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Multivariate Statistical Assessment of Surface Water Quality and Pollution Sources in Jakara River Basin, Northwestern Nigeria

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Abstract

This study investigates the physicochemical parameters and heavy metal concentrations in Jakara River, Kano State, Nigeria, using multivariate statistical techniques to identify pollution sources and assess water quality status. Fourteen water quality parameters were analyzed across multiple sampling points, including temperature, pH, dissolved oxygen (DO), biochemical oxygen demand (BOD), Total Dissolved Solids (TDS), Electrical Conductivity (EC), Turbidity, Nutrients (NO_3^-, PO_4^{3-}) were analyzed using Standard methods, and Heavy Metals (Pb, Cd, Cu, Cr, Ni) were analyzed using Atomic Absorption Spectrophotometer (AAS) (PerkinElmer AAnalyst 400). Pearson correlation analysis revealed significant positive correlations between TDS and NO_3^- ($r = 0.516$, $p < 0.01$), indicating common pollution sources. Principal Component Analysis (PCA) extracted five varimax factors explaining 64.58% of total variance, representing: (1) erosion-induced turbidity and metal contamination, (2) mineral dissolution and agricultural runoff, (3) organic pollution from domestic wastewater, (4) heavy metal contamination from anthropogenic activities, and (5) natural physicochemical processes. The KMO (0.600) and Bartlett's sphericity test ($\chi^2 = 607.337$, $p < 0.01$) confirmed PCA suitability. Mean concentrations showed elevated TDS (535.25 mg/L), EC (1055.27 μS/cm), and turbidity (113.24 NTU), with some parameters exceeding national and international guidelines. The findings demonstrate significant anthropogenic impacts from agricultural activities, domestic wastewater discharge, and urban runoff, posing ecological risks and potential human health concerns. This research provides critical baseline data for water resource management and pollution control strategies in semi-arid urban river systems.

Introduction

Deterioration of water quality in freshwater ecosystems constitutes a critical global environmental challenge, especially in developing areas facing rapid urbanisation, agricultural intensification, and insufficient wastewater management (Anyanwu & Nwachukwu, 2020; Ipeaiyeda & Obaje, 2017). Surface water bodies in semi-arid regions are highly susceptible due to limited dilution capacity, seasonal hydrological variability, and escalating anthropogenic pressures (Mustapha et al., 2014). The Jakara River, which flows through the Kano metropolis and its agricultural hinterland in northwestern Nigeria, is an urban plain river subjected to even more pollution inputs from domestic, industrial, and agricultural sources.

Nitrate pollution is a common occurrence in freshwater systems globally, arising from both natural sources such as atmospheric deposition and soil organic matter nitrification, as well as anthropogenic activities including the use of inorganic fertilizers, manure, and septic waste (Gutiérrez et al., 2018). Elevated nitrate concentrations promote eutrophication, toxic algal blooms, and hypoxia, which basically alter the structure and function of aquatic ecosystems (Wu et al., 2020). In addition, nitrate-contaminated drinking water presents significant health issues, including methemoglobinemia, thyroid disorders, and gastric cancer (Ward et al., 2018), 2019a, 2019b).

The urban rivers must face wider range of issues like persistence, bioavailability and adverse impact to aquatic organisms or humans (Anyanwu & Nwachukwu, 2020). Lead (Pb), cadmium (Cd), chromium (Cr), copper (Cu) and nickel (Ni) are introduced in aquatic systems from geological weathering, Industrial effluents, agricultural amendments and atmospheric deposition (Anyanwu & Nwachukwu, 2020; Upahi et al., 2021).

It has been observed that multivariate statistical techniques, especially Principal Component Analysis (PCA) and Factor Analysis (FA), have been applied to extract meaning from the heavy, multiyear water quality dataset through dimension reduction and to identify causative pollutant sources (Mustapha & Aris, 2012). These methodologies convert the correlated original variables into uncorrelated principal components to reveal latent patterns and improve source apportionment (Mustapha & Aris, 2012).

