators of water quality deterioration. The study further demonstrated that downstream river sections experienced greater environmental pressure due to cumulative pollutant inputs from urban and agricultural sources. Poor waste management practices also represent a significant source of water quality deterioration in many developing regions. Ebuete *et al.* (2022) highlighted the environmental consequences of indiscriminate waste disposal in the Niger Delta, noting that inadequate waste management can contribute to pollution of surface-water resources and degradation of aquatic ecosystems. These findings reinforce the need for integrated watershed management strategies that address both hydrological processes and anthropogenic pollution sources.

Analytical Approaches for Assessing Water Quality Drivers

The increasing complexity of environmental systems has encouraged the use of integrated analytical approaches for investigating water quality dynamics. Traditional assessments based solely on descriptive statistics and regulatory compliance evaluations provide useful information regarding water suitability but often offer limited insight into the processes responsible for observed patterns. Consequently, researchers increasingly employ statistical and multivariate techniques to identify dominant environmental controls and characterize water quality variability.

Correlation analysis is widely used to evaluate relationships among hydrological and water quality variables, while non-parametric methods such as the Mann–Kendall test and Sen's slope estimator are commonly applied to detect trends in environmental datasets. These approaches are particularly valuable in data-scarce environments because they require relatively few assumptions and are robust to non-normal data distributions. Furthermore, multivariate techniques such as principal component analysis (PCA) facilitate the identification of major factors influencing water quality by reducing complex datasets into a smaller number of interpretable components (Singh *et al.,* 2020; Akintola *et al.,* 2023). Integrated analytical frameworks combining seasonal assessment, trend analysis, correlation analysis, and multivariate statistics have proven effective for investigating hydrology–water quality relationships in river systems. Such approaches improve understanding of environmental processes, support pollution source identification, and provide scientific evidence for water resources management. Their application is particularly important in tropical river basins where environmental pressures are increasing and monitoring data remain limited.

Research Gap

Although numerous studies have examined river water quality and hydrological variability, relatively few investigations have integrated seasonal hydrological assessment, trend analysis, correlation analysis, and multivariate statistical evaluation within a single framework, particularly in data-scarce tropical river basins. Existing research in Nigeria has often focused either on hydrochemical characterization or on water quality status without explicitly evaluating the interactions between hydrological conditions and water quality dynamics.

Furthermore, limited availability of long-term monitoring data continues to constrain understanding of temporal water quality variability and the environmental factors influencing river health in many tropical catchments. Addressing these limitations is important for developing effective watershed management strategies and supporting sustainable water resource planning under increasing environmental and climatic pressures.

This study addresses these gaps by integrating hydrological indicators, seasonal water quality assessment, Mann–Kendall trend analysis, Sen's slope estimation, correlation analysis, and principal component analysis to evaluate hydrology–water quality interactions within a data-scarce tropical river basin. The findings contribute to improved understanding of the drivers of water quality variability and provide evidence to support sustainable river basin management in southwestern Nigeria.

MATERIALS AND METHODS

Study Area Description

The Ogbese River Basin is located in southwestern Nigeria, spanning parts of Ondo, Ekiti, and Edo States. The basin lies between latitudes 6°35'–7°15' N and longitudes 5°15'–5°45' E, covering an estimated catchment area of approximately 1,200 km². The river originates from the uplands of Ekiti State and flows southwestward, eventually draining into the Benin River system. The basin supports a range of socio-economic activities, including domestic water supply, small-scale irrigation, artisanal fisheries, and sand mining. The climate of the basin is classified as humid tropical, characterized by distinct wet (April–October) and dry (November–March) seasons controlled by the seasonal migration of the Intertropical Convergence Zone (ITCZ). Annual rainfall ranges from 1,200 to 1,600 mm, with peak precipitation typically occurring in July and September, separated by a short dry spell in August. Mean annual temperatures range between 25°C and 28°C, while potential evapotranspiration exceeds 1,400 mm/year, indicating high atmospheric demand.

Topographically, the basin is characterized by gently undulating terrain, with elevations ranging from approximately 30 m in the lowlands to over 300 m in the headwaters. The geology is dominated by Precambrian Basement Complex formations, which influence groundwater occurrence, recharge processes, and hydrochemical characteristics. Land use within the basin is heterogeneous, consisting of rainfed agriculture, secondary forest, grassland, and expanding built-up areas. Major crops cultivated include yam, cassava, maize, and cocoa, while riparian zones are characterized by palm groves and wetland vegetation. Increasing anthropogenic pressures, including agricultural runoff (fertilizers and pesticides), domestic wastewater discharge, sand mining, and localized oil contamination from machinery, represent potential sources of water quality degradation. The combination of climatic variability, geological controls, and land-use pressures makes the Ogbese River Basin highly sensitive to hydrological fluctuations and environmental change. These characteristics make it an appropriate case study for investigating hydrology–water quality interactions in tropical river systems.

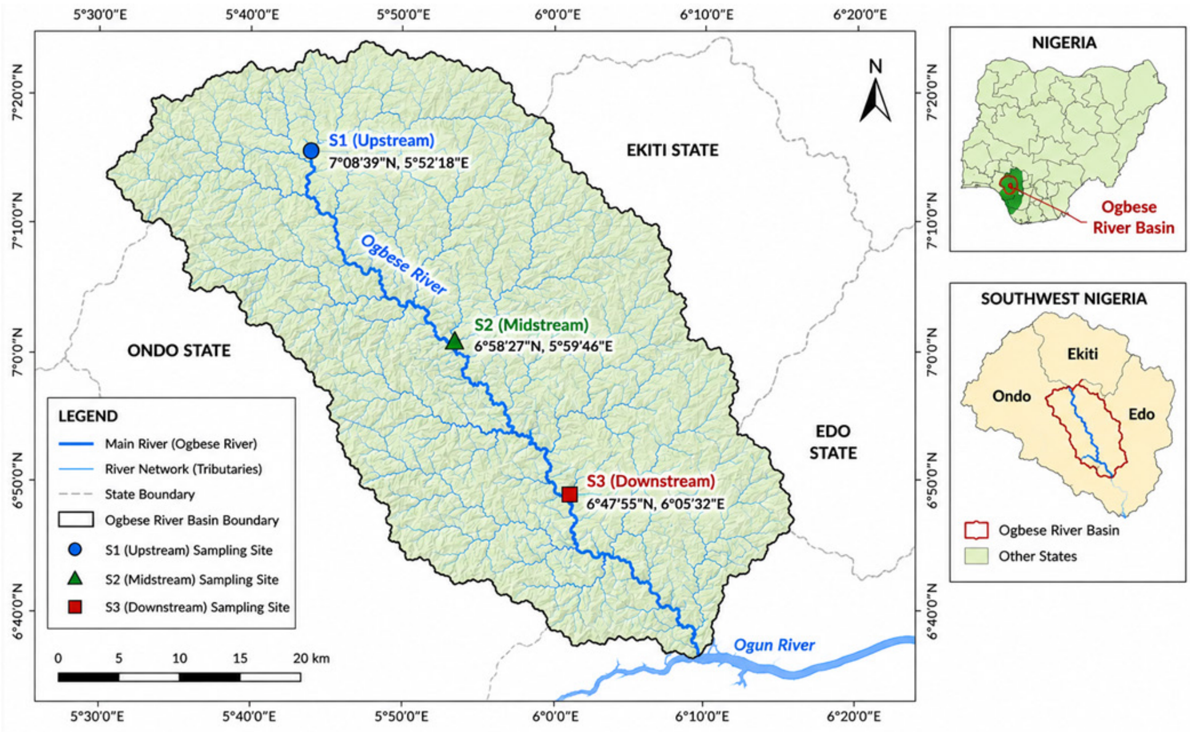

Figure 1: Ogbese River Basin showing the river network and sampling locations (S1–S3)

Sampling Design and Data Collection

A structured sampling design was adopted to capture spatial and temporal variations in hydrological and water quality characteristics within the Ogbese River Basin. Data were collected monthly throughout the study period and subsequently grouped into wet-season and dry-season categories for comparative analyses. Water samples were collected monthly at the three monitoring stations (S1–S3) from January 2021 to December 2023, yielding 108 site observations (36 observations per station). Three representative sampling locations were selected along the river continuum based on land-use characteristics and potential pollution sources: S1 (Upstream): Located in a relatively undisturbed area with minimal anthropogenic influence, serving as a reference condition. S2 (Midstream): Influenced primarily by agricultural activities, including crop cultivation and fertilizer application. S3 (Downstream): Situated near peri-urban settlements, characterized by increased human activities, wastewater inputs, and land-use disturbances.

Hydrological data included rainfall (mm), river discharge (m^3/s), and evapotranspiration (mm). Rainfall was measured using standard rain gauges installed within the basin, while river discharge was determined using a calibrated current meter following established hydrometric procedures. Evapotranspiration was estimated using Class A evaporation pan measurements, with appropriate correction factors applied. Water sampling was conducted seasonally at all sites to capture variations between wet and dry periods. Samples were collected following standard protocols to minimize contamination. Pre-cleaned polyethylene bottles were used for sample collection, and samples were preserved and transported to the laboratory under controlled conditions. For metal analysis, samples were acidified immediately after collection, while microbial samples were stored at low temperatures and analyzed within the recommended holding time.

In situ measurements of key parameters such as pH, temperature, and electrical conductivity (EC) were conducted at the time of sampling using calibrated portable meters. This approach ensured that field conditions were accurately captured and minimized potential alterations during sample transport. The sampling design integrates both spatial gradients (upstream–downstream) and temporal variability (seasonal and interannual), providing a comprehensive dataset suitable for hydrological analysis, water quality assessment, and multivariate statistical evaluation.

