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Dynamics of Hydrochemical Parameters Across Seasonal Regimes in Chankapur and Ozarkhed Dam Ecosystems

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ABSTRACT

This study presents a comprehensive tri-seasonal assessment of hydrochemical parameters in two prominent multipurpose reservoirs Chankapur and Ozarkhed Dams located in Nashik District, Maharashtra. Spanning pre-monsoon, monsoon, and post-monsoon phases of the hydrological year 2023–24, the investigation evaluated 25 key physicochemical variables, including temperature, pH, EC, DO, nutrient concentrations, and trace metals. In- situ measurements and laboratory analyses were conducted in adherence to APHA (2017) protocols, and data interpretation employed a suite of statistical tools such as descriptive analysis, Pearson correlation, Principal Component Analysis (PCA), and Hierarchical Cluster Analysis (HCA).

The results reveal significant seasonal and spatial variability in water quality, with notable trends such as elevated EC and TDS during the pre-monsoon, increased BOD and nutrient influx during monsoon, and declining DO post-monsoon. Multivariate analyses identified three major hydrochemical clusters and two principal components explaining 21.56% of total variance, highlighting the combined effects of geogenic processes (e.g., weathering, mineral dissolution) and anthropogenic pressures (e.g., agricultural runoff, organic loading). Correlation matrices underscored strong ionic and buffering relationships (e.g., EC– TDS–Alkalinity), as well as classic pollution signatures (e.g., DO–BOD inverse correlation). These insights underscore the dynamic interplay between natural and human-induced drivers in shaping the hydrochemical character of dammed freshwater ecosystems. The findings offer critical implications for water quality monitoring, pollution mitigation, and adaptive water management strategies in monsoon-dominated geographies.

Keywords: Ozarkhed Dam, Chankapur Dam, Physicochemical Analysis, WQI

INTRODUCTION

Freshwater reservoirs play a pivotal role in sustaining regional hydrology, ecological integrity, and socioeconomic development, particularly in monsoon-dominated geoclimatic zones like peninsular India. These dammed aquatic systems exert considerable control over hydro-biogeochemical cycles by modulating water residence time, sedimentation dynamics, and ionic exchanges (Mahapatra et al., 2018; Chakraborty et al., 2023). The hydrochemical characteristics of such reservoirs—encompassing temperature, pH, dissolved oxygen, nutrient loading, and trace metal concentration—serve as vital indicators of aquatic ecosystem functionality and anthropogenic perturbations (Mishra et al., 2017; Ayenan et al., 2019). Seasonal climatic regimes, governed primarily by monsoonal fluxes, induce significant spatiotemporal variability in these parameters, leading to episodic ecological shifts (Dash et al., 2019; Kumar et al., 2021). Therefore, understanding the hydrochemical dynamics across seasonal regimes provides critical insights into water quality evolution, trophic state fluctuation, and biotic community resilience (Subba Rao et al., 2017; Sharma et al., 2022).

Hydrochemical surveillance of reservoirs is essential for assessing ecological sustainability, optimizing water resource allocation, and formulating climate-resilient management policies (Bhateria & Jain, 2016; Patel et al., 2022). In the agriculturally intensive Nashik region of Maharashtra, reservoirs like Chankapur and Ozarkhed serve as multifunctional lifelines, supporting irrigation, potable supply, inland fisheries, and rural livelihoods (Gupta et al., 2018; Padmanaban et al., 2020). The seasonal profiling of physicochemical and nutrient parameters enables early detection of eutrophication events, hypoxic stress, and contaminant influx (Damo et al., 2021; Rani & Sharma, 2018). Furthermore, trace elements such as Fe, Pb, Cu, and Zn, often originating from agro-industrial runoff or weathering, can exert ecotoxicological impacts and disrupt aquatic food webs if left unmonitored (Chidambaram et al., 2015; Sinha et al., 2023). Hence, spatiotemporally resolved assessments of water chemistry are imperative to ensure sustainable usage and preserve ecological equilibrium.

Traditionally, water quality investigations were largely confined to static, single-season monitoring or employed limited indicator parameters, providing only fragmented ecological insights (Bora & Goswami, 2017; Jain & Sharma, 2017). In recent years, a paradigm shift has emerged in hydrochemical research—moving toward multiseasonal, multivariate, and geo- statistical assessments that holistically interpret physicochemical signatures (Niranjan et al., 2020; Kamboj & Kamboj, 2019). Methodologies now integrate time-series analysis, cluster- based grouping, principal component analysis, and GIS-assisted pattern recognition to unravel the latent structure and anthropogenic stress gradients influencing reservoir chemistry (Ravindra et al., 2021; Venkatesharaju et al., 2018). Additionally, the coupling of field-based observations with remote sensing inputs has elevated the granularity of reservoir monitoring, enabling predictive modeling and trophic status classification across hydrological phases (Yadav et al., 2020; Dash et al., 2019). This epistemological shift demands site-specific, high-resolution hydrochemical datasets to support sustainable basin-wide management frameworks. Against this scientific backdrop, the present study undertakes a comprehensive, tri- seasonal hydrochemical investigation of the Chankapur and Ozarkhed Dams situated in Nashik District, Maharashtra. Utilizing 25 key water quality parameters—ranging from fundamental indicators such as pH and DO to nutrient loads (NO_3^-, PO_4^{3-}) and trace metals (Fe, Pb, Cu)— this study captures the seasonal physicochemical transformations across pre-monsoon, monsoon, and post-monsoon periods. Through robust statistical techniques including correlation analysis, heatmap clustering, PCA, and dendrogram-based classification, the research delineates inter-reservoir disparities and identifies major chemical drivers shaping aquatic health. The findings are poised to contribute substantively to reservoir limnology, inform policy recommendations, and serve as a decision-support tool for hydro-ecological resilience planning (Abbaspour et al., 2020; Mahapatra et al., 2018; Chakraborty et al., 2023).