The objectives of this study are to: determine the physicochemical and heavy metal status of Jakara River water, use correlation analysis to clarify inter-parameter interactions, use PCA/FA to identify the main sources of pollution, and evaluate the implications for human health and the environment. The findings provide a scientific basis for targeted pollution control strategies and sustainable water resource management in similar semi-arid urban river systems across sub-Saharan Africa.

Materials and Methods

Study Area and Location

Jakara River is located in Kano State, northwestern Nigeria (latitude 11°50' to 12°30' N, longitude 8°20' to 9°00' E), draining through both agricultural and urban landscapes before discharging into the Challawa River system. The region experiences a semi-arid climate with distinct wet (June–September) and dry (October–May) seasons, mean annual rainfall of 800–900 mm, and temperatures ranging from 16°C to 38°C. The river receives untreated domestic sewage, industrial effluents, agricultural runoff, and solid waste leachate, making it representative of anthropogenically impacted water bodies in developing regions.

Sample Collection and Analyses

Water samples were taken at several locations along the Jakara River for one year. Standard procedures were followed for sampling, preservation, and transportation (APHA, 2017). Calibrated portable meters (Hanna Instruments) were used to measure temperature, pH, dissolved oxygen (DO), and electrical conductivity (EC) in situ. Following a five-day incubation period at 20°C, the biochemical oxygen demand (BOD) was measured. EC readings were used to compute total dissolved solids (TDS). A turbidimeter (Hach 2100Q) was used to measure turbidity. Using standard colourimetric techniques, nitrate (NO_3^-) and phosphate (PO_4^{3-}) were measured with UVvisible spectrophotometry (Shimadzu UV-1800). Following acid digestion, heavy metals (Pb, Cd, Cu, Cr, and Ni) were measured using atomic absorption spectrophotometry (PerkinElmer AA Analyst 400). Reagent blanks, duplicate samples, and certified reference materials with recoveries between 90 and 110% were all part of quality assurance.

Statistical Analysis

Data were analysed using IBM SPSS® version 20 and Excel Stat 2013 (Microsoft Office®). Normality was assessed using the Shapiro-Wilk test, and parameters with skewed distributions were log-transformed before analysis. Pearson correlation matrix was computed to examine inter-parameter relationships. Suitability for PCA was evaluated using the Kaiser-Meyer-Olkin (KMO) measure of sampling adequacy (>0.5 acceptable) and Bartlett's test of sphericity ($p < 0.05$). PCA with varimax rotation (Kaiser normalisation) was applied to extract principal components with eigenvalues >1, representing dominant pollution sources. Factor loadings >0.5 were considered significant for interpretation (Ustaoğlu et al., 2020). Descriptive statistics (range, minimum, maximum, mean ± standard error) were calculated for all parameters.

Results

Table 1 presents descriptive statistics for fourteen water quality parameters in the Jakara River. Water temperature ranged from 16.50 to 34.00°C (mean 25.51 ± 0.16°C), reflecting seasonal and diurnal variations. pH values differed from slightly acidic (6.10) to alkaline (9.00), with a mean of 7.59 ± 0.02, indicating predominance of alkaline conditions potentially influenced by dissolved minerals. Dissolved oxygen ranged widely from 0.80 to 8.90 mg/L (mean 5.05 ± 0.06 mg/L), with minimum values approaching hypoxic conditions. BOD ranged 0.10 to 12.32 mg/L (mean 2.31 ± 0.04 mg/L), suggesting variable organic pollution loads.

TDS showed considerable variation (42.00–2140.00 mg/L, mean 535.25 ± 12.21 mg/L), with maximum exceeding NDWQS desirable limit (500 mg/L). EC ranged 20.00–4360.00 µS/cm (mean 1055.27 ± 29.26 µS/cm), indicating substantial mineralization. Turbidity exhibited extreme variation (12.70–1730.00 NTU, mean 113.24 ± 12.29 NTU), reflecting high suspended solids from erosion and runoff.