Laboratory Analysis

Water samples collected from the three sampling sites were analyzed for physicochemical, heavy metal, and microbiological parameters using standard methods to ensure accuracy, reliability, and comparability of results. Physicochemical parameters, including pH, electrical conductivity (EC), total dissolved solids (TDS), dissolved oxygen (DO), and biochemical oxygen demand (BOD_5), were determined following procedures outlined by the American Public Health Association (APHA, 2017). pH and EC were measured using calibrated digital meters, while TDS was derived from conductivity measurements using standard conversion factors. Dissolved oxygen was determined using an electrochemical probe, and BOD_5 was measured using the 5-day incubation method at 20°C. Heavy metal concentrations, including lead (Pb), cadmium (Cd), and iron (Fe), were determined after acid digestion of water samples using standard analytical procedures. Quantification was carried out using atomic absorption spectrophotometry (AAS), with appropriate calibration standards and detection limits (Abba *et al.,* 2022; Li *et al.,* 2022). All reagents used were of analytical grade, and deionized water was employed throughout the analysis. Microbiological analysis focused on Escherichia coli and total coliforms, which were determined using the membrane filtration technique. Water samples were filtered through sterile membrane filters, which were then incubated on selective culture media under controlled conditions. Colony counts were recorded and expressed as colony-forming units per 100 mL (CFU/100 mL).

Quality assurance and quality control (QA/QC) procedures were strictly followed throughout the analysis. These included calibration of instruments before use, analysis of reagent blanks, duplicate sampling, and use of standard reference materials where applicable. These measures ensured the precision and reliability of analytical results. All laboratory analyses were conducted within recommended holding times to prevent sample degradation, particularly for microbiological parameters, which were analyzed within 24 hours of collection.

Statistical and Hydrological Analyses

A combination of descriptive statistics, non-parametric tests, and advanced hydrological and multivariate analytical techniques was employed to evaluate seasonal variability, temporal trends, and relationships between hydrological and water quality parameters in the Ogbese River Basin.

Descriptive and Comparative Statistics

Descriptive statistics, including mean, minimum, maximum, standard deviation (SD), and coefficient of variation (CV%), were used to summarize the distribution and variability of hydrological and water quality parameters across seasons. To assess seasonal differences between wet and dry periods, the Mann–Whitney U test was applied. This non-parametric test was selected due to the non-normal distribution commonly observed in environmental datasets and provides a robust comparison of median values between two independent groups.

Trend Analysis

Temporal trends in rainfall, discharge, turbidity, and Escherichia coli were evaluated using the Mann–Kendall (MK) test and Sen's slope estimator. The Mann–Kendall test was used to determine the statistical significance of monotonic trends, while Sen's slope provided a robust estimate of trend magnitude. These methods are widely used in hydrological studies due to their resistance to outliers and suitability for non-normally distributed data. Statistical significance was assessed at the 95% confidence level ($p < 0.05$).

Flow Duration Curve (FDC) Analysis

Flow duration curves (FDCs) were developed to characterize discharge variability and hydrological regime behavior. Discharge values were ranked in descending order, and the exceedance probability was calculated using the Weibull plotting position:

$$P = (m / (n + 1)) \times 100$$

where P is the exceedance probability (%), m is the rank of the discharge value, and n is the total number of observations. Characteristic flows, including Q_{10} (high flow), Q_{50} (median flow), and Q_{90} (low flow), were derived from the FDC to represent different flow conditions.

Cross-Correlation Analysis

Cross-correlation functions (CCF) were used to examine the temporal relationships between rainfall and selected water quality parameters, specifically turbidity and Escherichia coli. Correlation coefficients were computed across a range of time lags to identify response times and lag effects. Positive lag values indicate delayed responses of water quality variables to rainfall, while peak correlation coefficients identify the most influential lag period. This analysis provides insight into hydrological connectivity and contaminant transport mechanisms.

Principal Component Analysis (PCA)

Principal Component Analysis (PCA) was applied to standardized variables as an exploratory dimension-reduction tool for identifying dominant controls on water quality variability. Prior to analysis, variables were normalized to zero mean and unit variance to reduce scale effects. Components were interpreted based on variance contribution, loading structure, and hydro-environmental plausibility, rather than as definitive source-apportionment results. This cautious interpretation is appropriate for short-term environmental datasets from data-scarce basins.

Hydrological Regime Assessment

Hydrological variability was evaluated using seasonal analysis, trend detection, and flow duration curve interpretation. Given the relatively short duration of the dataset, formal breakpoint or regime-shift detection was not attempted; instead, the analysis was restricted to exploratory assessment of changes in variability, magnitude, and seasonal response.

Software and Data Processing

All statistical analyses and graphical visualizations were performed using SPSS Version 25 tools and standard data processing software. This ensured reproducibility, accuracy, and consistency across all analyses.

RESULTS AND DISCUSSION

Seasonal Hydrological Dynamics

Seasonal variations in hydrological parameters within the Ogbese River Basin are summarized in Table 1 and illustrated in Figures 2 and 3. The results reveal a strongly seasonal hydrological regime characteristic of humid tropical catchments, with clear contrasts between wet and dry season conditions.

Rainfall exhibited a marked seasonal increase from a mean value of 32.80 mm in the dry season to 230.03 mm during the wet season, representing an approximately seven-fold increase (Table 1). The high coefficient of variation observed in the dry season (CV = 53.24%) indicates irregular and episodic rainfall events, whereas the lower variability in the wet season (CV = 26.15%) reflects more

Table 1: Seasonal descriptive statistics of hydrological parameters in the Ogbese River Basin (2021–2023)

Season	Parameter	Mean	Min	Max	SD	CV (%)
Dry	Rainfall (mm)	32.80	2.00	59.00	17.46	53.24
	Discharge (m^3/s)	14.20	5.73	24.46	5.55	39.09
	Evapotranspiration (mm)	120.86	90.76	152.80	21.07	17.44
Wet	Rainfall (mm)	230.03	122.00	318.00	60.15	26.15
	Discharge (m^3/s)	47.05	25.11	64.39	12.04	25.58
	Evapotranspiration (mm)	87.63	60.86	115.96	17.23	19.66

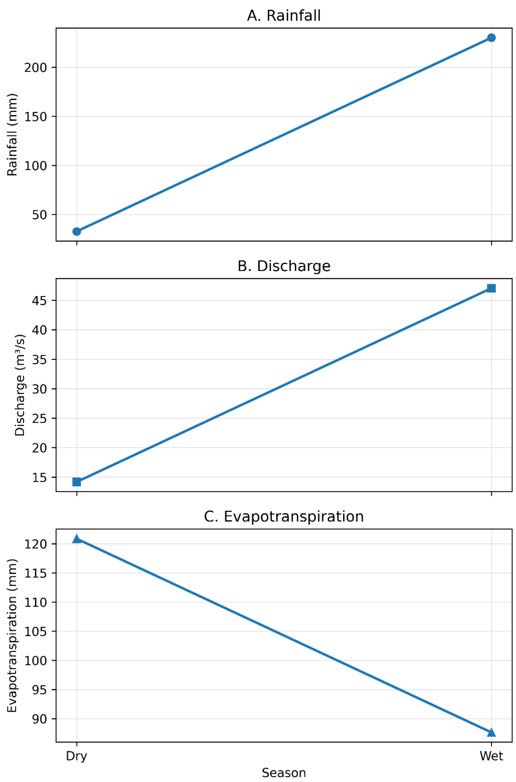

Figure 2: Seasonal variation of rainfall, discharge, and evapotranspiration in the Ogbese River Basin (2021–2023)

sustained and consistent precipitation associated with the northward migration of the Intertropical Convergence Zone (ITCZ).

River discharge responded strongly to this rainfall pattern, increasing from a mean of 14.20 m^3/s in the dry season to 47.05 m^3/s in the wet season (Table 1), corresponding to more than a threefold increase in flow. This amplification of discharge relative to rainfall suggests efficient runoff generation and rapid catchment response during the wet season.

Rainfall and discharge are higher during the wet season, whereas evapotranspiration is higher in the dry season, indicating strong climatic control on hydrological processes.

The rainfall–discharge relationship is further illustrated in Figure 3, where peak discharge coincides with elevated rainfall, indicating a direct hydrological linkage between precipitation input and streamflow. The higher variability in discharge during the dry season (CV = 39.09%) compared to the wet season (CV = 25.58%) reflects the sensitivity of baseflow conditions to limited and irregular rainfall inputs.

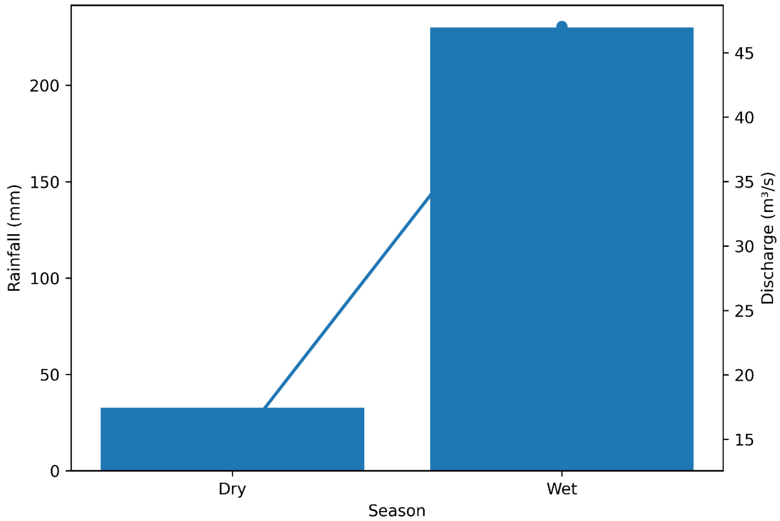

Figure 3: Seasonal hydrograph of rainfall and river discharge in the Ogbese River Basin (2021–2023)

Rainfall is represented as bars and discharge as a line plot, showing a strong seasonal response of river flow to precipitation input.

