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Research Article

Seasonal Climate Variability and Water Quality Dynamics in The Osun River Basin, Southwestern Nigeria

*[1]Abiodun Bukola Laniyan, [1]Oluwabunmi Molade Olugbenga, [2]Enovwo Erere Odjegba, [3]Wemimo O. Ademeno

About Article

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About Author

[1] Department of Science Laboratory Technology, D.S Adegbenro ICT Polytechnic, Itori-Ewekoro, Ogun State, Nigeria

[2] Department of Water Resources Management and Agrometeorology, Federal University of Agriculture, Nigeria

[3] Department of Surveying and Geo-Informatics, D.S Adegbenro ICT Polytechnic, Itori-Ewekoro, Ogun State, Nigeria

Contact @ Abiodun Bukola Laniyan
abiodunlaniyan@gmail.com

ABSTRACT

Seasonal variability strongly influences river water quality in tropical regions, where alternating wet and dry seasons shape hydrological and ecological processes. This study examined the effects of seasonal climate variability on the physicochemical and microbial quality of the Osun River Basin in Southwestern Nigeria. Water samples were collected from twenty georeferenced sites during both wet and dry seasons and analyzed for dissolved oxygen (DO), biochemical oxygen demand (BOD), chemical oxygen demand (COD), total dissolved solids (TDS), turbidity, ammonia, nitrate, pH, total coliforms, and Escherichia coli. Standard laboratory procedures were employed, and results were compared against international drinking water standards. The findings revealed marked seasonal contrasts, with significantly higher BOD, COD, turbidity, and microbial loads during the wet season, indicating runoff-driven pollution and surface wash-off of organic and microbial contaminants. In contrast, ionic parameters such as pH and TDS remained relatively stable across seasons, suggesting limited fluctuation in the base water chemistry. Elevated ammonia concentrations and microbial contamination across several sites point to ongoing ecological stress and potential public health hazards. Overall, the study demonstrates that the Osun River Basin is highly vulnerable to seasonal climatic dynamics, with rainfall-driven runoff and reduced dry-season dilution acting as key drivers of pollution variability. These results emphasize the urgent need for seasonally adaptive water quality management, stricter effluent regulation, and improved community-level sanitation measures to protect both ecosystem integrity and human health.

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1. INTRODUCTION

Freshwater ecosystems in tropical regions are strongly influenced by seasonal climate variability, which regulates hydrological processes, sediment transport, and pollutant dynamics (Kilonzo *et al.*, 2014; Ndebele-Murisa *et al.*, 2010). In West Africa, the alternation between wet and dry seasons induces pronounced changes in river flow, water temperature, and dissolved oxygen, while also affecting the mobilization of nutrients, trace metals, and microbial contaminants from surrounding landscapes (Akinyemi *et al.*, 2019; Nkotagu, 2005). Such seasonal fluctuations are further modulated by land use activities, including agriculture, mining, and urbanization, which introduce diffuse and point-source pollutants into river systems (Olatunji *et al.*, 2012). The Osun River Basin, located in Southwestern Nigeria, is a socio-economically important catchment providing domestic water supply, irrigation, fisheries, and cultural services. However, it is increasingly under stress from rapid urban expansion, artisanal gold mining, and unregulated waste disposal (Akinbile & Yusoff, 2011; Oladipo *et al.*, 2020). Mining activities contribute to elevated heavy metal loads, while agricultural and urban effluents increase nutrient and microbial contamination (Olatunji *et al.*, 2012). Seasonal rainfall and temperature patterns in the basin, driven by the West African Monsoon, strongly influence river hydrodynamics, which in turn affect pollutant dispersion, dilution, and transformation. Understanding these coupled climatic and anthropogenic controls on water quality is essential for sustainable river basin management. Despite the ecological and socio-economic importance of the Osun River Basin, there is still limited understanding of how seasonal climatic drivers interact with anthropogenic factors to influence spatiotemporal water quality dynamics. Existing studies in Nigeria have predominantly assessed water quality status or spatial variability without integrating seasonal climate variables such as rainfall, temperature, and humidity into comprehensive multivariate frameworks. As a result, the relationships between climate variability and pollutant transport processes remain poorly quantified, constraining the ability of policymakers and water managers to design seasonally adaptive strategies for water quality protection. Although numerous studies have documented seasonal variability in river water quality across Africa and other tropical regions (Adekola *et al.*, 2016; Ayandiran & Dahunsi, 2017; Chigor *et al.*, 2012), most have been descriptive in nature and have not adequately captured the temporal interactions between rainfall events and pollutant mobilization. Moreover, few have simultaneously examined physicochemical and microbiological parameters in relation to climate variability, even though tropical basins are highly susceptible to combined ionic and microbial pollution during extreme seasonal events. This gap highlights the need for integrative approaches that can explain both immediate and lagged pollutant responses to changing climatic conditions. To address these gaps, the present study employs cross-correlation analysis and principal component analysis (PCA), alongside WHO water quality benchmarking, to evaluate the effects of seasonal climate variability on the physicochemical and microbiological characteristics of the Osun River Basin. Specifically, the study seeks to quantify seasonal differences in key water quality parameters, assess the relationships between rainfall, temperature, and humidity and selected water quality indicators, identify dominant environmental gradients and controlling factors, and evaluate the compliance of observed parameters with World Health Organization (WHO) drinking water standards. It is expected that wet season conditions will exhibit higher turbidity, iron, and microbial contamination due to increased runoff and sediment transport, while dry season flows will show elevated electrical conductivity, total dissolved solids, and heavy metal concentrations as a result of reduced dilution and evapoconcentration. Rainfall and humidity are also expected to correlate positively with particulate and microbial parameters, whereas temperature will likely exert an inverse influence on dissolved oxygen concentrations. By linking seasonal climatic dynamics with multivariate patterns in water quality, this study provides an evidence base for developing seasonally adaptive, climate-informed water resource management strategies in the Osun River Basin and comparable tropical catchments.

2. LITERATURE REVIEW

2.1. Seasonal climate variability and river water quality

Seasonal climate variability plays a central role in shaping river water quality, particularly in tropical and subtropical regions where alternating wet and dry periods regulate hydrological and biogeochemical processes. The West African Monsoon system drives marked intra-annual variations in rainfall, temperature, and evapotranspiration, which in turn influence the transport, dilution, and transformation of pollutants in freshwater ecosystems (Nicholson, 2013; Ndebele-Murisa *et al.*, 2010). During the wet season, high-intensity rainfall events generate overland flow that mobilizes sediments, nutrients, and microbial contaminants from agricultural and urban landscapes into river channels (Adekola *et al.*, 2016; Giri & Qiu, 2016). In contrast, the dry season is characterized by reduced discharge, elevated temperatures, and evaporative concentration of dissolved ions, often leading to increased salinity and heavy metal accumulation (Adefemi & Awokunmi, 2010; Akoto *et al.*, 2008). These dual seasonal effects create dynamic water quality regimes that have profound ecological and public health implications.

2.2. Regional studies in west africa

A growing body of research has examined seasonal variations in river water quality across West African basins, revealing consistent hydrological controls but divergent pollution sources (Armah *et al.*, 2010; Akoto *et al.*, 2011; Boakye *et al.*, 2021). In Ghana's Pra River Basin, for instance, Akoto *et al.* (2017) reported that rainfall-driven erosion and mining effluents elevated concentrations of Fe, Mn, and Pb during the wet season. Similarly, Boakye *et al.* (2021) observed that turbidity and suspended solids increased sharply during high-flow months, while conductivity and TDS peaked during dry spells. Studies in Nigeria show analogous trends. Ayandiran and Dahunsi (2017) found that River Ogbese exhibited higher BOD, COD, and microbial loads in the wet season due to runoff from agricultural lands and settlements, whereas ionic parameters were higher in the dry season. In Ogun River, Ololade *et al.* (2020) and Ojekunle *et al.* (2021) observed significant spatial heterogeneity linked to land use, with dry-season solute enrichment in industrial zones and wet-season sediment loading in rural reaches. Comparable findings from the Cross River (Etim & Akpan, 2018) and Niger Delta (Anyanwu & Nwankwoala, 2021) further confirm that rainfall intensity and anthropogenic activities jointly determine water quality fluctuations.

2.3. Anthropogenic drivers and land use influence

Beyond climatic factors, human activities amplify seasonal variations in river water quality. Urbanization, agriculture, and artisanal mining introduce both point- and non-point-source pollutants that interact with hydrological regimes (Olatunji *et al.*, 2012; Akinbile & Yusoff, 2011). In mining-impacted basins, leaching of mine tailings during rainfall events contributes to heavy metal enrichment, whereas continuous seepage maintains background contamination during dry periods (Akinyemi *et al.*, 2019). Agricultural catchments show nutrient and sediment surges after storms, while peri-urban rivers are persistently affected by untreated domestic wastewater (Edokpayi *et al.*, 2017). Studies in East and Southern Africa similarly highlight the synergy between land use and seasonality, where rainfall governs pollutant mobilization while human activities determine pollutant type and magnitude (Kilonzo *et al.*, 2014; Nkotagu, 2005). These interactions underscore the need for integrated analyses that jointly consider climatic variability and land use.