Nitrate concentrations ranged 3.10–154.11 mg/L (mean 13.47 ± 0.78 mg/L), with maximum exceeding drinking water guidelines. Phosphate ranged 0.06–15.87 mg/L (mean 3.15 ± 0.11 mg/L), indicating nutrient enrichment. Heavy metal concentrations (mg/L) followed: Pb (0.00–0.49, mean 0.1318 ± 0.01), Cd (0.00–0.23, mean 0.0351 ± 0.00), Cu (0.00–0.41, mean 0.0741 ± 0.01), Cr (0.00–1.46, mean 0.1661 ± 0.01), Ni (0.00–0.21, mean 0.0997 ± 0.00).

Pearson Correlation Analysis

Pearson correlation matrix (Table 2) revealed significant relationships among parameters, indicating common sources and biogeochemical coupling. Temperature showed weak positive correlations with pH ($r = 0.250$, $p < 0.01$), turbidity ($r = 0.148$, $p < 0.01$), Pb ($r = 0.151$, $p < 0.01$), and a negative correlation with DO ($r = -0.209$, $p < 0.01$), consistent with temperature-dependent oxygen solubility.

A strong positive correlation between TDS and NO_3^- ($r = 0.516$, $p < 0.01$) suggests agricultural runoff as a common source, as nitrate from fertilisers contributes to dissolved solids. EC correlated positively with TDS ($r = 0.473$, $p < 0.01$) and NO_3^- ($r = 0.340$, $p < 0.01$), reflecting ionic contribution from dissolved salts and nutrients.

DO exhibited significant negative correlations with BOD ($r = -0.478$, $p < 0.01$), TDS ($r = -0.376$, $p < 0.01$), turbidity ($r = -0.415$, $p < 0.01$), NO_3^- ($r = -0.284$, $p < 0.01$), Pb ($r = -0.268$, $p < 0.01$), and Ni ($r = -0.323$, $p < 0.01$), indicating oxygen depletion associated with organic pollution and contaminant loading.

Heavy metals displayed inter-correlations: Pb-Cd ($r = 0.298$, $p < 0.01$), Pb-Cu ($r = 0.352$, $p < 0.01$), Pb-Ni ($r = 0.283$, $p < 0.01$), Cd-Cu ($r = 0.263$, $p < 0.01$), Cd-Ni ($r = 0.284$, $p < 0.01$), suggesting common anthropogenic sources. Cr showed positive correlations with pH ($r = 0.160$, $p < 0.01$), NO_3^- ($r = 0.251$, $p < 0.01$), PO_4^{3-} ($r = 0.200$, $p < 0.01$), and negative correlations with Pb (r = -0.247, $p < 0.01$) and Cd (r = -0.183, $p < 0.01$), indicating different source pathways.

Principal Component Analysis

The Kaiser-Meyer-Olkin (KMO) measure of sampling adequacy was 0.600, and Bartlett's test of sphericity was significant ($\chi^2 = 607.337$, $p < 0.01$), assuring PCA's suitability. PCA extracted five principal components with eigenvalues >1, explaining 64.58% of total variance after varimax rotation (Table 3). This indicates effective dimensionality reduction with minimal information loss.