Evapotranspiration exhibited an inverse seasonal pattern, with higher mean values during the dry season (120.86 mm) compared to the wet season (87.63 mm) (Table 1). This trend is consistent with increased solar radiation, higher temperatures, and reduced cloud cover during the dry season, which enhance atmospheric evaporative demand. The relatively low variability of evapotranspiration across seasons (CV = 17.44% in the dry season and 19.66% in the wet season) suggests that evapotranspiration is primarily controlled by atmospheric energy balance rather than short-term hydrological fluctuations. Statistical analysis using the Mann–Whitney U test confirmed that seasonal differences in rainfall, discharge, and evapotranspiration are highly significant ($p < 0.001$), demonstrating the dominant influence of climatic forcing on basin hydrology.

Overall, the results highlight a hydrological regime characterized by strong wet-season flow dominance and dry-season flow limitation. Similar seasonal dynamics have been reported in tropical river systems, where precipitation variability governs discharge and catchment response (Lapworth *et al.,* 2017; Masindi & Foteinis, 2023; Li *et al.,* 2014; Gao *et al.,* 2023). The pronounced increase in discharge during the wet season suggests enhanced surface runoff and potential mobilization of sediments and pollutants, while reduced dry-season flows may lead to decreased dilution capacity and increased vulnerability to water quality deterioration (Alkhadher *et al.,* 2025). From a water resource perspective, these findings underscore the importance of seasonally adaptive management strategies. The strong coupling between rainfall and discharge, combined with the contrasting behavior of evapotranspiration, highlights the need for integrated hydrological monitoring to support sustainable water use, pollution control, and ecosystem protection within the basin.

Seasonal Water Quality Dynamics

Seasonal variations in physicochemical, heavy metal, and microbial water quality parameters in the Ogbese River Basin are summarized in Table 2 and illustrated in Figures

Table 2: Seasonal descriptive statistics of physicochemical, heavy metal, and microbial water quality parameters in the Ogbese River Basin (2021–2023)

Season	Parameter	Mean	Min	Max	SD	CV_%
Dry	pH	7.3133	6.841	7.774	0.297387	4.066386

Wet	pH	6.840767	6.471	7.169	0.217016	3.172399
Dry	EC_uScm	252.1592	123.16	372.092	79.76064	31.63106
Wet	EC_uScm	103.0451	52.637	147.585	28.86551	28.0125
Dry	TDS_mgL	158.1384	77.769	249.395	51.67313	32.67589
Wet	TDS_mgL	72.64	36.837	99.781	17.79463	24.49701
Dry	DO_mgL	4.464633	3.044	5.696	0.752695	16.85906
Wet	DO_mgL	5.552067	4.024	7.455	1.085018	19.5426
Dry	BOD5_mgL	4.202267	2.282	5.819	0.97415	23.18153
Wet	BOD5_mgL	5.4345	3.347	7.934	1.513438	27.8487
Dry	Turbidity_NTU	30.13063	8.697	49.988	13.56788	45.03017
Wet	Turbidity_NTU	84.49797	26.533	154.761	38.7867	45.90252
Dry	Pb_mgL	0.118433	0.041	0.179	0.042714	36.06561
Wet	Pb_mgL	0.038767	0.021	0.073	0.015312	39.49815
Dry	Cd_mgL	0.006567	0.003	0.01	0.002079	31.66264
Wet	Cd_mgL	0.003667	0.001	0.006	0.001516	41.3508
Dry	Fe_mgL	0.345167	0.112	0.583	0.12965	37.5617
Wet	Fe_mgL	0.7833	0.257	1.559	0.395129	50.44421
Dry	Ecoli_CFU100mL	314.3	82	487	138.1289	43.94811
Wet	Ecoli_CFU100mL	931.7	406	1551	351.0294	37.67623
Dry	TotalColiforms_CFU100mL	1337.533	410	2854	720.7614	53.88736
Wet	TotalColiforms_CFU100mL	4002.2	930	7727	2303.906	57.56598

4 and 5. The results indicate a strong seasonal influence on water quality, driven primarily by hydrological processes and anthropogenic activities within the basin.

Physicochemical Characteristics

The seasonal behavior of key physicochemical parameters in the Ogbese River Basin is summarized in Table 2 and

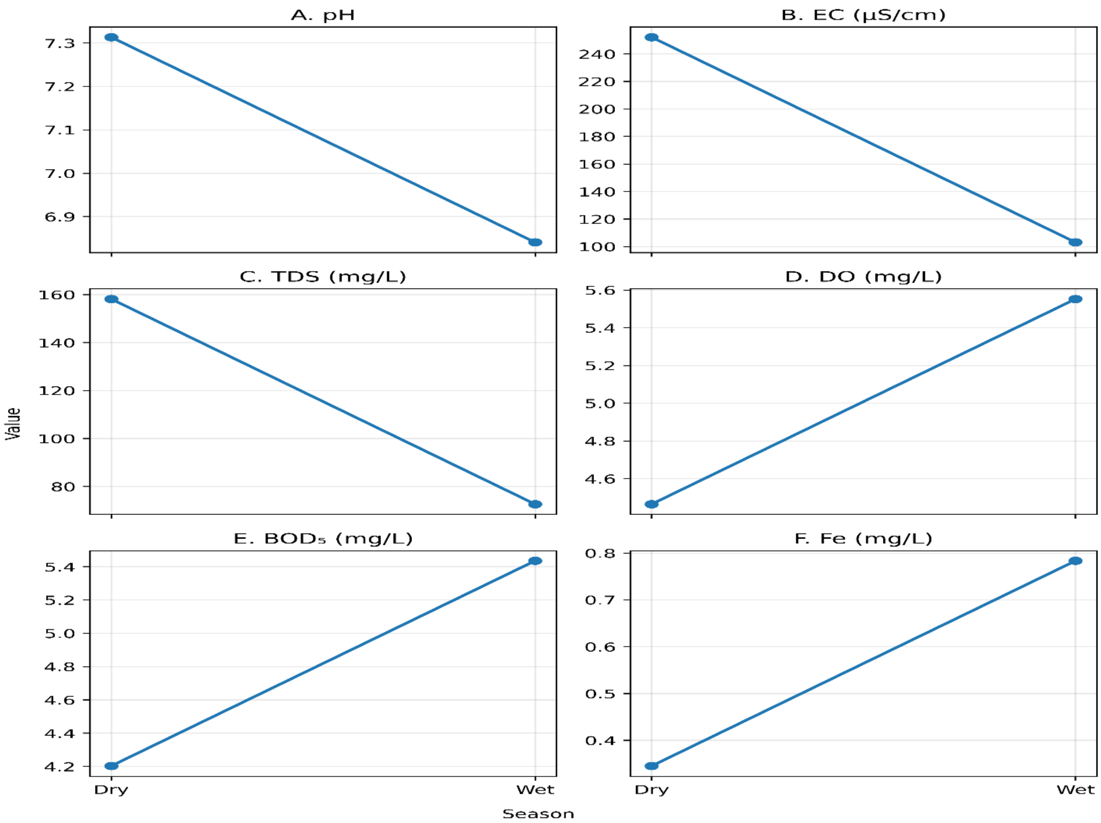

Figure 4: Seasonal variation of key physicochemical parameters (pH, EC, TDS, DO, BOD_5, and Fe) illustrating hydrological control on water quality in the Ogbese River Basin (2021–2023)

illustrated in Figure 4. The results reveal clear seasonal contrasts driven primarily by hydrological processes, particularly rainfall variability, runoff generation, and dilution effects.

The pH values remained within a slightly alkaline range across both seasons, with a marginal decrease during the wet season (Figure 4A). This shift reflects dilution of alkaline constituents by increased rainfall and runoff during the wet period. The relatively low coefficient of variation (CV < 5%) indicates that pH is stable and largely controlled by the buffering capacity of the basin, suggesting limited influence from short-term anthropogenic inputs.

Electrical conductivity (EC) and total dissolved solids (TDS) exhibited higher mean values during the dry season (Figure 4B and 4C), indicating concentration of dissolved ions under low-flow conditions. Reduced discharge during the dry season limits dilution, allowing dissolved minerals and ions derived from rock–water interaction and anthropogenic sources to accumulate. Conversely, the observed decrease in EC and TDS during the wet season reflects dilution effects associated with increased water volume. This inverse relationship between discharge and solute concentration is typical of tropical river systems and indicates strong hydrological control on ionic composition. Dissolved oxygen (DO) showed an increase during the wet season (Figure 4D), likely due to enhanced aeration resulting from higher flow velocities and turbulence. Increased mixing during high-flow conditions promotes oxygen diffusion into the water column. In contrast, lower DO values during the dry season may be associated with reduced flow, higher temperatures, and increased residence time, which can limit oxygen replenishment.