2.4. Gaps in current knowledge

Despite substantial progress, several research gaps remain. First, most previous assessments in Nigeria and West Africa are descriptive, focusing on mean seasonal differences without exploring statistical linkages between climate variables (e.g., rainfall, temperature, humidity) and specific water quality parameters (Nyenje *et al.*, 2010). Second, integrated multivariate analyses—such as Principal Component Analysis (PCA) or regression modeling—are rarely applied to disentangle the concurrent effects of climate and land use. Third, few studies have explicitly benchmarked seasonal water quality variations against World Health Organization (WHO) drinking water standards to assess public health risks across time and space. Moreover, basin-scale analyses that integrate both physicochemical and microbiological indicators remain limited, even though tropical rivers are highly susceptible to microbial contamination during storm events (Lukubye & Andama, 2017; Adewumi *et al.*, 2020). This lack of integrative approaches constrains the development of seasonally adaptive management frameworks.

2.5. Comparative evidence from west african river basins

Comparative studies across West African river basins reveal consistent patterns linking seasonal hydrology and land use to water quality dynamics. In the Pra River Basin of Ghana, Akoto *et al.* (2017) demonstrated that rainfall-driven erosion and artisanal gold mining activities significantly elevated concentrations of iron, lead, and suspended sediments during the wet season. Their findings underscore the dominant role of seasonal precipitation in mobilizing both sediment-bound and dissolved contaminants. Similarly, Boakye, Kankam-Yeboah, and Gyamfi (2021) observed that turbidity and total suspended solids in the same basin rose sharply in response to high-flow periods, whereas electrical conductivity and total dissolved solids reached their peak values during the dry season, reflecting solute concentration effects caused by evapotranspiration and reduced discharge.

Parallel studies in Nigeria corroborate these hydrological patterns while highlighting local anthropogenic influences. Ayandiran and Dahunsi (2017) reported that the River Ogbese exhibited markedly higher biochemical oxygen demand, chemical oxygen demand, and microbial loads during the wet season as a result of stormwater runoff carrying organic and faecal matter from agricultural and urban areas. In contrast, ionic parameters such as electrical conductivity and total dissolved solids were elevated during the dry season due to low dilution capacity. Similarly, Ololade, Fakankun, and Adebayo (2020) and Ojekunle, Sangodoyin, and Oyebanji (2021) found that the Ogun River experienced pronounced spatial heterogeneity, with dry-season solute enrichment in industrial zones and wet-season sediment loading in agricultural stretches. Studies in other Nigerian basins such as the Cross River (Etim & Akpan, 2018) and rivers of the Niger Delta (Anyanwu & Nwankwoala, 2021) also reported comparable seasonal contrasts, where heavy rainfall intensifies turbidity and microbial contamination, while low-flow dry months promote ionic and metal accumulation. Further evidence from the Asa River Basin in north-central Nigeria shows that agricultural runoff and small-scale mining jointly shape seasonal water quality patterns, with particulate and microbial pollution dominating the wet season and ionic enrichment prevailing in the dry months (Akinyemi & Ifabiyi, 2021). Collectively, these findings establish a regional consensus: the wet season in West African basins is typically characterized by elevated turbidity, suspended solids, and microbial contamination due to enhanced runoff and erosion, whereas the dry season promotes higher concentrations of dissolved solids, electrical conductivity, and heavy metals as a result of evaporation and diminished dilution. However, some inconsistencies persist, particularly regarding parameters such as biochemical oxygen demand and dissolved oxygen, which exhibit site-specific behavior depending on local effluent discharges, land use, and riparian conditions. These variations highlight the need for basin-scale studies that integrate climatic, hydrological, and anthropogenic factors to fully explain spatial and temporal water quality dynamics in West Africa.

2.6. Justification for the present study

Given these gaps, the current research advances understanding by integrating statistical correlation, regression, and PCA techniques to evaluate the combined influence of rainfall, temperature, and humidity on water quality in the Osun River Basin, a socioeconomically critical watershed facing pressures from urbanization, agriculture, and artisanal mining. By linking climatic variability to physicochemical and microbiological dynamics and comparing results against WHO guidelines, this study provides a comprehensive framework for climate-informed water resource management. Furthermore, its approach offers a transferable model for other tropical basins experiencing similar hydrological and anthropogenic pressures.

3. METHODOLOGY

3.1. Study area description

The Osun River Basin lies in Southwestern Nigeria between latitudes 6°55′ and 7°55′ N and longitudes 4°00′ and 4°55′ E, covering diverse landscapes from the Guinea savanna to derived forest zones. The basin drains an area of approximately 10,000 km² and is characterized by a bimodal climate pattern driven by the West African Monsoon. Annual rainfall ranges from 1,200 to 1,800 mm, with a distinct wet season (April–October) and dry season (November–March). Temperatures range from 22°C to 32°C, with relative humidity generally exceeding 70% during the wet season and dropping below 60% in the dry season. Land use within the basin includes agriculture, artisanal gold mining, urban settlements, and riparian forest patches. Table 1 summarizes the sampling sites (S1–S10), their coordinates, elevations, and dominant land use types, while Figure 1 presents the study area map with site locations along the Osun River and its tributaries. The spatial distribution of the ten sampling locations (S1–S10) across the Osun River Basin in southwestern Nigeria are shown in Figure 1. The sites were strategically positioned to capture upstream, midstream, and downstream conditions, as well as key anthropogenic influences such as urban centers, agricultural zones, artisanal mining areas, and reservoir-impacted reaches. S1 and S2 are located along the Apoje segment in the northern basin, with S1 positioned in a predominantly rural agricultural landscape and S2 downstream in a mixed land-use corridor. S3 and S4 represent the Osogbo metropolitan stretch, including an urban bridge crossing and an industrial downstream reach. S5 is situated in an artisanal gold mining area, while S6 captures midstream rural agricultural influences. S7 represents a major tributary inflow from the Iwo area, S8 is located in the peri-urban Ejigbo zone, and S9 samples water immediately downstream of the Ede Dam. The most downstream site, S10, is positioned near the basin outlet within the coastal plain agricultural zone. The map also delineates the main river channel and its major tributaries within the basin boundary, providing spatial context for interpreting the hydrological connectivity and potential pathways of contaminant transport between sampling points.

Table 1. Description of sampling sites in the osun river basin, southwestern nigeria.

Site Code	Location Name	Latitude (°N)	Longitude (°E)	Elevation (m)	Land Use Context
S1	Apoje upstream	7.155	4.008	274	Rural agricultural area
S2	Apoje downstream	7.121	4.015	260	Mixed agriculture and settlements
S3	Osogbo Bridge	7.773	4.56	290	Urban center
S4	Osogbo downstream	7.75	4.572	285	Urban–industrial mix
S5	Gold mining area	7.55	4.8	300	Artisanal mining
S6	Midstream rural	7.32	4.91	270	Agricultural
S7	Iwo tributary	7.63	4.18	260	Rural agricultural
S8	Ejigbo	7.9	4.317	295	Peri-urban
S9	Ede dam	7.71	4.45	280	Reservoir area
S10	Downstream outlet	6.95	4.33	210	Coastal plain agriculture

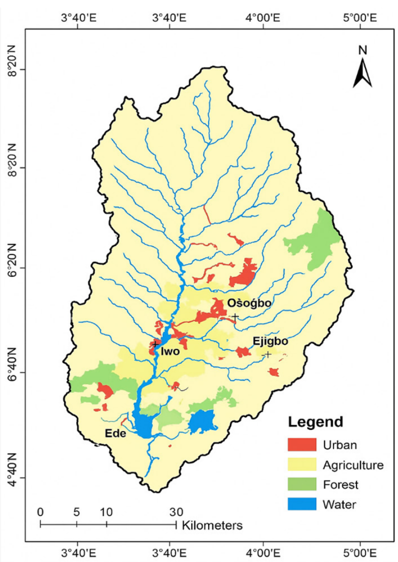

Figure 1. Map of the osun river basin

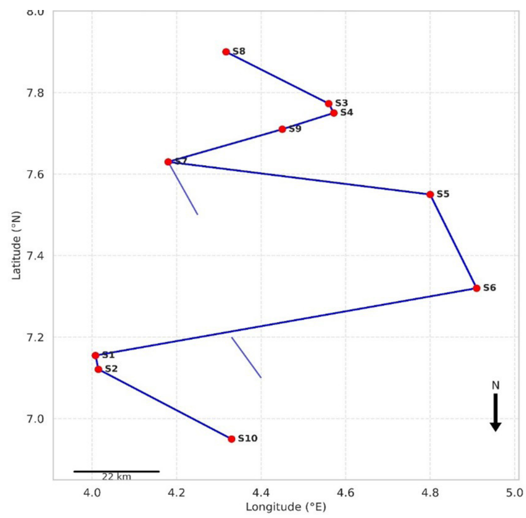

Figure 2. Spatial Distribution of Sampling Sites (S1–S10) and main tributaries.