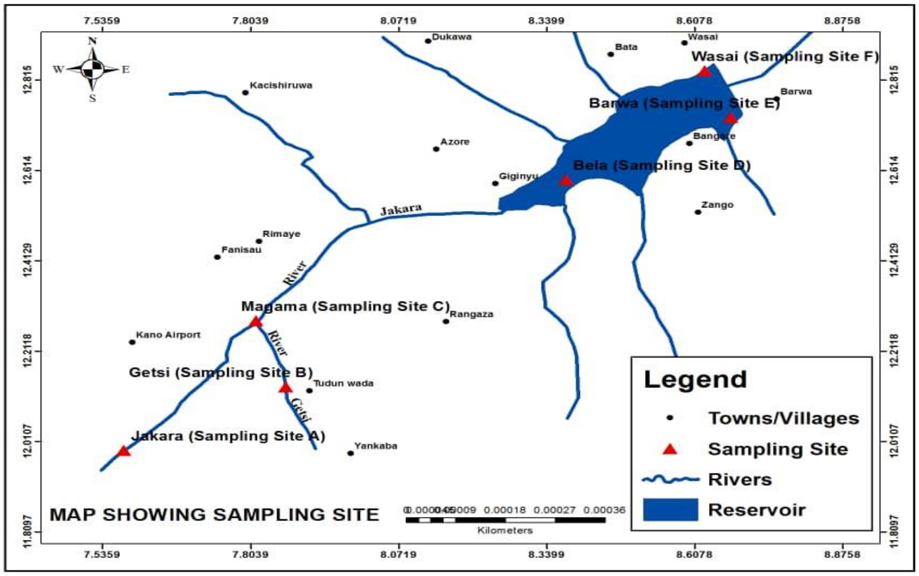

Figure 1: Map of Jakara River showing the sampling sites and/or locations

Source: Cartography lab FUD (July 2024)

Table 1: Descriptive Statistics of Water Quality Parameters in Jakara River

Parameters	Range	Min	Max	Mean ± Standard Error
Temp (°C)	17.50	16.50	34.00	25.51± 0.16
pH	2.90	6.10	9.00	7.59 ± 0.02
DO(mg/l)	8.10	.80	8.90	5.05 ± 0.06
BOD(mg/l)	12.22	.10	12.32	2.31 ± 0.04
TDS(mg/l)	2098.00	42.00	2140.00	535.25 ± 12.21
EC(uS/cm)	4340.00	20.00	4360.00	1055.27 ± 29.26
Tur(NTU)	1717.30	12.70	1730.00	113.24 ± 12.29
NO_3(mg/l)	151.01	3.10	154.11	13.47 ± 0.78
PO_4(mg/l)	15.81	0.06	15.87	3.15 ± 0.11
Pb(mg/l)	0.49	0.00	0.49	0.1318 ± 0.01
Cd(mg/l)	0.23	0.00	0.23	0.0351 ± 0.00
Cu(mg/l)	0.41	0.00	0.41	0.0741 ± 0.01
Cr(mg/l)	1.46	0.00	1.46	0.1661 ± 0.01
Ni(mg/l)	0.21	0.00	0.21	0.0997± 0.00
Valid N (listwise)				

Key(s): Temperature (Temp), Dissolved Oxygen (DO), Biochemical Oxygen Demand (BOD), Total Dissolved Solids (TDS), Electrical Conductivity (EC), Turbidity (Tur), Nitrate (NO3). Phosphate (PO4), Lead (Pb), Cadmium (Cd), Copper (Cu), Chromium (Cr), Nickel (Ni)

Table 2: Pearson Correlation Matrix of Physicochemical Parameters in Jakara River

	Temp	pH	DO	BOD	TDS	EC	Tur	NO_3	PO_4	Pb	Cd	Cu	Cr	Ni
Temp	1													
pH	.250**	1												
DO	-.209**	0.092	1											
BOD	-0.069	.272**	-.478**	1										
TDS	-0.036	-0.008	-.376**	-0.07	1									
EC	.097*	0.046	-.162**	0.039	.473**	1								
Tur	.148**	0.013	-.415**	-.268**	0.029	-.477**	1							
NO_3	-.095*	.149**	-.284**	.178**	.516**	.340**	-0.039	1						
PO_4	-0.071	.149**	-0.023	.276**	.216**	.117*	-0.031	.389**	1					
Pb	.151**	-0.043	-.268**	-.145**	0.076	-0.056	.420**	-.112*	0.048	1				
Cd	.109*	0.017	-0.069	-.128**	0.091	-.134**	.380**	-0.09	-.150**	.298**	1			
Cu	.118*	0.076	0.078	0.078	-0.009	0.024	0.079	-0.064	.115*	.352**	.263**	1		
Cr	-.161**	.160**	.103*	.123*	0.022	0.044	-.164**	.251**	.200**	-.247**	-.183**	.184**	1	
Ni	-0.079	0.025	-.323**	-.105*	.221**	-0.036	.226**	.242**	0.002	.283**	.284**	0.023	0.069	1