Biochemical oxygen demand (BOD_5) exhibited higher values during the wet season (Figure 4E), suggesting increased input of biodegradable organic matter transported through surface runoff. This pattern indicates that rainfall events facilitate the transfer of organic pollutants from surrounding land areas into the river system. The simultaneous increase in BOD_5 and DO during the wet season suggests a dynamic balance between organic loading and oxygen replenishment driven by hydrological conditions. Turbidity showed a pronounced seasonal increase, rising significantly during the wet season (Table 2), reflecting enhanced erosion, sediment mobilization, and transport processes. Elevated turbidity levels are indicative of increased surface runoff and land disturbance, particularly in areas influenced by agriculture and sand mining activities. The high coefficient of variation for turbidity (>45%) in both seasons further highlights the influence of episodic rainfall events and localized disturbances on sediment dynamics.

Overall, the physicochemical characteristics of the basin demonstrate a clear seasonal pattern controlled by the interplay between dilution during high-flow conditions and concentration during low-flow periods. These findings are consistent with previous studies in tropical environments, where rainfall-driven hydrological processes govern water chemistry (Li *et al.,* 2014; Gao *et al.,* 2023). The observed relationships between discharge, solute concentration, and sediment load emphasize the sensitivity of the basin to climatic variability and highlight the importance of hydrological processes in shaping water quality dynamics.

Heavy Metals and Microbial Contamination

Seasonal variations in heavy metal concentrations and microbial indicators in the Ogbese River Basin are presented in Table 2 and illustrated in Figures 4 and 5. The results indicate that both geogenic processes and anthropogenic activities contribute to water quality deterioration, with strong seasonal modulation driven by hydrological conditions.

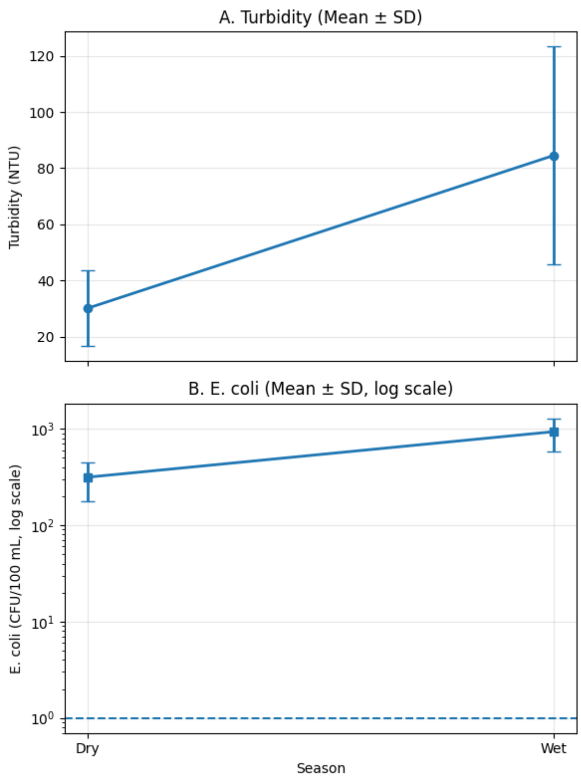

Figure 5: Seasonal variation of turbidity and Escherichia coli concentrations in the Ogbese River Basin (2021-2023), showing mean ± SD and exceedance of WHO guideline values for drinking water

Heavy metal concentrations exhibited moderate variability across seasons. Iron (Fe) increased during the wet season (Figure 4F), suggesting enhanced mobilisation of geogenic materials through weathering, soil erosion, and surface runoff. This seasonal enrichment is typical of tropical environments, where intense rainfall promotes the transport of iron-bearing particles from surrounding lithology into surface waters. In contrast, lead (Pb) and cadmium (Cd) were of greater toxicological concern because their mean concentrations exceeded WHO drinking-water guideline values in both seasons. Mean Pb concentrations were 0.118 mg L-1 in the dry season and 0.039 mg L-1 in the wet season, both above the WHO guideline value of 0.01 mg L-1. Mean Cd concentrations were 0.0066 mg L-1 in the dry season and 0.0037 mg L-1 in the wet season, also exceeding the WHO guideline value of 0.003 mg L-1. These exceedances suggest persistent trace-metal contamination, probably linked to local anthropogenic inputs such as mechanical activities, agrochemical residues, waste disposal, and runoff from disturbed land surfaces. Because Pb and Cd are persistent and bioaccumulative, their occurrence requires continuous monitoring and risk communication, even where concentrations vary seasonally.

Microbial contamination exhibited the most pronounced seasonal variation among all water quality parameters. Escherichia coli concentrations increased significantly from a mean value of 314.30 CFU/100 mL in the dry season to 931.70 CFU/100 mL during the wet season (Table 2; Figure 5B). Similarly, total coliform counts showed a substantial increase during the wet season, indicating widespread fecal contamination. These values far exceed the World Health Organization (WHO) guideline of 0 CFU/100 mL for drinking water, indicating that the water is unsuitable for direct consumption without treatment. The elevated microbial loads during the wet season are primarily attributed to rainfall-driven runoff, which transports fecal matter from surrounding land surfaces into the river system. Potential sources include open defecation, livestock waste, poorly managed sanitation facilities, and agricultural runoff. The strong seasonal increase highlights the vulnerability of the basin to contamination during periods of high rainfall.

A clear relationship between turbidity and microbial contamination is evident, as both parameters increase concurrently during the wet season (Figure 5). Suspended sediments provide surfaces for microbial attachment, enhancing the transport, survival, and persistence of pathogens in aquatic environments. This interaction underscores the role of sediment dynamics in influencing microbial water quality and highlights the importance of integrated hydrological and water quality assessments. Statistical analysis using the Mann–Whitney U test confirmed that seasonal differences in microbial indicators and turbidity are highly significant ($p < 0.001$), reinforcing the dominant role of hydrological processes in controlling contaminant transport. The combined influence of surface runoff, sediment mobilization, and anthropogenic inputs explains the observed seasonal variability.

The findings are consistent with previous studies in sub-Saharan Africa, where inadequate sanitation infrastructure and intense rainfall contribute to elevated microbial contamination in water sources (Bain *et al.,* 2021; Masindi & Foteinis, 2023). The persistent exceedance of microbial standards, even during the dry season, indicates chronic contamination and underscores the need for improved sanitation practices and water treatment interventions. From a public health perspective, the high levels of E. coli and total coliforms represent a significant risk of waterborne diseases, particularly for communities relying on untreated surface water. The seasonal amplification of contamination during the wet season further emphasizes the need for targeted risk management strategies, including improved sanitation infrastructure, watershed protection, and routine water quality monitoring.

Public Health and WASH Implications of Microbial and Metal Contamination

The microbial results have direct public-health implications because E. coli and total coliforms exceeded the WHO guideline value of 0 CFU/100 mL for drinking water in both seasons. Such contamination indicates faecal pollution and potential exposure to enteric pathogens associated with diarrhoea, cholera, typhoid fever, dysentery, and gastroenteritis, particularly among children, older adults, and immunocompromised individuals. The wet-season amplification of E. coli and turbidity suggests that rainfall events increase the risk of pathogen transport from open defecation sites, livestock areas, poorly managed sanitation facilities, and agricultural land into the river. The concurrent exceedance of Pb and Cd guideline values further raises concern because these metals are persistent, toxic, and capable of long-term accumulation. From a WASH perspective, untreated river water should not be used for drinking without treatment. Priority interventions include household water treatment, protection of riparian zones, improved sanitation coverage, safe disposal of faecal waste, community health education, and routine microbial and chemical monitoring before and after major rainfall events.

Hydrology–Water Quality Relationships

The relationships between hydrological processes and water quality parameters in the Ogbese River Basin were examined to identify the dominant mechanisms controlling water quality variability. The results reveal strong interactions between rainfall, discharge, physicochemical parameters, and microbial indicators, reflecting the combined influence of hydrological dynamics and anthropogenic inputs. A strong positive relationship was observed between rainfall and river discharge, confirming that precipitation is the primary driver of hydrological response within the basin. This relationship, previously illustrated in Figures 2 and 3, underpins many of the observed water quality patterns. Increased rainfall during the wet season enhances surface runoff, which in turn influences sediment transport, solute dilution, and contaminant mobilization.

Turbidity increased concurrently with discharge and wet-season rainfall, suggesting that sediment transport is strongly influenced by runoff processes. During periods of high discharge, increased erosion and runoff mobilize suspended particles into the river system, resulting in elevated turbidity levels. This finding is consistent with the seasonal patterns presented in Figure 4, where turbidity peaks during the wet season. Microbial indicators, particularly Escherichia coli, also showed a positive relationship with both rainfall and turbidity. This suggests that rainfall-driven runoff facilitates the transport of fecal contaminants into the river system, while suspended sediments provide surfaces for microbial attachment and persistence (Pakoksung et al 2025). The coupling between turbidity and microbial contamination highlights the role of sediment-associated transport mechanisms in controlling pathogen dynamics.

In contrast, electrical conductivity (EC) and total dissolved solids (TDS) decreased during periods of higher discharge, indicating dilution effects under wet-season flow conditions. As discharge increases during the wet season, the concentration of dissolved ions decreases due to increased water volume, whereas lower flows in the dry season promote concentration of solutes. This inverse relationship confirms the dominant role of hydrological dilution in regulating ionic composition. Dissolved oxygen (DO) showed a positive relationship with discharge, likely due to enhanced aeration under turbulent flow conditions. Conversely, biochemical oxygen demand (BOD_5) demonstrated a positive association with turbidity and rainfall, indicating that organic matter inputs are linked to runoff processes. The simultaneous increase in BOD_5 and microbial indicators during the wet season suggests that organic pollution and fecal contamination share common sources, primarily surface runoff from anthropogenic activities.