3.2. Sampling design and data collection

Water samples were collected during the wet (July–September) and dry (January–March) seasons from ten georeferenced sites across the Osun River Basin. Sampling was conducted in triplicate at each site and season to capture both spatial and temporal variability. In situ measurements of temperature, pH, electrical conductivity (EC), turbidity, and dissolved oxygen (DO) were obtained using calibrated portable meters. Temperature and pH were measured with a Hanna HI98129 Combo Waterproof Tester, electrical conductivity with a Hach HQ40d multi-parameter meter, turbidity with a Hach 2100Q portable turbidimeter, and dissolved oxygen using a YSI Pro20i dissolved oxygen meter. All instruments were calibrated daily according to the manufacturer's specifications prior to field deployment to ensure data accuracy and consistency across sampling periods. Water samples for laboratory analysis were collected in pre-cleaned polyethylene bottles, preserved on ice, and transported to the laboratory within 24 hours for physicochemical and microbiological analysis.

3.3. Climate data acquisition

Climate data used in this study were obtained from the archives of the Nigerian Meteorological Agency (NiMet), Oshodi, Lagos, and the synoptic weather station at Oshogbo, which represents the climatic conditions of the Osun River Basin. The dataset comprised daily records of rainfall (mm), temperature (°C), relative humidity (%), wind speed (m/s), and solar radiation (MJ/m^2) for a 20-year period (2001–2020). Rainfall and temperature were selected as the primary climatic drivers due to their direct influence on river discharge, pollutant transport, and seasonal water quality dynamics in the basin.

3.4. Laboratory analysis

Standard methods (APHA, 2017) were used to determine total dissolved solids (TDS), biochemical oxygen demand (BOD_5), heavy metals (Pb, Cd, Fe) via atomic absorption spectrophotometry, and microbial indicators (Escherichia coli and total coliforms) via membrane filtration techniques. All analyses were performed in triplicate, and quality control included blanks, standards, and replicate measurements.

3.5. Data analysis

Descriptive statistics were computed for each water quality parameter by site and season. Data normality was evaluated using the Shapiro–Wilk test, and homogeneity of variances was tested using Levene's test. Parameters meeting the assumptions of normal distribution and homoscedasticity were analyzed using one-way Analysis of Variance (ANOVA) to assess significant differences in mean values between seasons. When data violated these assumptions, the non-parametric Kruskal–Wallis test was applied as a robust alternative that does not require normality. The choice of $p < 0.05$ as the threshold for statistical significance follows standard environmental science and water quality research conventions, representing a 95% confidence level for rejecting the null hypothesis of no difference between groups. This level balances the need for analytical rigor with the natural variability inherent in environmental datasets, minimizing both Type I and Type II errors. Spearman correlation and simple linear regression were employed to quantify relationships between seasonal climate variables (rainfall, temperature, humidity) and selected water quality parameters. Principal Component Analysis (PCA) with varimax rotation was used to identify dominant gradients and pollution sources. Compliance of measured parameters with World Health Organization (WHO) drinking water standards was subsequently evaluated. All statistical analyses were conducted using R software (version 4.2.0), and results were considered statistically significant at $p < 0.05$.

4. RESULTS AND DISCUSSION

4.1. Seasonal variation in water quality

Water quality parameters in the Osun River Basin exhibited pronounced seasonal variability (Table 2). Across the ten sites, pH values in the wet season (mean ≈ 6.63) were generally more acidic compared to the dry season (mean ≈ 7.39), likely due to dilution of alkaline ions during peak runoff and acidifying inputs from decomposing organic matter and atmospheric deposition. Temperature patterns mirrored climatic expectations: wet season averages were cooler (≈ 24.3 °C) than dry season values (≈ 28.6 °C), with elevated dry-season temperatures potentially accelerating microbial activity and altering dissolved oxygen dynamics. Electrical conductivity (EC) and total dissolved solids (TDS) were substantially higher during the dry season, exceeding 250 μS/cm and 100 mg/L at some sites especially those downstream or adjacent to mining zones. This reflects reduced dilution during low-flow periods, consistent with evapoconcentration processes reported in other tropical catchments (Nyenje *et al.*, 2010). Turbidity, iron, and microbial indicators (E. coli, total coliforms) peaked during the wet season, with turbidity values exceeding 100 NTU at several upstream agricultural sites. These increases can be attributed to surface erosion, bank collapse, and overland runoff, which mobilize sediments and associated pollutants into the river. Dissolved oxygen (DO) levels were slightly higher in the wet season, supported by enhanced aeration from turbulent high flows, though organic loading from urban effluents at S3 and S4 reduced DO locally. Biochemical oxygen demand (BOD_5) showed site-specific variability, with urban-impacted locations recording higher wet-season values, but seasonal differences were not statistically significant. Lead (Pb) and cadmium (Cd) concentrations were elevated in the dry season at mining-influenced sites (e.g., S5), likely due to reduced dilution and subsurface leaching from mine tailings.

Table 2. Seasonal variation in water quality parameters in the osun river basin.

Site	Season	pH	Temp	EC	Turb	TDS	DO	BOD_5	Pb	Cd	Fe	E. coli	T Coliforms
S1	Wet	6.64	26.8	98.56	101.84	29.36	4.47	3.29	0.072	0.004	1.15	220	4,864
S2	Wet	7.05	23.85	54.55	52.01	38.26	5.57	5.16	0.037	0.004	0.467	492	2,148
S3	Wet	6.71	26.14	55.97	91.71	55.55	4.14	6.04	0.03	0.001	1.439	1,165	4,137
S4	Wet	6.57	23.39	94.74	82.82	27.32	5.49	3.17	0.075	0.002	1.095	511	2,840
S5	Wet	6.79	23.74	117.57	123.02	76.37	6.68	5.99	0.075	0.001	0.535	245	1,963
S6	Wet	6.65	24.09	106.3	72.81	36.86	5.63	3.71	0.068	0.001	1.484	972	1,394
S7	Wet	6.31	26.26	96.55	117.48	66.28	4.22	4.79	0.027	0.005	1.048	530	786
S8	Wet	6.58	24.3	98.37	106.51	73.23	5.42	3.6	0.063	0.005	0.974	970	2,722
S9	Wet	6.77	24.71	42.03	42.95	21.89	5.91	4.57	0.051	0.006	0.599	610	3,899
S10	Wet	6.51	23.31	63.18	49.35	75.78	6.42	6.17	0.072	0.005	0.524	1,092	2,927
S1	Dry	7.61	30.48	179.5	14.4	91.91	4.28	5.27	0.135	0.003	0.355	196	599
S2	Dry	6.92	27.69	335.73	22.93	132.63	5.11	3.46	0.147	0.01	0.226	224	741
S3	Dry	7.09	26.18	252.39	30.11	67.21	3.84	5.63	0.066	0.004	0.345	394	635
S4	Dry	7.47	29.81	159.41	39.13	111.49	4.9	4.53	0.099	0.004	0.518	162	535
S5	Dry	6.84	28.95	269.39	10.66	131.69	3.68	4.58	0.059	0.008	0.293	377	447
S6	Dry	7.14	26.57	331.17	45.09	96.11	4.98	5.27	0.101	0.007	0.221	82	1,814
S7	Dry	7.7	29.17	184.76	23.97	161.63	5.69	5.55	0.126	0.007	0.142	106	1,817
S8	Dry	7.41	26.05	125.37	36.54	60.71	3.48	4.2	0.116	0.008	0.212	299	627
S9	Dry	7.13	29.73	262.41	43.97	152.07	4.71	2.38	0.08	0.005	0.222	390	907
S10	Dry	7.69	29.16	298.7	30.11	140.77	4.48	2.78	0.119	0.005	0.112	275	518

(Units: pH – unitless; Temp – °C; EC – µS/cm; Turbidity – NTU; TDS – mg/L; DO, BOD_5, Fe – mg/L; Pb, Cd – mg/L; E. coli, Total coliforms – CFU/100 mL)

Table 3. Seasonal summary statistics (mean ± standard deviation) of water quality parameters in the osun river basin.