** Correlation is significant at the 0.01 level (2-tailed).
Correlation is significant at the 0.05 level (2-tailed).
Key(s): Temperature (Temp), Dissolved Oxygen (DO), Biochemical Oxygen Demand (BOD), Total Dissolved Solid (TDS), Electrical Conductivity (EC), Turbidity (Tur), Nitrate (NO3). Phosphate (PO4), Lead (Pb), Cadmium (Cd), Copper (Cu), Chromium (Cr), Nickel (Ni)

Table 3: Rotated Component Matrix and Variance of Physicochemical parameters and Heavy Metals in Jakara River

Parameter	PC1	PC2	PC3	PC4	PC5
Turbidity	0.693	-0.219	-0.225	0.337	0.243
Ni	0.638	0.202	-	0.255	-0.155
DO	-0.523	-0.517	0.409	-	-0.197
TDS	0.198	0.804	-	-	-
EC	-0.411	0.804	-	-	-
NO_3^-	0.266	0.652	0.431	-0.152	-
BOD	-0.217	-0.139	0.705	-	0.104
PO_4^{3-}	0.152	0.266	0.602	-	-
Cr	-	-	0.582	-	-0.170
Cu	-0.190	-	0.269	0.782	-
Pb	0.260	-	-0.178	0.698	0.102
Cd	0.135	-	-0.165	0.684	-
Temp	-0.124	-	-0.248	0.148	0.812
pH	-	-	0.460	-	0.686
Eigenvalue	2.847	2.435	1.684	1.555	1.166
Variance (%)	18.983	16.231	11.224	10.369	7.771
Cumulative (%)	18.983	35.215	46.439	56.808	64.578

Extraction Method: Principal Component Analysis. Rotation Method: Varimax with Kaiser Normalisation. Rotation converged in 7 iterations. Loadings >0.4 shown in bold.

Discussion

Erosion-Induced Turbidity and Metal Contamination (18.98% Variance)

The first principal component (PC1) showed strong positive loading for turbidity (0.693) and Ni (0.638), with moderate negative loading for DO (-0.523). This component represents erosion and surface runoff processes transporting suspended solids and particle-bound metals into the river system. Turbidity, reflecting suspended and colloidal particles too small to settle (Mustapha et al., 2014), indicates soil erosion from agricultural lands and urban surfaces during rainfall events. The positive Ni loading suggests association of this metal with suspended particulate matter, consistent with its affinity for clay minerals and organic matter.

The negative DO loading (-0.523) indicates oxygen depletion accompanying turbidity events, attributable to several mechanisms: (1) reduced light penetration limiting photosynthetic oxygen production; (2) respiratory oxygen consumption by suspended microorganisms; and (3) biochemical oxygen demand from organic matter associated with eroded particles. Similar negative DO-turbidity relationships have been reported in anthropogenically-impacted rivers (Shrestha & Kazama, 2007; Mustapha et al., 2014). This component aligns with observations by Kovacevik et al. (2016) and Mustapha et al. (2019) that erosive processes in urban and rural areas mobilize soil materials into water systems. Rainfall infiltration dissolves host materials and minerals, adding dissolved and particulate constituents to water bodies. The mixed sources of groundwater pollution associated with PC1 reflect the complexity of non-point source pollution in mixed land-use catchments.

Ecologically, elevated turbidity and reduced DO synergistically impair aquatic life. High turbidity reduces visual feeding efficiency in fish, smothers benthic habitats, and decreases primary production (Ipeaiyeda & Obaje, 2017). Low DO causes mortality, alters behavior and distribution, and reduces growth rates of aquatic organisms (Breitburg, 2002). The combination represents significant degradation of aquatic ecosystem -health in Jakara River.

Mineral Dissolution and Agricultural Runoff (16.23% Variance)

PC2 exhibited strong positive loadings for TDS (0.804), EC (0.804), and NO_3^- (0.652), representing mineral content and nutrient enrichment from agricultural activities. TDS and EC reflect total dissolved ions, including major cations (Ca^{2+}, Mg^{2+}, Na^+, K^+) and anions (HCO_3^-, Cl^-, SO_4^{2-}) derived from rock weathering, soil leaching, and anthropogenic inputs (Mustapha et al., 2014).