Heavy metals, particularly iron (Fe), showed moderate positive correlations with turbidity and discharge, suggesting that their transport is influenced by particulate-bound processes. This indicates that metal mobilization is partly controlled by erosion and sediment transport, rather than solely by dissolved-phase processes. Overall, the correlation patterns indicate that groundwater and surface water quality in the basin are governed by two dominant mechanisms: (i) dilution–concentration processes driven by seasonal hydrological variability, and (ii) contaminant mobilization associated with rainfall-induced runoff and sediment transport. These processes operate simultaneously and interact to shape the observed spatial and temporal variability in water quality.

The observed relationships are consistent with findings from similar hydrogeochemical studies, where runoff-driven transport and dilution effects are identified as key controls on water quality dynamics (Helena *et al.,* 2000; Li *et al.,* 2014; Pakoksung et al 2025). The strong coupling between hydrology and water quality highlights the importance of integrated analysis in understanding basin-scale environmental processes. From a management perspective, the results emphasize that water quality deterioration is closely linked to hydrological events, particularly during the wet season. Therefore, effective water resource management strategies should focus on controlling runoff pathways, reducing sediment transport, and minimizing contamination from anthropogenic sources. Implementing best management practices in agriculture, improving sanitation infrastructure, and protecting riparian zones are critical measures for reducing pollutant inputs and improving water quality.

Advanced Hydrological Analyses

Seasonal Trend Detection

Temporal trends in key hydrological and water quality parameters were evaluated using non-parametric methods, including Sen's slope estimator and Kendall's tau, to determine the magnitude and statistical significance of seasonal variations. The results are presented in Table 3 and illustrated in Figures 6 and 7.

The seasonal time-series patterns of rainfall, discharge, turbidity, and Escherichia coli are shown in Figure 6, where observed data are overlaid with Sen's slope trend lines. Rainfall exhibited a statistically significant increasing trend (Sen's slope = 1.13, p = 0.017), indicating a gradual intensification of precipitation over the study period. This increasing tendency is evident in Figure 6, where higher rainfall peaks are observed in successive wet seasons. River discharge showed a positive but non-significant trend (Sen's slope = 0.23, p = 0.103), closely reflecting rainfall variability. The similarity in trend patterns between rainfall and discharge confirms strong hydrological coupling within the basin, indicating that precipitation remains the primary driver of streamflow dynamics.

Table 3: Seasonal trend statistics for rainfall, discharge, turbidity, and Escherichia coli based on Sen's slope and p-values

Parameter	Sen's slope	p-value
Rainfall	1.13	0.017
Discharge	0.23	0.103
Turbidity	0.36	0.095
E. coli	3.27	0.144

Turbidity exhibited a moderate increasing trend (Sen's slope = 0.36, p = 0.095), suggesting progressive intensification of sediment transport processes. Although not statistically significant at the 95% confidence level, the upward tendency indicates increasing erosion and runoff-driven sediment mobilization, particularly during the wet season. Similarly, Escherichia coli concentrations showed an increasing trend (Sen's slope = 3.27, p = 0.144), with substantial variability across seasons. This pattern reflects the influence of episodic rainfall events and localized contamination sources, which contribute to fluctuations in microbial water quality. The overall magnitude and direction of these trends are summarized in Figure 7, which presents Sen's slope estimates for all

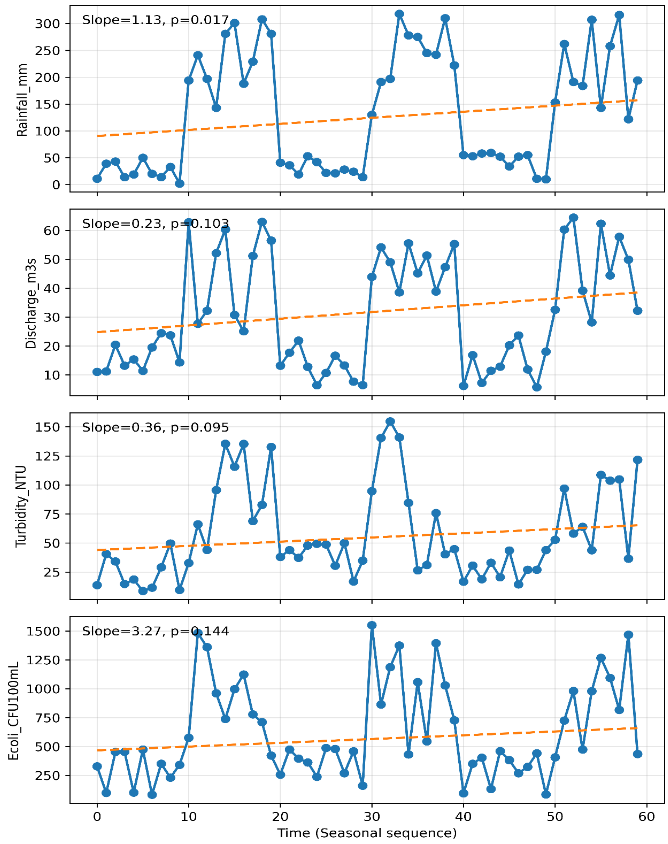

Figure 6: Seasonal time-series plots of rainfall, discharge, turbidity, and Escherichia coli in the Ogbese River Basin (2021–2023), with Sen's slope trend lines

variables alongside their corresponding p-values. The figure clearly indicates that rainfall exhibits the strongest and statistically significant upward trend, while discharge, turbidity, and E. coli display positive but non-significant tendencies.

The combined interpretation of Table 3 and Figures 6 and 7 reveals a consistent pattern of increasing hydrological intensity and associated water quality responses. While only rainfall shows a statistically significant trend, the concurrent positive tendencies observed in discharge, turbidity, and microbial contamination suggest an emerging trajectory toward greater hydrological variability and potential water quality deterioration (Saturday *et al.,* 2025).. These findings are consistent with previous studies reporting increasing hydrological variability and associated environmental impacts in tropical river

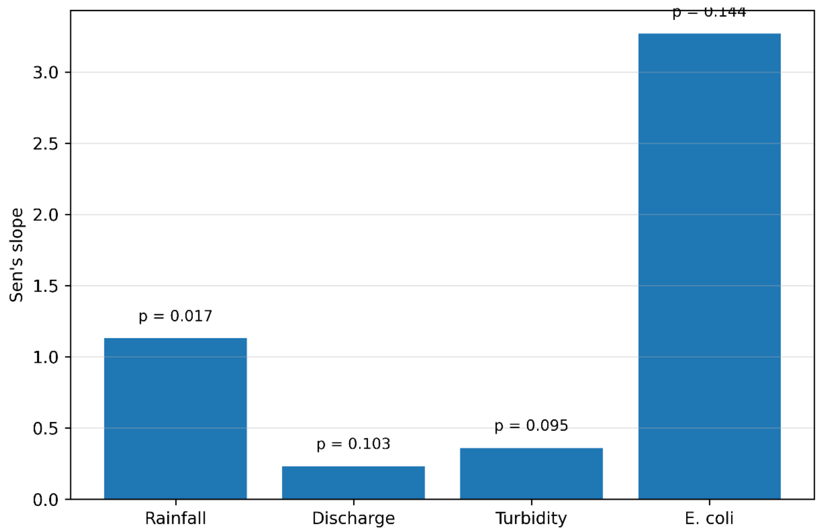

Figure 7: Sen's slope estimates with corresponding p-values for rainfall, discharge, turbidity, and Escherichia coli in the Ogbese River Basin

systems under changing climatic and land-use conditions (Masindi & Foteinis, 2023; Qin *et al.,* 2023). The results underscore the importance of continuous monitoring and adaptive management strategies to mitigate the impacts of evolving hydrological regimes on water resources and public health.

Flow Duration Curves (FDC)

Flow duration curves (FDCs) were developed to characterize the variability and reliability of river discharge in the Ogbese River Basin and to provide insight into the hydrological behavior of the system across different flow conditions. The FDC represents the percentage

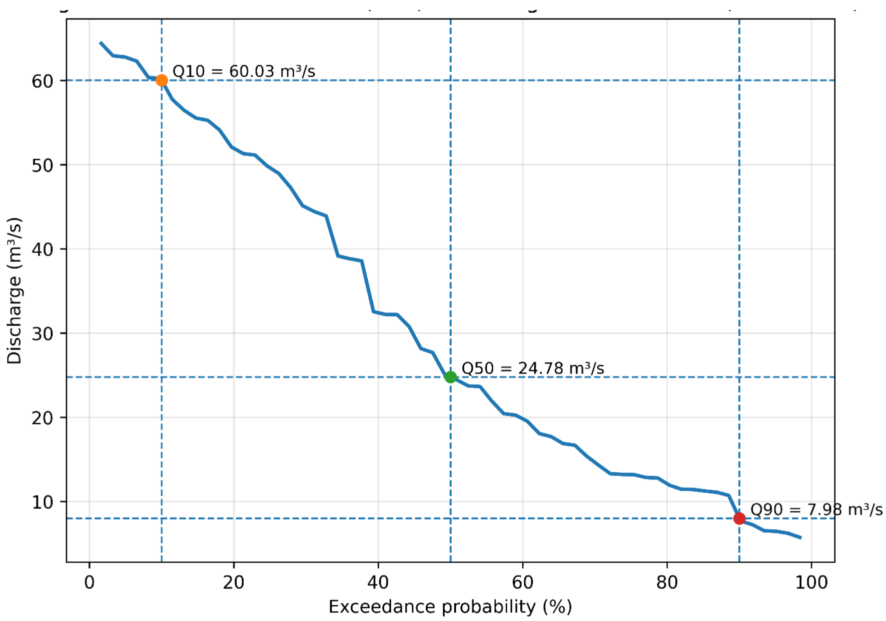

Figure 8: Flow duration curve (FDC) for river discharge in the Ogbese River Basin (2021-2023), showing discharge magnitude and exceedance probability

of time that specific discharge values are equaled or exceeded, thereby integrating both high-flow and low-flow characteristics into a single framework.