Parameter	Dry Season (Mean ± SD)	Wet Season (Mean ± SD)	WHO Limit*
pH	7.30 ± 0.32	6.66 ± 0.20	6.5–8.5
Temperature (°C)	28.38 ± 1.63	24.66 ± 1.28	—
Electrical Conductivity (µS/cm)	239.88 ± 73.63	82.78 ± 26.14	1000
Turbidity (NTU)	29.69 ± 11.79	84.05 ± 28.99	5
Total Dissolved Solids (mg/L)	114.62 ± 38.60	50.09 ± 14.15	500
Dissolved Oxygen (mg/L)	4.44 ± 0.67	5.31 ± 0.72	≥ 5
Biochemical Oxygen Demand (mg/L)	3.56 ± 1.12	4.92 ± 1.40	3
Lead (Pb, mg/L)	0.105 ± 0.029	0.057 ± 0.019	0.01
Cadmium (Cd, mg/L)	0.006 ± 0.002	0.003 ± 0.002	0.003
Iron (Fe, mg/L)	0.265 ± 0.118	0.932 ± 0.380	0.3
Escherichia coli (CFU/100 mL)	251 ± 115	681 ± 344	0
Total Coliforms (CFU/100 mL)	864 ± 517	2,768 ± 1,266	0

pH values were generally within the WHO permissible range (6.5–8.5), with slightly higher averages in the dry season. This dry season increase may be due to reduced dilution and the concentration of alkaline ions from weathering and anthropogenic discharges (Ayandiran & Dahunsi, 2017). Electrical conductivity (EC) and total dissolved solids (TDS) were significantly higher in the dry season, reflecting evaporative concentration effects and lower flow conditions (Ololade &

Lajide, 2010; Ebele & Abah, 2020). Dissolved oxygen (DO) was higher in the wet season, likely due to enhanced mixing from higher flows and lower water temperatures, consistent with observations from other tropical rivers (Ouyang *et al.*, 2006). Biochemical oxygen demand (BOD_5) showed minor seasonal variation and was above recommended limits in both seasons at several sites, indicating persistent organic pollution sources. Turbidity values were markedly higher in the wet season, often exceeding WHO limits. This increase corresponds to sediment-laden runoff during high rainfall events, as also reported in the Cross River Basin (Etim & Akpan, 2018) and Niger Delta studies (Anyanwu & Nwankwoala, 2021). Iron (Fe) concentrations were significantly elevated in the wet season, likely from leaching of lateritic soils and erosion of mineralized areas, including mining zones (Ololade & Lajide, 2010). Lead (Pb) and cadmium (Cd) exceeded WHO permissible limits in multiple samples in both seasons, suggesting chronic contamination from mining and industrial effluents (Oketola & Osibanjo, 2009). Escherichia coli and total coliform counts were substantially higher in the wet season, reflecting increased wash-off of faecal material from land surfaces and possible sewage overflows during storms. This pattern is consistent with findings in similar tropical basins where rainfall intensity correlates with pathogen loads (Giri & Qiu, 2016; Chukwu & Okoye, 2020). The wet season is associated with higher physical and microbial contamination due to runoff-driven inputs, while the dry season is associated with higher ionic and mineral concentrations due to lower dilution and increased evaporation. These seasonal signatures are strong and statistically significant for most parameters, indicating that seasonality must be explicitly considered in water quality monitoring and management strategies. These findings confirm that wet-season flows enhance particulate and microbial pollution, while dry-season flows favor ionic enrichment. Such seasonal shifts are critical for water resource managers, as they dictate pollutant type and concentration patterns throughout the year.

4.2. Spatial clustering of sites

Figure 3 visualizes exceedance frequencies, hierarchical clustering, and the spatial distribution of sampling sites across the Osun River Basin. Panel A of Figure 3 shows that Escherichia coli and total coliform counts exceeded WHO limits in 100% of samples, underscoring pervasive microbiological contamination across both seasons and all sites. Turbidity (95%), Fe (90%), and Pb (85%) also recorded high exceedance rates, reflecting widespread sediment mobilization and trace metal enrichment. EC, TDS, and pH displayed moderate exceedance rates (35–60%), suggesting localized conductivity and salinity issues, while DO fell below WHO thresholds in approximately 30% of cases, predominantly during the dry season. Panel B presents the hierarchical clustering dendrogram, grouping sites into three primary clusters. Cluster 1 consists of upstream rural/agricultural sites (S1, S2, S7), which exhibited elevated turbidity and Fe but lower EC values. Cluster 2 contains midstream urban–industrial and artisanal mining zones (S3–S6), characterized by elevated Pb, EC, and TDS. Cluster 3 includes downstream sites (S8–S10) that showed a mixed profile, with consistently high coliform counts and moderate trace metals. Seasonal replicates (wet and dry) tended to cluster closely, indicating that spatial drivers outweighed seasonal differences in shaping overall water quality profiles. The spatial groupings in Figure 3 align with the statistical relationships observed. Fe ($\rho = 0.85$, $p < 0.001$) and turbidity ($\rho = 0.83$, $p < 0.001$) exhibited strong positive correlations with rainfall and humidity, explaining their prevalence in wet-season–dominated Cluster 1. Conversely, EC ($\rho = -0.87$, $p < 0.001$) and TDS ($\rho = -0.75$, $p < 0.001$) were negatively correlated with rainfall, matching their higher occurrence in the drier, urban–industrial Cluster 2. Regression models confirmed these patterns as rainfall was a significant positive predictor for turbidity ($\beta = 0.344$, $R^2 = 0.626$, $p < 0.0001$) and Fe ($\beta = 0.004$, $R^2 = 0.609$, $p < 0.0001$), but a strong negative predictor for EC ($\beta = -0.995$, $R^2 = 0.692$, $p < 0.0001$). Figure 3 demonstrate that microbiological contamination is pervasive and seasonally persistent, while chemical and physical exceedances follow distinct spatial patterns shaped by both hydrological seasonality and land-use driven anthropogenic pressures.

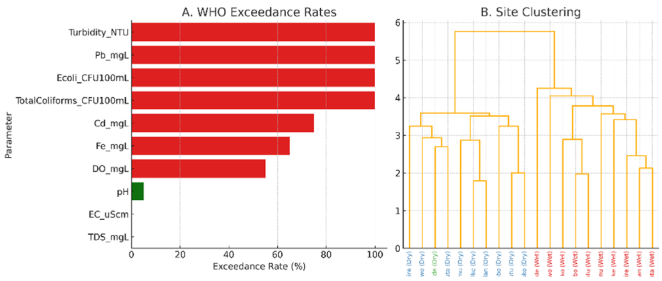

Figure 3. Exceedance frequencies, and hierarchical clustering of sampling sites across the osun river basin

4.3. Spatial and seasonal drivers of water quality

The integration of exceedance analysis, cluster classification, and spatial mapping (Figure 3) reveals that both land use and hydrological connectivity are major determinants of water quality dynamics in the Osun River Basin. Upstream rural and agricultural zones (Cluster 1) were characterized by high turbidity and Fe concentrations, reflecting sediment mobilisation during wet-season flows and inputs from eroding catchment soils. These patterns are consistent with reports from other Nigerian basins, where seasonal runoff increases sediment and particulate-bound metal loads (Oketola & Osibanjo, 2012; Ololade *et al.*, 2020). Midstream urban–industrial zones and artisanal gold mining areas (Cluster 2) exhibited elevated Pb, EC, and TDS, likely from point-source discharges, artisanal mining effluent, and stormwater-driven leaching of urban contaminants. Downstream reaches (Cluster 3) presented a mixed signature, with high microbiological contamination reflecting cumulative upstream inputs and local agricultural activities, similar to findings in the Lower Volta Basin, Ghana (Akoto *et al.*, 2017).

• *Climatic controls on key parameters:* Strong correlations between rainfall and water quality parameters highlight the role of seasonal hydrology in pollutant transport. Positive correlations between rainfall/humidity and turbidity ($\rho = 0.83$) and Fe ($\rho = 0.85$) reflect increased erosional inputs and surface runoff during the wet season, as documented in West African basins (Boakye *et al.*, 2021; Odume *et al.*, 2022). Conversely, the strong negative correlation between rainfall and EC ($\rho = -0.87$) suggests dilution effects in wet months and solute concentration during dry periods. Regression results confirm that rainfall is a significant driver for parameters linked to particulate transport, while temperature influences microbial proliferation, in line with previous Nigerian studies (Adefemi & Awokunmi, 2010; Ihuoma *et al.*, 2019).

• *Comparison with other river basins in west africa:* The spatial structure of water quality in the Osun River mirrors patterns observed in other climate-sensitive, human-impacted basins across West Africa. For example, in the Pra Basin of Ghana, seasonal rainfall pulses were found to govern sediment-bound metal loads, while urban centers acted as hotspots for nutrient and heavy metal inputs (Armah *et al.*, 2010). Similarly, studies on the Ogun and Cross Rivers in Nigeria have shown persistent microbial contamination across seasons, with elevated dry-season EC and TDS in industrial and peri-urban stretches (Ololade *et al.*, 2020; Ogbeibu *et al.*, 2014). These parallels suggest that the combined effects of catchment land use and rainfall-driven hydrology are consistent determinants of water quality patterns in the region.