The strong NO_3^- loading within this component confirms agricultural runoff as primary nitrate source, consistent with global patterns of fertilizer-driven nitrate pollution (Ward et al., 2018; Gutiérrez et al., 2018). Nitrate has become the second most significant chemical contaminant of surface and ground waters after pesticides (Gutiérrez et al., 2018), with concentrations in Jakara River (mean 13.47 mg/L) approaching or exceeding guideline values.

The TDS-NO_3^- association reflects simultaneous input of dissolved salts and nitrogen fertilizers from agricultural lands. Similar patterns have been attributed to drainage returning from irrigated agriculture and wastewater discharges (Mustapha et al., 2014). The biogeochemical processes governing pollutant fate during transport include dissolution/precipitation, adsorption, complexation, ion exchange, and biotic/abiotic degradation, modulated by soil characteristics and aquifer matrix composition (Gutiérrez et al., 2018). Elevated TDS (>500 mg/L maximum desirable level) poses health risks, particularly for individuals with heart and kidney diseases (Shrestha & Basnet, 2018). High EC values (mean 1055.27 μS/cm) indicate significant mineralization, potentially affecting water suitability for irrigation and domestic use.

Organic Pollution from Domestic Wastewater (11.22% Variance)

PC3 showed significant loadings for BOD (0.705), PO_4^{3-} (0.602), Cr (0.582), pH (0.460), and NO_3^-

(0.431), representing organic pollution from domestic wastewater discharge. BOD, measuring oxygen required for microbial decomposition of organic matter, directly indicates biodegradable organic pollution. The positive loading of phosphate, often limiting nutrient in freshwater systems, confirms wastewater influence, as domestic sewage contains phosphates from detergents and human waste. The dual loading of nitrate (also in PC2) suggests multiple sources: agricultural runoff and wastewater. Phosphate loading (0.602) indicates nutrient enrichment promoting eutrophication. Chromium occurrence may reflect industrial contributions or natural weathering, though positive correlation with organic pollution parameters suggests wastewater-mediated transport.

The pH loading (0.460) reflects biogeochemical processes during organic matter decomposition. Aerobic bacteria decompose organic materials to produce CO_2, nitrates, sulfates, and carbonates, influencing pH. When oxygen becomes limiting, anaerobic decomposition generates methane, ammonia, hydrogen sulfide, and amines—substances with unpleasant odors and toxic properties (Ipeaiyeda & Obaje, 2017). Biodegradable organic compounds cause diverse water quality problems: harmful algal blooms, reduced transparency, oxygen depletion, taste and odor issues, fish kills, and biodiversity loss (Mustapha & Aris, 2012). Nutrient enrichment from organic pollution seriously degrades aquatic ecosystems, impairing water uses for drinking, industry, agriculture, and recreation.

Heavy Metal Contamination from Anthropogenic Activities (10.37% Variance)

PC4 exhibited strong loadings for Cu (0.782), Pb (0.698), and Cd (0.684), representing heavy metal contamination from multiple anthropogenic sources. The co-loading of these metals suggests common source pathways or similar geochemical behavior. Pb and Cd are typically associated with transportation (vehicle emissions, tire wear) and agricultural activities (pesticides, fertilizers), while Cu may derive from both geologic sources and anthropogenic inputs (agrochemicals, industrial discharges). Cd, the most toxic among these metals with high health risks, is particularly linked to phosphate fertilizers and pesticides in agricultural systems (Anyanwu & Nwachukwu, 2020). Pb contamination in urban rivers often reflects historical and ongoing atmospheric deposition from leaded gasoline, industrial emissions, and urban runoff. Cu, while essential micronutrient, becomes toxic at elevated concentrations and may originate from fungicides, algicides, and industrial effluents (Anyanwu & Nwachukwu, 2020).