The FDC (Figure 8) exhibits a steep slope in the upper segment (low exceedance probabilities), indicating high variability in peak flows. This suggests rapid hydrological response to rainfall events and short-duration, high-magnitude discharge peaks during the wet season. In contrast, the lower segment of the curve (high exceedance probabilities) shows reduced discharge persistence during low-flow conditions. Because no formal baseflow separation was performed, this pattern should be interpreted cautiously as evidence of limited low-flow persistence rather than a definitive estimate of groundwater contribution. The result is consistent with the seasonal hydrological dynamics described in Section 3.1, where reduced rainfall during the dry season leads to diminished flow and lower dilution capacity.

The mid-section of the FDC represents intermediate flows and provides insight into overall flow regime stability. The moderate slope observed in this region indicates transitional behavior between storm-driven flows and baseflow conditions. This suggests that the basin exhibits mixed hydrological control, with both direct runoff and subsurface contributions influencing discharge under varying conditions. The wide range between high-flow and low-flow conditions reflects significant hydrological variability within the basin. Such variability has important implications for water resource management, including water supply reliability, sediment transport, and contaminant dilution capacity. High-flow events enhance sediment mobilization and pollutant transport, while low-flow conditions may lead to concentration of contaminants due to reduced dilution.

The characteristics of the FDC are consistent with findings from similar tropical river systems, where strong seasonality and rainfall-driven runoff dominate hydrological behaviour (Li *et al.,* 2014; Vogel and Fennessey, 1994). The reduced persistence of low flows highlights the basin's sensitivity to climatic variability and potential vulnerability to prolonged dry periods. Overall, the FDC analysis complements the seasonal and trend analyses by showing how the river alternates between high-flow transport conditions and low-flow periods with reduced dilution capacity.

From a water resource management perspective, the FDC provides valuable operational information. High-flow thresholds can inform flood hazard assessments and early warning systems, while low-flow statistics support drought management planning and environmental flow allocation. For the Ogbese River Basin, the marked disparity between high- and low-flow conditions emphasizes the need for integrated catchment management strategies that address both flood risk mitigation and dry-season water security. Similar hydrological responses characterized by increasing discharge variability, steep high-flow gradients, and extended low-flow durations have been documented in other southwestern Nigerian basins such as Ogun

(Akinyemi *et al.,* 2022) and Osun (Ayeni *et al.,* 2023). This consistency supports the interpretation that observed changes in the Ogbese River are part of a broader regional hydroclimatic signal affecting West African river systems.

Cross-Correlation Between Rainfall and Water Quality

Cross-correlation analysis was performed to evaluate the temporal relationships between rainfall and key water quality parameters, including turbidity and Escherichia coli, with the aim of identifying lag effects and understanding the response time of the river system to precipitation events. This approach provides insight into the dynamic coupling between hydrological processes and contaminant transport.

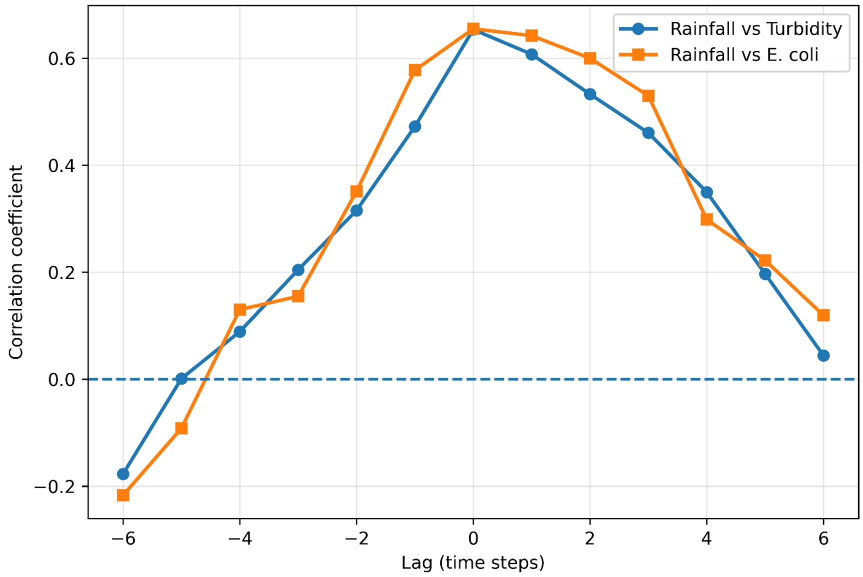

Figure 9: Cross-correlation functions (CCF) between rainfall and selected water quality parameters (turbidity and Escherichia coli) in the Ogbese River Basin

The cross-correlation results (Figure 9) reveal strong positive correlations between rainfall and turbidity at short time lags, with peak correlation occurring at lag 0 to lag 1. This indicates that turbidity responds almost immediately to rainfall events, reflecting rapid mobilization of sediments through surface runoff. Such near-instantaneous response suggests that the basin is highly responsive to precipitation, with limited delay between rainfall input and sediment transport. Similarly, E. coli concentrations exhibit positive correlations with rainfall, with peak correlation observed at short lags (lag 0–2). This pattern indicates that microbial contamination is closely linked to rainfall-driven runoff processes, which transport fecal matter from surrounding land surfaces into the river system. The slightly delayed peak compared to turbidity suggests that microbial transport may involve additional processes, such as infiltration, resuspension, or delayed runoff pathways.

The rapid response observed for both turbidity and E. coli highlights the dominance of overland flow and direct runoff in controlling water quality dynamics within the basin. These findings are consistent with the seasonal patterns observed in Section 3.2 and the hydrological responses described in Section 3.1, where increased rainfall leads to elevated sediment loads and microbial contamination. At longer time lags, the correlation coefficients decline significantly, indicating reduced influence of rainfall on water quality parameters beyond short-term responses. This suggests that the system lacks substantial storage or delayed-release mechanisms, such as strong groundwater contributions, and is primarily driven by event-based hydrological processes.

The strong coupling between rainfall and water quality at short time scales has important implications for water resource management. It indicates that contamination events are closely tied to rainfall occurrences, particularly during the wet season, and that water quality can deteriorate rapidly following precipitation events. This highlights the need for real-time monitoring and early warning systems to manage water quality risks. The observed lag relationships are consistent with findings from similar studies in tropical environments, where rapid runoff processes and limited catchment storage result in short response times between rainfall and water quality changes (Boateng *et al.,* 2022; Helena *et al.,* 2000; Li *et al.,* 2014). The results further emphasize the importance of integrating hydrological and water quality analyses to better understand system behavior. Overall, the cross-correlation analysis demonstrates that the Ogbese River Basin exhibits a rapid and direct response to rainfall, with minimal lag between precipitation and water quality deterioration. This reinforces the vulnerability of the system to contamination during rainfall events and underscores the importance of implementing effective watershed management and pollution control strategies.

From a management perspective, the early detection of these patterns emphasizes the importance of sustained hydrological monitoring that integrates both flow and climate data. Incorporating socio-environmental factors such as land-cover change, population growth, sanitation coverage, and water-use statistics would further improve attribution of observed trends to their underlying drivers.

Exploratory Assessment of Hydrological Variability

Exploratory assessment of hydrological variability was conducted to examine changes in the behaviour of key hydrological and water quality variables within the Ogbese River Basin. Given the short study period (2021-2023), the analysis focused on changes in variability, magnitude, and seasonal behaviour rather than formal detection of statistical breakpoints.

The time-series patterns do not indicate any abrupt or statistically distinct change during the study period. Instead, the results suggest a hydrological system dominated by strong seasonal variability, with recurring high wet-season flows and low dry-season conditions. Nevertheless, rainfall and discharge show increasing fluctuations over time, particularly during the wet season, while turbidity and E. coli display occasional higher peaks in later periods. These patterns suggest gradual intensification of hydrological and water-quality variability rather than a discrete shift in system state.

The absence of a clear abrupt change is expected given the limited temporal coverage. Robust detection of hydrological breakpoints generally requires long-term records. The observed increases in variability should therefore be interpreted as early-warning evidence of system sensitivity rather than proof of a regime transition (Alkhadher *et al.,* 2025). Continued monitoring is needed to determine whether these patterns persist over longer timescales.

This cautious interpretation is consistent with studies in tropical river systems showing that gradual increases in variability may precede more persistent hydrological alteration (Qin *et al.,* 2023; Sarkar *et al.,* 2022). The results highlight the need for proactive water-resource management that accounts for increasing hydrological uncertainty.