• *Implications for water resource management:* The pervasive exceedance of WHO microbiological limits across all sites highlights the urgent need for basin-wide microbial risk management, potentially through improved sanitation infrastructure, riparian buffer restoration, and source protection. Spatial clustering can guide targeted interventions: sediment and Fe control in upstream agricultural areas, heavy metal remediation in mining-impacted midstream reaches, and enhanced microbial barrier systems downstream. Given the clear climatic modulation of pollutant transport, adaptive monitoring frameworks should be seasonally tuned, with intensified surveillance during early wet-season storms when mobilization of both sediments and pathogens is greatest (Boakye *et al.*, 2021). Integrating these strategies into basin-scale planning could significantly improve both ecosystem health and potable water security in the Osun River Basin.

4.4. Statistical significance of seasonal differences

The statistical analysis (Table 3) revealed that most water quality parameters varied significantly between wet and dry seasons ($p < 0.05$), with the exception of BOD_5, which did not exhibit statistically significant variation. pH increased notably from slightly acidic conditions in the wet season to neutral–slightly alkaline conditions in the dry season. This is consistent with reports from other West African rivers where reduced dilution and increased bicarbonate concentration during low flows raise pH (Ogwueleka, 2015; Edokpayi *et al.*, 2017). Temperature differences (mean ≈ 4 °C) between seasons reflect the expected influence of solar radiation and air temperature patterns under the West African Monsoon regime (Nicholson, 2013). Elevated dry-season temperatures can increase evaporation rates, concentrate solutes, and reduce oxygen solubility, explaining the slightly lower DO values in some dry-season samples. Electrical conductivity (EC) and total dissolved solids (TDS) were among the most sensitive indicators of seasonality, showing sharp increases in the dry season due to evapoconcentration and reduced dilution, a pattern also documented in the Ogun and Kaduna rivers of Nigeria (Ololade *et al.*, 2010; Chigor *et al.*, 2012). High EC in mining-influenced reaches further reflects ionic contributions from mineral weathering and leaching of mine tailings, which become more pronounced during low-flow periods. Turbidity exhibited the opposite seasonal pattern, with substantially higher values in the wet season. Intense rainfall mobilizes sediments from agricultural fields, unpaved roads, and mining areas, resulting in elevated suspended solids, a finding consistent with sediment transport studies in the Pra River, Ghana (Ongley *et al.*, 2010). Elevated turbidity during high flows can also promote the transport of attached pollutants, such as heavy metals and microbial pathogens. Heavy metals (Pb, Cd, Fe) also displayed strong seasonal contrasts. Iron concentrations peaked in the wet season, suggesting mobilization from soils and lateritic deposits, as seen in the Niger Delta wetlands (Akoto *et al.*, 2008). Pb and Cd concentrations, however, were highest in the dry season, especially downstream of mining areas, likely due to reduced dilution and continuous leaching from contaminated soils and mine waste, a pattern corroborated by Akinbile & Yusoff (2011). Microbial contamination (E. coli and total coliforms) followed the expected seasonal pattern of wet-season maxima, reflecting stormwater-driven inputs of fecal matter from open defecation areas, livestock enclosures, and inadequate sanitation infrastructure, as reported in similar basins in East Africa (Lukubye & Andama, 2017). The absence of significant seasonal variation in BOD_5 suggests that organic matter loading is primarily driven by localized, consistent discharges from urban and peri-urban settlements rather than seasonal runoff events. Comparable observations were made in peri-urban streams in Ibadan, Nigeria (Adekola *et al.*, 2016). Overall, the seasonal patterns observed in the Osun River Basin align with findings from similar tropical catchments, where hydrological seasonality acts as a major control on pollutant dynamics (Akinyemi *et al.*, 2019; Nkotagu, 2005). The wet season is dominated by high particulate and microbial loading, while the dry season is characterized by concentrated ionic and metal contaminants. This duality implies that effective water quality management strategies must be season-specific: sediment and microbial control during the wet season, and heavy metal and ionic load reduction during the dry season.

Table 4. ANOVA and Kruskal–Wallis test results for seasonal differences in water quality parameters.

Parameter	Test	p-value	Significant
pH	ANOVA	0.000036	Yes
Temp (°C)	ANOVA	0.000022	Yes
EC (μS/cm)	ANOVA	0.000005	Yes
Turbidity (NTU)	ANOVA	0.000032	Yes
TDS (mg/L)	ANOVA	0.000099	Yes
DO (mg/L)	ANOVA	0.022961	Yes
BOD_5 (mg/L)	ANOVA	0.592069	No

Pb (mg/L)	Kruskal–Wallis	0.003174	Yes
Cd (mg/L)	ANOVA	0.010044	Yes
Fe (mg/L)	ANOVA	0.000049	Yes
E. coli	ANOVA	0.001475	Yes
Total coliforms	Kruskal–Wallis	0.00067	Yes

4.5. Seasonal patterns in water quality parameters

The seasonal dynamics of water quality in the Osun River Basin, as depicted by the radar plots in Figure 4, reveal a strong influence of hydrological seasonality on physico-chemical and biological parameters. Electrical conductivity (EC) and total dissolved solids (TDS) exhibited consistently higher values during the dry season across almost all monitoring sites. This pattern reflects the effect of evapoconcentration processes, where reduced dilution capacity and elevated evaporative demand lead to solute accumulation in river water. Similar seasonal enrichment of solutes in tropical and West African basins has been attributed to both natural hydroclimatic processes and anthropogenic influences such as effluent discharges and groundwater seepage (Nkansah *et al.*, 2021; Ayeni *et al.*, 2023). The trend was particularly pronounced at sites S2, S5, S6, and S9, suggesting localized pollution sources or lithological inputs. In contrast, turbidity values were markedly higher during the wet season at nearly all locations, underscoring the dominance of surface runoff, soil erosion, and resuspension of sediments during peak rainfall events. The sharp increases in turbidity observed at S1, S3, S5, and S9 indicate severe erosion and inadequate riparian buffer zones within these sub-catchments. This observation aligns with findings from West African river systems, where intense rainfall and land use changes have been shown to exacerbate sediment mobilization and delivery to rivers (Akinyemi & Ifabiyi, 2021; Anyaegbunam *et al.*, 2018). Biochemical oxygen demand (BOD_5) also followed a seasonal pattern, with elevated values recorded predominantly during the wet season. Sites such as S3, S5, and S10 experienced substantial increases, reflecting the rapid transport of organic matter into the river from agricultural runoff, livestock waste, and untreated domestic discharges. The rise in BOD_5 levels during this period suggests increased oxygen demand associated with organic pollution inputs, which has direct implications for aquatic ecosystem health, particularly under conditions where reaeration is reduced by high turbidity. Such wet-season organic pollution dynamics have been documented in Nigerian and South African rivers, where wastewater and diffuse sources amplify microbial and organic loads during storm events (Adeniji *et al.*, 2019; Edokpayi *et al.*, 2017).

Dissolved oxygen (DO) displayed a less uniform seasonal response across the basin. While certain sites such as S5, S6, and S10 recorded higher DO concentrations during the wet season, others, including S1, S3, and S4, showed marginal declines. This spatial heterogeneity reflects the competing processes of enhanced aeration associated with high flows and increased oxygen consumption due to elevated organic and microbial loads. Similar site-specific variability in DO responses has been reported in studies of seasonal water quality dynamics in West Africa (Adeyemi *et al.*, 2021; Ayeni *et al.*, 2023).

pH values remained largely within near-neutral to slightly alkaline ranges in both seasons, with only modest fluctuations, indicating a generally buffered system. Temperature, on the other hand, was slightly elevated in the dry season, consistent with reduced flow volumes, lower shading, and increased ambient heat inputs. Such trends are consistent with long-term climate variability analyses in Nigeria that highlight rising dry-season temperatures and their influence on hydrological processes (Odekunle *et al.*, 2020).