The grouping of these metals in a single component indicates that their concentrations in Jakara River are controlled by similar factors, likely mixed urban-agricultural sources. This finding aligns with studies showing that metals in surface waters often exhibit spatial coherence when derived from diffuse anthropogenic sources (Anyanwu & Nwachukwu, 2020).

Natural Physicochemical Processes (7.77% Variance)

PC5 showed strong loadings for temperature (0.812) and pH (0.686), representing natural physicochemical processes giving a baseline for water quality. Temperature, a primary factor affecting aquatic biota, controls metabolic rates, dissolved gas solubility, and chemical reaction kinetics. Aligned with DO, temperature provides vital signs for defining the health of a river ecosystem (Chapra et al., 2021).

pH loading reflects natural buffering processes, including carbonate equilibria, silicate weathering, and biological activity (photosynthesis/respiration). The pH range observed (6.10–9.00) indicates capacity to accommodate both acidic and alkaline inputs while remaining within tolerance limits for most aquatic organisms at mean values (7.59). The separation of these parameters from pollution-related components suggests that while temperature and pH respond to natural drivers, they may also modulate ecosystem responses to pollutant inputs. Temperature effects on metal toxicity, nutrient cycling, and oxygen dynamics are well-documented, highlighting indirect roles in water quality degradation.

Conclusions

This study demonstrates the effectiveness of multivariate statistical techniques for assessing complex water quality data and identifying pollution sources in the Jakara River. The major conclusions are:

Jakara River water quality shows significant spatial and seasonal variations, with several parameters (TDS, turbidity, NO_3^-, heavy metals) exceeding guideline values at certain locations, indicating pollution pressure.

Pearson correlation analysis revealed significant inter-parameter relationships, particularly TDS-NO_3^- coupling, DO depletion with pollution indicators, and metal associations suggesting common sources.

PCA extracted five dominant pollution sources explaining 64.58% of variance: erosion-induced turbidity and metal transport (PC1), mineral dissolution and agricultural runoff (PC2), organic pollution from domestic wastewater (PC3), heavy metal contamination from mixed anthropogenic activities (PC4), and natural physicochemical processes (PC5).

Agricultural activities, domestic wastewater discharge, and urban runoff represent the primary pollution sources affecting the river, with implications for eutrophication, oxygen depletion, metal toxicity, and human health risks.

Integrated management strategies addressing multiple pollution sources through catchment-based approaches, combining regulatory controls, best management practices, and infrastructure development, are essential for restoring and protecting Jakara River water quality.

This research provides scientific baseline for evidence-based water resource management in semi-arid urban river systems and demonstrates methodological approaches applicable to similar environments globally.

Environmental Implications and Management Recommendations

The PCA results revealed that the quality of Jakara River water is affected by multiple pollution sources requiring integrated management approaches, such as agricultural pollution in PC2 and PC3 components, which necessitates improved fertiliser management, buffer zones along waterways, and promotion of sustainable agricultural practices to reduce runoff of nutrient. Extension services promoting precision fertiliser application and integrated nutrient management could significantly reduce nitrate and phosphate loads.

Erosion and sedimentation (PC1) require catchment-level soil conservation measures, including contour farming, terracing, revegetation of riparian zones, and construction of sediment traps. Urban stormwater management incorporating retention basins and green infrastructure can reduce turbidity from urban runoff. Domestic wastewater (PC3) demands investment in sewage treatment infrastructure. Given the resource constraints in developing regions, decentralised treatment systems may provide cost-effective solutions for reducing organic pollution.

Heavy metal contamination (PC4) requires source-directed controls: regulation of industrial effluents, phasing out leaded products, promoting clean production technologies, and establishing vehicle emission standards. Phytoremediation and sediment dredging may be considered for contaminated hotspots.

Water quality monitoring should be strengthened through regular sampling, inclusion of additional parameters (biological indicators, emerging contaminants), and engagement of citizen science programs to enhance spatial and temporal coverage.

Conflict of Interest

The author declares no conflict of interest regarding the publication of this manuscript

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