Principal Component Analysis (PCA)

Principal Component Analysis (PCA) was applied to the standardized dataset as an exploratory tool to identify major associations among physicochemical parameters, heavy metals, and microbial indicators. The first three components explained approximately 69% of the total variability (PC1 = 49.7%, PC2 = 11.1%, PC3 = 8.2%). Given the short-term nature of the dataset, the PCA results are interpreted as indicative process groupings rather than definitive source apportionment.

Table 4: Principal component loadings for water quality parameters in the Ogbese River Basin

	PC1	**PC2**	**PC3**
pH	0.297044	0.179024	0.341174
EC_uScm	0.366257	0.08978	-0.0236
TDS_mgL	0.356035	0.043503	-0.19839
DO_mgL	-0.26371	0.552085	-0.10579
BOD5_mgL	-0.23305	0.567952	-0.51681
Turbidity_NTU	-0.33037	-0.28176	-0.19819
Pb_mgL	0.359444	0.084238	-0.31232
Cd_mgL	0.300675	0.369175	0.229816
Fe_mgL	-0.27404	0.317764	0.608515
Ecoli_CFU100mL	-0.35093	-0.08296	0.073974

PC1 is positively associated with EC, TDS, Pb, Cd, and pH, and negatively associated with turbidity and E. coli. This component represents a mineralisation factor linked to water-rock interaction, solute concentration during lower-flow periods, and possible low-level anthropogenic metal inputs. The negative association with turbidity and microbial indicators suggests that PC1 reflects relatively stable, low-runoff conditions rather than event-driven contamination.

PC2 is dominated by strong positive loadings of DO and BOD_5, along with moderate contributions from Cd and Fe. This component reflects organic matter dynamics and oxygen-related processes within the river system. The simultaneous increase in DO and BOD_5 suggests active organic loading and oxygen exchange processes, likely influenced by increased flow turbulence during the wet season.This component indicates biogeochemical processes, including microbial activity and organic matter decomposition, and is strongly linked to rainfall-driven inputs of organic pollutants.

PC3 is characterized by strong positive loading of Fe, along with contributions from pH and Cd, and negative contributions from BOD_5 and TDS. This component reflects metal mobilization processes, likely driven by erosion, runoff, and changes in redox conditions. The strong association with Fe suggests a geogenic source enhanced by hydrological processes, while the presence of Cd indicates possible anthropogenic contributions. This component can therefore be interpreted as representing a mixed geogenic–anthropogenic factor influenced by seasonal runoff and land-use activities.

The PCA results demonstrate that water quality in the Ogbese River Basin is controlled by three main processes:

1. Geogenic mineralisation and low-runoff solute concentration processes (PC1)

2. Organic pollution and biogeochemical activity (PC2)
3. Metal mobilization influenced by runoff and anthropogenic inputs (PC3)

The separation of these components highlights the combined influence of natural geological processes and human activities, with hydrological variability acting as the key driver linking these processes. The results are consistent with previous studies where PCA has been successfully used to identify dominant hydrochemical processes and pollution sources in tropical river systems (Helena *et al.,* 2000; Li *et al.,* 2014; Sarkar *et al.,* 2022 Ghosh & Panigrahi, 2024). The clear grouping of variables also supports earlier findings from Sections 3.2 and 3.3, confirming the strong coupling between hydrology and water quality. The identification of distinct controlling factors has important implications for water resource management:

- Geogenic contributions require monitoring but are less controllable
- Anthropogenic inputs (microbial and organic pollution) require urgent intervention
- Runoff-driven processes highlight the importance of watershed management

The PCA provides a useful exploratory framework for understanding the complexity of water quality dynamics in the basin and supports the development of targeted mitigation strategies (Arman *et al.,* 2025).

Hydrological and Management Implications

The findings from this study reveal emerging hydrological and water quality dynamics with important implications for basin management and ecological sustainability. The observed delay in wet-season peak discharge and the extension of low-flow periods suggest subtle but progressive modifications in the flow regime of the Ogbese River. Such changes are consistent with broader evidence that land-cover alterations and hydrological variability can influence river discharge patterns through modifications in evapotranspiration and runoff generation processes (Costa *et al.,* 2012). Similar patterns have been reported across tropical West African basins, where shifts in rainfall timing and runoff response are associated with both climatic variability and increasing land-use pressures (Akinsanola & Zhou, 2018; Oguntunde *et al.,* 2021). Prolonged low-flow conditions may reduce dilution capacity, thereby increasing pollutant concentrations and posing risks to aquatic ecosystem integrity and dry-season water availability (Smakhtin, 2001; Gerten *et al.,* 2011).

From a management perspective, the observed upward tendencies in wet-season discharge, turbidity, and microbial contamination indicate an increasing influence of surface runoff and diffuse pollution sources, particularly from agricultural and peri-urban areas. These findings are consistent with studies in comparable basins such as the Ogun and Osun River systems, where land-use intensification and vegetation loss have been shown to enhance sediment and contaminant transport during high-flow events (Akinyemi *et al.,* 2022; Ayeni *et al.,* 2023). To mitigate these impacts, integrated catchment management strategies should be prioritized, including riparian buffer restoration, erosion control measures, and sustainable land-use planning. Such interventions can enhance sediment retention, reduce pollutant transport, and improve overall water quality resilience (Edokpayi *et al.,* 2017). In addition, strengthening community-based water governance and regulating dry-season water abstraction will be critical for maintaining environmental flows and ensuring long-term water security.

The methodological framework adopted in this study demonstrates the value of short-term hydrological datasets as preliminary diagnostic tools for assessing system sensitivity in data-scarce regions. While longer-term datasets are required for definitive trend and exploratory hydrological variability assessment, the integrated use of trend analysis, flow duration curves, cross-correlation, and multivariate techniques provides a robust basis for identifying emerging patterns and potential risks. When applied consistently, such approaches can support early warning systems and inform adaptive water resource management strategies (Richter *et al.,* 1996; Yue & Wang, 2004). Expanding monitoring efforts through low-cost sensor networks, coupled with periodic water quality assessments, would further strengthen local data availability and enhance decision-making capacity (Saturday *et al.*, 2025; Ndehedehe *et al.,* 2020).

Overall, the results highlight the need to transition from reactive to proactive water resource management in tropical river systems. By integrating hydrological analysis with water quality assessment and management strategies, this study provides a framework for improving basin resilience under conditions of increasing environmental variability. The approach is transferable to other data-limited basins across tropical regions and contributes to ongoing efforts toward sustainable water resource management (Poff *et al.,* 1997; Sylla *et al.,* 2022).

Policy, WASH, and Sustainable Development Implications

The findings support an integrated watershed-management approach that links hydrological monitoring with public-health protection. At policy level, priority actions should include routine water-quality surveillance, rainfall-event-based microbial monitoring, enforcement of sanitation setbacks from river channels, protection and restoration of riparian buffers, and control of sediment-generating activities such as sand mining and poorly managed cultivation near stream banks. Community-level WASH interventions are also essential, including safe household water storage, point-of-use disinfection, hygiene education, and improved sanitation facilities in settlements close to the river. These actions align with SDG 6 by promoting safe water and sanitation, while also supporting SDG 3 through reduction of waterborne disease risks and SDG 11 through improved environmental management in rapidly changing settlements. Because the basin is data-scarce, low-cost monitoring networks and periodic community-based sampling can provide an affordable early-warning system for identifying contamination episodes and guiding timely interventions.

CONCLUSION

This study presents a comprehensive assessment of hydrological dynamics and water quality in the Ogbese River Basin, integrating seasonal analysis, trend detection, flow regime characterization, cross-correlation analysis, and multivariate statistical techniques. The results demonstrate that water quality variability in the basin is strongly controlled by hydrological processes, particularly rainfall-driven runoff, which governs sediment transport, contaminant mobilization, and dilution capacity. Seasonal analysis revealed pronounced wet-season increases in discharge, turbidity, and Escherichia coli, while dry-season conditions were characterized by higher concentrations of dissolved ions. Trend analysis indicated increasing tendencies in key parameters, although only rainfall exhibited statistically significant change. Flow duration curve analysis highlighted high hydrological variability and reduced low-flow persistence, while cross-correlation results confirmed rapid system response to rainfall with minimal lag. Principal Component Analysis further identified three dominant controlling factors: geogenic mineralization, organic pollution, and runoff-driven metal mobilization influenced by anthropogenic activities.

Although no abrupt hydrological change was detected, increasing variability across hydrological and water quality parameters suggests emerging system sensitivity and potential vulnerability to future environmental change. The results support sustained monitoring and proactive watershed management, especially during wet-season runoff events when turbidity and microbial contamination increase. The study makes a useful contribution by integrating multiple hydrological and water quality techniques within a short-term dataset to provide a process-based understanding of hydrology-water quality interactions in a data-scarce tropical basin. From a management perspective, the results highlight the need for improved sanitation infrastructure, riparian buffer restoration, erosion control, routine water-quality monitoring, and regulation of dry-season abstraction. The framework is transferable to similar data-limited tropical basins and can support sustainable water-resource planning and policy development.