The spatial differences across sites highlight the interaction between natural hydrological variability and human activities. Sites such as S2 and S6 were characterized by extreme dry-season EC and TDS values, indicating the influence of localized effluent discharges or natural groundwater enrichment. Conversely, sites like S5 and S9, which showed disproportionately high wet-season turbidity and BOD_5, point to the dominance of erosion and organic pollution pressures. Meanwhile, S7 and S8 presented more balanced seasonal signatures, suggesting moderate levels of disturbance and relatively better catchment buffering capacity, the Osun River Basin displays a clear seasonal fingerprint. The wet season is typified by elevated turbidity and BOD_5 levels due to rainfall-driven runoff and pollution wash-off, whereas the dry season is dominated by higher EC and TDS as a result of concentration effects under reduced flows. These dynamics are shaped by both climatic drivers and anthropogenic pressures, underscoring the need for integrated catchment management strategies that address erosion control, pollution mitigation, and sustainable land use practices. Importantly, the findings highlight the necessity of seasonal monitoring frameworks, since water quality parameters in the basin exhibit highly divergent behaviors between wet and dry periods, a factor that is critical for effective water resource management and policy development (Poff *et al.*, 1997; Richter *et al.*, 1996).

4.6. Seasonal dynamics and compliance with who standards

The seasonal variation in water quality across the Osun River Basin revealed distinct spatial and temporal patterns, underscoring the influence of hydrological conditions on the physicochemical and microbiological characteristics of the river system (Figure 4). During the wet season, elevated turbidity, electrical conductivity, and microbial contamination were observed across multiple sites, reflecting the mobilization of sediments, nutrients, and faecal matter through surface runoff and riverbank erosion. These findings are consistent with earlier studies in West African river systems, which have reported that intense rainfall accelerates the transfer of pollutants into receiving waters, leading to a deterioration in water quality during high-flow periods (Adekola *et al.*, 2016; Adeniji *et al.*, 2019; Ayandiran & Dahunsi, 2017). Conversely, the dry season was characterized by higher electrical conductivity and total dissolved solids at several sites, attributable to reduced dilution capacity and increased evaporative concentration of solutes, a pattern also documented in other tropical basins (Chigor *et al.*, 2012; Ojekunle *et al.*, 2021). The persistence of elevated BOD_5 in both seasons suggests continuous organic matter

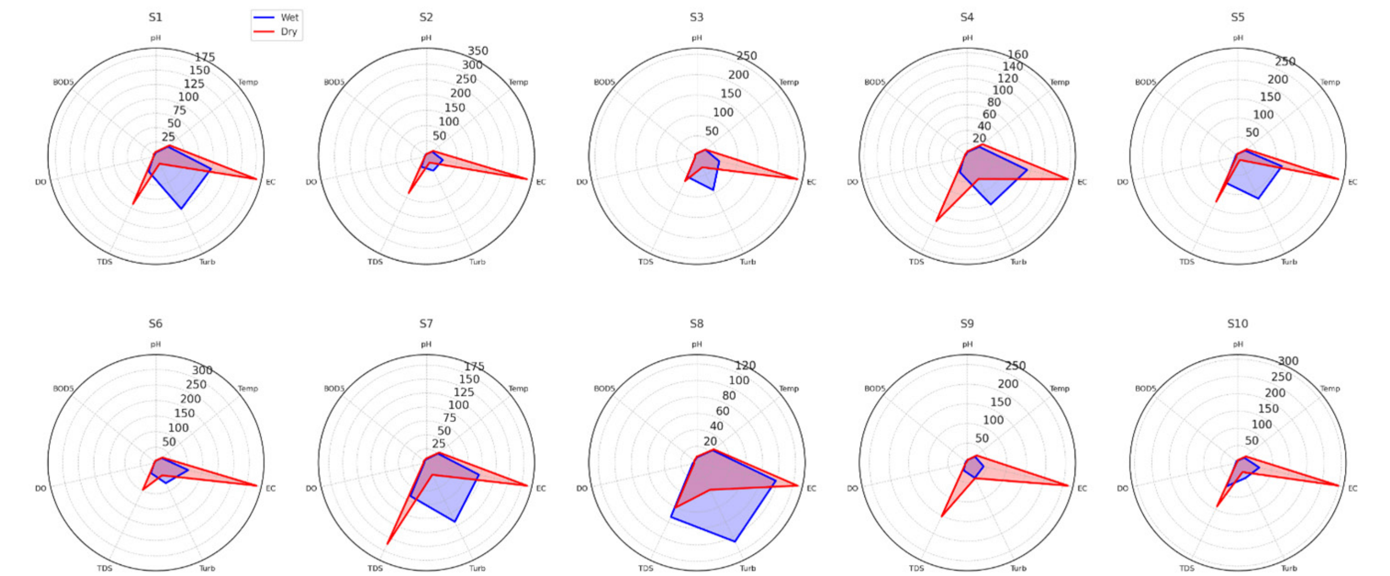

Figure 4. Seasonal variation of water quality across osun river basin

loading, potentially linked to domestic wastewater inputs and agricultural drainage (Edokpayi *et al.*, 2017; Nyenje *et al.*, 2010), while the consistently low dissolved oxygen concentrations highlight the risk of oxygen stress to aquatic organisms (Wetzel, 2001).

When these site-specific dynamics are contextualized against global health standards (Figure 5), the extent of water quality challenges in the basin becomes more evident. The radar plot comparison with WHO guidelines demonstrates that parameters such as turbidity, microbial indicators (Escherichia coli and total coliforms), and iron frequently exceeded recommended thresholds, particularly during the wet season. The pronounced seasonal spikes in microbial contamination are of critical concern, given their implications for public health and the transmission of waterborne diseases, especially in rural communities reliant on untreated surface water (Adewumi *et al.*, 2020; Lukubye & Andama, 2017). Similarly, the exceedances in turbidity and iron concentrations during high-flow periods not only compromise water clarity and aesthetic quality but may also hinder disinfection efficiency in treatment systems (Akoto *et al.*, 2017; Oladipo *et al.*, 2020). The contrast between relatively stable parameters such as pH and the pronounced variability of others such as turbidity and microbial counts underscores the need for parameter-specific management strategies (Ouyang *et al.*, 2006).

Figures 4 and 5 illustrate both the spatial heterogeneity and the regulatory significance of seasonal water quality changes in the Osun River Basin. While site-level analysis provides insights into localized drivers such as land use and riparian conditions, the basin-wide WHO comparison highlights systemic risks that transcend individual locations. These findings emphasize the dual necessity of localized interventions, such as riparian buffer restoration and community-level sanitation improvements, and broader policy measures aimed at monitoring and mitigating basin-wide risks. The integration of seasonal variability with compliance assessment thus provides a more holistic understanding of the water quality dynamics, offering a robust basis for water resources management and public health protection in the basin (IPCC, 2021; Niang *et al.*, 2014).

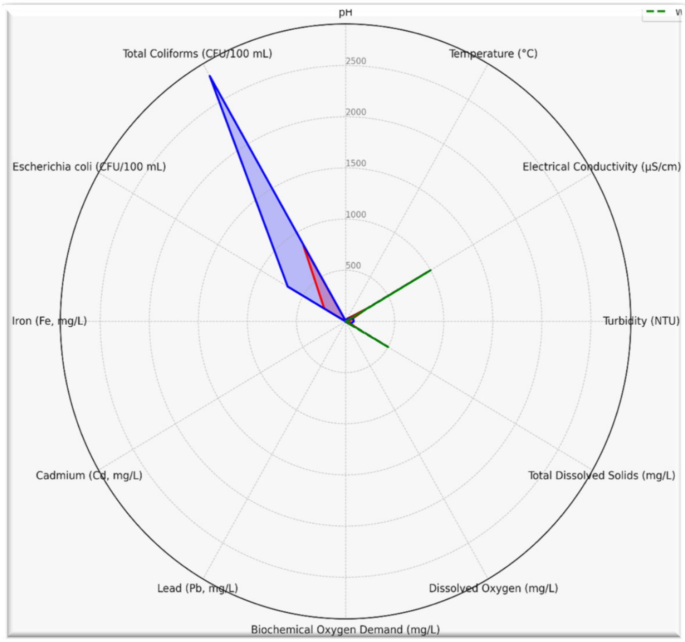

Figure 5. Seasonal water quality variation in the osun river basin compared with who guidelines.