REFERENCES

Abba, S. I., Hadi, S. J., & Abdullahi, J. (2022). River water quality assessment using multivariate statistical techniques and water quality indices. *Environmental Science and Pollution Research, 29,* 23456–23472. https://doi.org/10.1007/s11356-022-18567-3

Adefisan, E. A., & Lawal, K. A. (2020). Seasonal variations of rainfall over southwestern Nigeria. *Atmospheric Science Letters, 21*(3), e964. https://doi.org/10.1002/asl.964

Adeniji, A. O., Okoh, O. O., & Okoh, A. I. (2019). Microbial contamination of water sources in rural communities of Africa: An overview. *Applied Sciences, 9*(17), 3941. https://doi.org/10.3390/app9173941

Adeyemi, O., Ojo, O. I., & Ogunleye, A. O. (2021). Impact of hydrological variability on water quality in tropical basins. *Environmental Monitoring and Assessment, 193,* 389. https://doi.org/10.1007/s10661-021-09138-1

Akinwumi, A. M., & Adewumi, J. R. (2021). Impact of climate change on streamflow of Ala River, Nigeria. *Sustainable Water Resources Management, 7,* 25. https://doi.org/10.1007/s40899-020-00484-7

Akinsanola, A. A., & Zhou, W. (2018). Projections of West African summer monsoon rainfall extremes. *Climate Dynamics, 50,* 3675–3691. https://doi.org/10.1007/s00382-017-3834-6

Alkhadher, S. A. A., Sidek, L. M., Khan, M. S. J., Al-Habshi, M. M. A., & Kurniawan T. A. (2025). Seasonal variations in water quality and hydrological dynamics in a tropical reservoir driven by rainfall, runoff, and anthropogenic activities. *Scientific Reports.* https://doi.org/10.1038/s41598-025-09808-z

American Public Health Association. (2017). *Standard methods for the examination of water and wastewater* (23rd ed.). American Public Health Association.

Arman, N. Z., Aris, A., Salmiati, S., Rosli, A. S., Foze, M. F., & Talib, J. (2025). Water quality assessment of Johor River Basin, Malaysia, using multivariate analysis and spatial interpolation method. *Environmental Science and Pollution Research.* https://doi.org/10.1007/s11356-024-35692-7

Ayeni, A. O., Olatunji, K. A., & Fasona, M. J. (2023). Flow regime and water quality response to land-use intensification in the Osun River Basin, Nigeria. *Water Practice and Technology, 18*(5), 1404–1419. https://doi.org/10.2166/wpt.2023.064

Bain, R., Cronk, R., Wright, J., Yang, H., Slaymaker, T., & Bartram, J. (2021). Fecal contamination of drinking-water in low- and middle-income countries. *Science of the Total Environment, 751,* 141674. https://doi.org/10.1016/j.scitotenv.2020.141674

Boateng, T. K., Opoku, F., & Akoto, O. (2022). Water quality assessment using statistical and index-based approaches in tropical rivers. *Environmental Monitoring and Assessment, 194,* 512. https://doi.org/10.1007/s10661-022-10125-x

Chen, X., Wu, J., Li, P., & Qian, H. (2022). Hydrogeochemical processes and groundwater quality assessment using integrated methods. *Environmental Earth Sciences, 81,* 1–17. https://doi.org/10.1007/s12665-022-10245-3

Costa, M. H., Botta, A., & Cardille, J. A. (2003). Effects of large-scale changes in land cover on river discharge. *Journal of Hydrology, 283,* 206–217. https://doi.org/10.1016/S0022-1694(03)00267-1

Ebuete, A. W., Puanoni, N. I., Ebuete, Y. I., & Ebuete, E. (2023). Water quality index (NSFWQI) of the River Nun, Bayelsa State, Nigeria. *American*

Journal of Environment and Climate, 2(2). https://doi.org/10.54536/ajec.v2i2.598

Ebuete, A. W., Wodu, D. P., & Ebuete, E. (2022). Dumping on waters: The lacunae in waste management in the Niger Delta, Nigeria. *American Journal of Environment and Climate, 1*(2). https://doi.org/10.54536/ajec.v1i2.602

Edokpayi, J. N., Odiyo, J. O., & Durowoju, O. S. (2017). Impact of wastewater on surface water quality. In H. Tutu (Ed.), *Water quality* (pp. 401–416). IntechOpen. https://doi.org/10.5772/66561

Gao, Y., Zhang, Y., & Wang, X. (2023). Spatiotemporal variation of water quality and its driving factors in river basins. *Science of the Total Environment, 857,* 159564. https://doi.org/10.1016/j.scitotenv.2022.159564

Gerten, D., Rost, S., von Bloh, W., & Lucht, W. (2011). Causes of change in global river discharge. *Geophysical Research Letters, 38,* L20405. https://doi.org/10.1029/2011GL049239

Ghosh, P., & Panigrahi, A. K. (2024). Assessment of water quality and source apportionment of pollution in a tropical river in eastern India: A study utilizing multivariate statistical tools and the APCS-MLR receptor model. *Environmental Monitoring and Assessment, 196*(9), 861. https://doi.org/10.1007/s10661-024-13022-1

Helena, B., Pardo, R., Vega, M., Barrado, E., Fernández, J. M., & Fernández, L. (2000). Temporal evolution of groundwater composition in an alluvial aquifer. *Water Research, 34*(3), 807–816. https://doi.org/10.1016/S0043-1354(99)00260-9

Laniyan, A. B., Ogunyinka, O. O., Afolabi, O. I., Odusanya, O. A., Oyefusi, A. S., & Adebukola, O. S. (2025). Hydrochemistry and predictive modelling of water quality in Ogun and Oshun Rivers, Southwestern Nigeria. *American Journal of Environmental Economics, 4*(1), 205–220. https://doi.org/10.54536/ajee.v4i1.6041

Lapworth, D. J., Nkhuwa, D. C. W., Okotto-Okotto, J., Pedley, S., Stuart, M. E., Tijani, M. N., & Wright, J. (2017). Urban groundwater quality in sub-Saharan Africa. *Hydrogeology Journal, 25,* 1093–1116. https://doi.org/10.1007/s10040-016-1516-6

Li, P., He, S., Yang, N., & Xiang, G. (2022). Groundwater quality assessment using water quality index and multivariate statistical methods. *Environmental Science and Pollution Research, 29,* 25063–25077. https://doi.org/10.1007/s11356-021-17257-3

Li, S., Zhang, Q., & Zhang, J. (2014). Hydrochemical characteristics and water quality assessment. *Environmental Earth Sciences, 71,* 3937–3951. https://doi.org/10.1007/s12665-013-2769-3

Masindi, V., & Foteinis, S. (2023). Groundwater and surface water contamination in sub-Saharan Africa: Emerging challenges and solutions. *Clean Engineering and Technology, 10,* 100589. https://doi.org/10.1016/j.clet.2022.100589

Ndehedehe, C. E., Ferreira, V. G., & Agutu, N. O. (2020). Hydrological variability across Africa. *Science of the Total Environment, 729,* 138995. https://doi.org/10.1016/j.scitotenv.2020.138995

Njuguna, S. M., Onyango, M. S., & Wamalwa, K. (2024). Impact of land use and seasonal variability on river water quality in tropical catchments. *Journal of Hydrology, 628,* 129123. https://doi.org/10.1016/j.jhydrol.2023.129123

Oguntunde, P. G., Abiodun, B. J., & Lischeid, G. (2021). Impacts of climate variability and land use change on water balance. *Hydrological Sciences Journal, 66*(3), 428–441. https://doi.org/10.1080/02626667.2020.1861044

Pakoksung, K., Inseeyong, N., Chawaloesphonsiya, N., Punyapalakul, P., Chaiwiwatworakul, P., Xu, M., & Chuenchum, P., (2025). Seasonal dynamics of water quality in response to land use changes in the Chi and Mun River Basins, Thailand. *Scientific Reports.* https://doi.org/10.1038/s41598-025-91820-4

Poff, N. L., Allan, J. D., Bain, M. B., Karr, J. R., Prestegaard, K. L., Richter, B. D., Sparks, R. E., & Stromberg, J. C. (1997). *The natural flow regime. BioScience, 47*(11), 769–784. https://doi.org/10.2307/1313099

Qin, Y., Li, P., & Wu, J. (2023). Hydrogeochemical evolution and groundwater quality assessment using multivariate statistical techniques. *Environmental Earth Sciences, 82,* 210. https://doi.org/10.1007/s12665-023-10810-5

Richter, B. D., Baumgartner, J. V., Powell, J., & Braun, D. P. (1996). A method for assessing hydrologic alteration. *Conservation Biology, 10*(4), 1163–1174.

Sarkar, M., Singh, P., & Tiwari, A. K. (2022). Hydrogeochemical processes and water quality assessment using statistical techniques. *Applied Water Science, 12,* 85. https://doi.org/10.1007/s13201-022-01585-3

Saturday, A., Herrnegger, M., Kangume, S., & Stecher, G. (2025). Spatiotemporal variability of surface water quality in tropical agriculture-dominated catchments: Insights from water quality indices. *Scientific Reports.* https://doi.org/10.1038/s41598-025-27066-x

Smakhtin, V. U. (2001). Low flow hydrology: A review. *Journal of Hydrology, 240,* 147–186. https://doi.org/10.1016/S0022-1694(00)00340-1

Sylla, M. B., Diallo, I., Pal, J. S., & Faye, A. (2022). Climate change over West Africa. *Climate Dynamics, 59,* 1321–1340. https://doi.org/10.1007/s00382-022-06186-y

Vogel, R. M., & Fennessey, N. M. (1994). Flow duration curves. *Journal of Water Resources Planning and Management, 120*(4), 485–504. https://doi.org/10.1061/(ASCE)0733-9496(1994)120:4(485)

World Health Organization. (2017). *Guidelines for drinking-water quality* (4th ed.). World Health Organization.

Yue, S., & Wang, C. Y. (2004). Modified Mann–Kendall test. *Water Resources Management, 18,* 201–218. https://doi.org/10.1023/B:WARM.0000043140.61082.60