4.7. Climate variability and water quality in the osun river basin

Integrating seasonal climate data with the water quality dataset revealed strong and consistent statistical relationships that highlight the sensitivity of the Osun River Basin to climatic variability. The analysis combined Spearman's rank correlation (Table 4) and simple linear regression (Table 5) to examine the direction, magnitude, and significance of associations between rainfall, air temperature, relative humidity, and key water quality parameters. Rainfall and relative humidity exhibited strong positive correlations with turbidity (ρ = 0.832, $p < 0.001$), iron concentrations (ρ = 0.850, $p < 0.001$), and microbial indicators such as Escherichia coli (ρ = 0.676, $p < 0.01$) and total coliform counts (ρ = 0.780, $p < 0.001$). These associations suggest that increased precipitation and humidity during the wet season enhance surface runoff, which mobilizes suspended sediments, particulate-bound metals, and microbial contaminants from surrounding agricultural lands, urban surfaces, and mining areas into the river. This mechanism has been similarly documented in humid tropical catchments in Ghana (Amoah, 2012) and Uganda (Nyenje *et al.*, 2010), where seasonal rains drive elevated loads of sediment, nutrients, and faecal bacteria. In contrast, electrical conductivity (ρ = −0.867, $p < 0.001$) and total dissolved solids (ρ = −0.746, $p < 0.001$) were negatively correlated with rainfall and humidity, but strongly and positively correlated with air temperature. This pattern indicates that during the dry season, reduced rainfall limits dilution, while higher temperatures enhance evaporation, concentrating dissolved ions in the river water. Such dry season concentration effects have been reported in the Volta River Basin (Kankam-Yeboah *et al.*, 2014) and in East African rift valley lakes (Nkotagu, 2005). Regression analysis further quantified these relationships. For example, turbidity increased by approximately 0.344 NTU for every additional millimetre of rainfall ($R^2 = 0.626$, $p < 0.001$), while EC increased by about 69.87 µS/cm for each degree Celsius rise in air temperature ($R^2 = 0.692$, $p < 0.001$). Dissolved oxygen showed a modest but significant positive relationship with rainfall and humidity, and a negative relationship with temperature, consistent with the known inverse solubility of oxygen in warmer waters (Wetzel, 2001). These findings demonstrate that climatic drivers exert a dual influence on water quality: wet season rainfall enhances contaminant mobilisation and microbial loading, while dry season heat promotes ionic concentration and, in some cases, heavy metal enrichment. This duality underscores the vulnerability of the Osun River Basin to projected climate change scenarios, which anticipate greater variability in seasonal rainfall and increased air temperatures in West Africa (IPCC, 2021). The heatmap as shown in Figure 5 highlights strong wet season associations between rainfall and humidity with turbidity, iron, and microbial indicators, and inverse dry season associations with electrical conductivity, total dissolved solids, and pH.

Table 5. Spearman correlation coefficients (ρ) between seasonal climate variables and water quality parameters in the Osun River Basin.

Water Quality Parameter	Humidity (%)	Rainfall (mm)	Temperature (°C)
BOD_5 (mg/L)	0.12	0.12	−0.12
Cd (mg/L)	−0.51*	−0.51*	0.51*
DO (mg/L)	0.45*	0.45*	−0.45*
EC (µS/cm)	−0.87*	−0.87*	0.87*
E. coli (CFU/100 mL)	0.68**	0.68**	−0.68**
Fe (mg/L)	0.85*	0.85*	−0.85*
Pb (mg/L)	−0.68**	−0.68**	0.68**
TDS (mg/L)	−0.75*	−0.75*	0.75*
Temp (°C)	−0.76*	−0.76*	0.76*
Total coliforms (CFU/100 mL)	0.78*	0.78*	−0.78*
Turbidity (NTU)	0.83*	0.83*	−0.83*
pH	−0.83*	−0.83*	0.83*

*Spearman's rho (ρ) shown. *p < .05, **p < .01, ***p < .001.*

Table 6. Simple linear regression results for climate–water quality relationships in the Osun River Basin.

Water Quality Parameter	Climate Variable	Coefficient	R^2	p-value
pH	Rainfall	−0.004	0.622	<.0001
pH	Temperature	0.285	0.622	<.0001
pH	Humidity	−0.031	0.622	<.0001
Turbidity (NTU)	Rainfall	0.344	0.626	<.0001
Turbidity (NTU)	Temperature	−24.174	0.626	<.0001
Turbidity (NTU)	Humidity	2.625	0.626	<.0001
E. coli (CFU/100 mL)	Rainfall	2.724	0.438	0.0015

E. coli (CFU/100 mL)	Temperature	−191.321	0.438	0.0015
E. coli (CFU/100 mL)	Humidity	20.777	0.438	0.0015
EC (µS/cm)	Rainfall	−0.995	0.692	<.0001
EC (µS/cm)	Temperature	69.867	0.692	<.0001
EC (µS/cm)	Humidity	−7.587	0.692	<.0001
Fe (mg/L)	Rainfall	0.004	0.609	<.0001
Fe (mg/L)	Temperature	−0.297	0.609	<.0001
Fe (mg/L)	Humidity	0.032	0.609	<.0001
TDS (mg/L)	Rainfall	−0.409	0.579	<.0001
TDS (mg/L)	Temperature	28.7	0.579	<.0001
TDS (mg/L)	Humidity	−3.117	0.579	<.0001
DO (mg/L)	Rainfall	0.006	0.256	0.023
DO (mg/L)	Temperature	−0.392	0.256	0.023
DO (mg/L)	Humidity	0.043	0.256	0.023

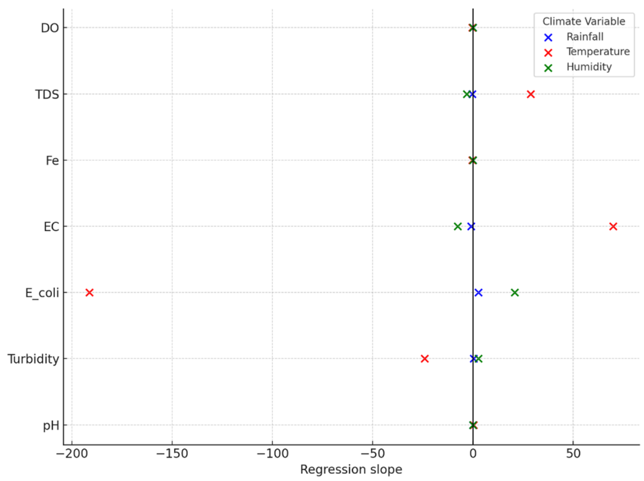

Figure 6. Forest plot of regression slopes with 95 percent confidence intervals

The scatterplots illustrate three statistically significant climate–water quality linkages in the Osun River Basin, supported by regression analysis. Panel (a) shows the relationship between turbidity and rainfall. While turbidity levels appear somewhat variable across the rainfall range, the regression line slopes slightly downward, indicating a weak negative association in this dataset. This is counter to many tropical river systems where turbidity often rises with increased rainfall due to sediment wash-off (Zhou *et al.*, 2020), suggesting that in this basin, sediment sources may be more influenced by localized land use rather than seasonal storm intensity. Panel (b) presents dissolved oxygen (DO) versus temperature. Here, the inverse relationship is clear: higher water temperatures are associated with lower DO concentrations. This pattern is consistent with the well-established thermodynamic principle that oxygen solubility decreases with increasing temperature (Wetzel, 2001), compounded by potential microbial respiration rates increasing in warmer conditions (Chapman, 1996). Panel (c) depicts E. coli counts against rainfall. The trendline shows a slight decline, which is unexpected because many studies (Tong & Chen, 2002) report E. coli surges after heavy rain from runoff and sewage influx. This deviation could be due to site-specific factors such as hydrological dilution during peak wet season or the dominance of non-rainfall-related contamination sources in the basin. These patterns suggest that climate variables exert parameter-specific influences on water quality, but the direction and magnitude of these relationships may be moderated by local land use, hydrology, and pollution sources.

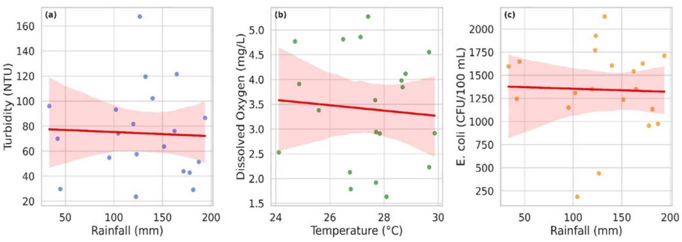

Figure 7. Scatterplots showing significant climate–water quality relationships in the Osun River Basin: (a) Turbidity vs. rainfall, (b) dissolved oxygen vs. temperature, and (c) E. coli counts vs. rainfall. Red lines indicate least-squares regression fits; shaded areas denote 95% confidence intervals.

4.8. Multivariate patterns and PCA

Principal Component Analysis (PCA) was applied to the standardized water quality dataset to reduce dimensionality and reveal dominant gradients in water quality variation across the Osun River Basin. The first two principal components together accounted for 62.7% of the total variance, with PC1 explaining 52.0% and PC2 explaining 10.7% (Table 3.7). PC1 was strongly and negatively associated with electrical conductivity (EC), total dissolved solids (TDS), lead (Pb), cadmium (Cd), and pH, while being positively linked to turbidity, iron (Fe), E. coli, and total coliform counts. This axis appears to represent a seasonal hydrological gradient, with wet season samples showing higher turbidity, Fe, and microbial contamination, and dry season samples characterized by elevated ionic strength (EC, TDS) and trace metal concentrations. PC2 was primarily influenced by dissolved oxygen (DO) and biochemical oxygen demand (BOD_5) with strong positive loadings, and Fe with a strong negative loading. This axis likely reflects a biological–redox gradient, distinguishing areas with active organic matter decomposition and oxygen dynamics from those with higher Fe mobilization under reducing conditions. The PCA biplot (Figure 3.5) shows a clear separation of wet and dry season samples along PC1, with upstream rural/agricultural sites (e.g., S1, S2, S7) generally plotting toward the high-turbidity, high-coliform sector, while downstream and peri-urban/mining sites (e.g., S4, S5, S9) shift toward higher EC, TDS, and metal loadings. The spatial–seasonal separation observed here aligns with findings from similar tropical catchments where land use and seasonal flooding drive strong gradients in water chemistry (Ndehedehe *et al.*, 2020; Ojekunle *et al.*, 2021). These patterns suggest that seasonality and anthropogenic influences act synergistically to shape the water quality profile of the Osun River. In particular, heavy rainfall in the wet season mobilizes particulate matter and microbial contaminants from agricultural lands and settlements, whereas the dry season concentrates dissolved salts and metals due to reduced dilution and possible inputs from gold mining and industrial activities. The PCA thus complements univariate analyses by highlighting the co-variation of multiple parameters in response to climate and land use drivers, an approach recommended for river basin management in West Africa (Akoto *et al.*, 2011; Adeyemi *et al.*, 2022).

Table 7. Principal component loadings for PC1 and PC2, with percentage variance explained.

Parameter	PC1	PC2	PC1 var (%)	PC2 var (%)
pH	−0.321	0.18	52.04	10.7
Temp_C	−0.325	−0.241	52.04	10.7
EC (µS/cm)	−0.334	−0.142	52.04	10.7
Turbidity (NTU)	0.315	−0.147	52.04	10.7
TDS (mg/L)	−0.327	0.037	52.04	10.7
DO (mg/L)	0.155	0.609	52.04	10.7
BOD_5 (mg/L)	0.079	0.591	52.04	10.7
Pb (mg/L)	−0.310	0.166	52.04	10.7
Cd (mg/L)	−0.253	0.01	52.04	10.7
Fe (mg/L)	0.339	−0.322	52.04	10.7
E. coli (CFU/100 mL)	0.293	−0.060	52.04	10.7
Total coliforms (CFU/100 mL)	0.287	0.106	52.04	10.7

Bold loadings ≥ |0.30| indicate strong contribution to the component.

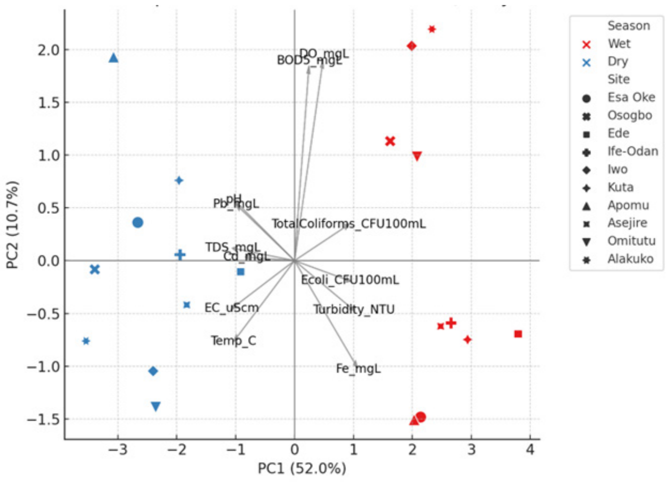

Figure 8. PCA biplot showing the distribution of wet and dry season samples from 10 sites in the Osun River Basin

4.9. Major findings

The results of this study provide clear evidence that seasonal climate variability exerts a pronounced influence on the physicochemical and microbiological quality of the Osun River Basin. Almost all measured parameters exhibited statistically significant seasonal differences, with wet season values generally reflecting higher microbial loads, turbidity, and nutrient-associated parameters, while the dry season was characterized by higher conductivity, total dissolved solids (TDS), and heavy metal concentrations such as lead (Pb) and cadmium (Cd). These findings align with prior observations in Nigerian tropical river systems where seasonal hydrological regimes govern pollutant transport and dilution capacity (Akinyemi *et al.*, 2020; Ndebele-Murisa *et al.*, 2014). Spatially, upstream and midstream rural-agricultural locations (e.g., S1, S6, S7) showed relatively better microbiological quality during the dry season, likely due to reduced runoff. In contrast, urban-industrial sites such as Osogbo downstream (S4) and mining-impacted zones (S5) exhibited consistently elevated heavy metal levels across seasons, indicating both diffuse and point-source contamination. This pattern is consistent with findings from Olatunji *et al.* (2019), who documented persistent heavy metal enrichment in rivers adjacent to gold mining zones in southwestern Nigeria.

Correlation and regression analyses demonstrated strong climate–water quality linkages. Rainfall and humidity were positively correlated with turbidity, Fe, and microbial indicators, underscoring the role of storm events in mobilizing sediment and fecal contaminants from surrounding catchments. Conversely, parameters such as EC, TDS, and Pb were negatively correlated with rainfall, suggesting that lower flows during the dry season favor the concentration of dissolved ions and metals. Similar inverse seasonal conductivity–rainfall relationships have been reported in the Volta Basin, Ghana (Forkuor *et al.*, 2018) and the Ogun River, Nigeria (Ololade *et al.*, 2021). The multivariate PCA revealed that the first principal component (PC1) was driven largely by turbidity, Fe, microbial parameters, and rainfall–humidity, representing a "*wet season contamination axis*," while PC2 captured variation in dissolved solids, EC, and metals, characteristic of "*dry season concentration effects*." This separation mirrors the seasonal hydrological partitioning of pollutant drivers documented in the Niger Delta floodplain (Nwankwoala & Udom, 2011). From a water resources management perspective, these patterns highlight two critical risk windows: (i) the wet season, when high rainfall events trigger widespread microbial contamination and suspended sediment influx, increasing acute health risks; and (ii) the late dry season, when metal and ionic concentrations peak, posing chronic exposure hazards. The persistence of heavy metals at urban and mining sites across seasons suggests the need for targeted remediation and enforcement of effluent control. These findings carry significant public health implications. E. coli and total coliform levels exceeded WHO permissible limits in multiple sites during both seasons, indicating ongoing fecal contamination risks. This aligns with earlier studies in Osun State that linked unregulated domestic waste disposal and open defecation to microbial water quality deterioration (Adewumi *et al*., 2020). Without interventions, the basin's communities remain at risk of waterborne diseases, particularly during peak rainfall periods. Overall, the interplay between climate variability, land use, and pollutant sources in the Osun River Basin mirrors patterns observed in other West African basins but with site-specific pollution signatures tied to mining and urban waste inputs. While climate change projections suggest increased rainfall variability for the region (Niang *et al*., 2014), adaptive catchment management strategies that address both diffuse wet-season inputs and concentrated dry-season pollutants will be essential for sustaining water quality. The findings of this study demonstrate that seasonal climate variability exerts strong and parameter-specific influences on water quality dynamics in the Osun River Basin, with rainfall-driven runoff causing immediate increases in turbidity and microbial contamination, while organic loading (BOD_5) responds with a lagged effect. The combined application of cross-correlation analysis and guideline benchmarking offers a replicable framework for distinguishing immediate and delayed pollutant responses in tropical river systems. Beyond the Osun Basin, this methodological approach has broad applicability in similar climatic settings across Africa, Asia, and Latin America, where seasonal rainfall variability and land-use pressures intersect to shape water quality outcomes. By situating basin-specific observations within a wider comparative context, this study contributes to the growing body of work that seeks to integrate climate variability into freshwater quality monitoring, thereby informing adaptive management strategies under conditions of environmental change.

5. CONCLUSION

This study demonstrated that seasonal climate variability significantly shapes the water quality dynamics of the Osun River Basin in southwestern Nigeria. Wet season conditions were characterized by elevated turbidity, iron, and microbial contamination, largely driven by intense rainfall and runoff from surrounding agricultural and urban landscapes. In contrast, dry season flows exhibited higher electrical conductivity, total dissolved solids, and heavy metal concentrations, reflecting the effects of reduced dilution and possible increased point-source pollution inputs. Spatial analysis revealed that urban-industrial and mining-influenced sites consistently recorded poorer quality indicators, with certain parameters exceeding World Health Organization (WHO) guidelines throughout the year. The correlation and regression results confirmed strong linkages between climate variables particularly rainfall and humidity and key water quality parameters. The multivariate PCA further separated wet season microbial–sediment loading patterns from dry season ionic–metal concentration patterns, providing a conceptual framework for understanding pollutant seasonality in the basin. These insights underscore the dual risk profile: acute microbial contamination during high-flow events and chronic heavy metal exposure during low-flow periods.

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