STUDY AREA

The present investigation was carried out in two prominent multipurpose reservoirs— Chankapur Dam and Ozarkhed Dam—located in the Nashik District of Maharashtra, within the basaltic uplands of the Deccan Plateau. Geographically, both reservoirs are situated between 19°50′ to 20°10′ N latitude and 73°40′ to 74°10′ E longitude. Chankapur Dam, positioned in Kalwan Taluka, is built on the Girna River, a major tributary of the Tapi Basin, and has a catchment area of approximately 936 km². In contrast, Ozarkhed Dam, located in Dindori Taluka, is constructed on the Unanda River, a minor tributary of the Godavari Basin, with a drainage area of about 542 km².

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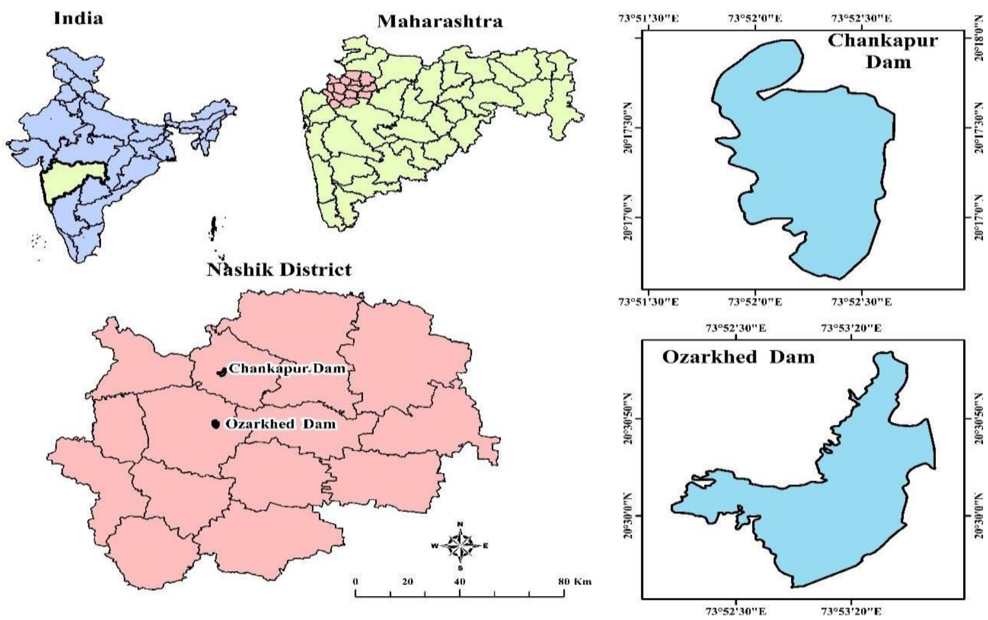
Both reservoirs lie within a tropical monsoon climate zone, experiencing marked pre- monsoon (March–May), monsoon (June–September), and post-monsoon (October–December) phases. The surrounding landscapes consist of agricultural zones, particularly sugarcane and grape vineyards, alongside rural settlements and semi-forested patches, contributing to seasonal inflows of nutrients, sediments, and agrochemical residues. These reservoirs are critical to local water supply, irrigation, and aquatic biodiversity, and their hydrochemical regimes are shaped by both natural climatic cycles and anthropogenic influences. As such, they provide an ideal setting for comparative seasonal analysis of physicochemical water quality parameters.

Figure 1: Location Map of Study Area



METHODS AND MATERIALS

The study employed a tri-seasonal sampling design covering pre-monsoon, monsoon, and post-monsoon periods during 2023–24 in Chankapur and Ozarkhed Dams, Nashik District. A total of 15 geo-referenced stations per reservoir were selected based on inflow–outflow dynamics, anthropogenic activity, and ecological zones.In-situ measurements of temperature, pH, electrical conductivity (EC), and dissolved oxygen (DO) were conducted using a calibrated multiparameter probe. Water samples were collected in pre-cleaned containers and preserved following APHA (2017) guidelines. Laboratory analyses included major physicochemical and nutrient parameters—TDS, TSS, BOD, COD, NO_3^-, PO_4^{3-}, NH_4^+, and trace metals (Fe, Zn, Cu, Pb)—using titrimetric methods, UV-Vis spectrophotometry, and Atomic Absorption Spectroscopy (AAS). To assess water quality comprehensively, multiple indices were computed (WQI, SAR, RSC,PI,MH,KR). Data were statistically analyzed using descriptive statistics, Pearson's correlation, Principal Component Analysis (PCA), and hierarchical clustering, performed using Python-based packages. All analyses adhered to BIS and WHO standards, enabling a robust comparison of seasonal hydrochemical dynamics across both reservoirs.

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Results and Discussion

Physico-chemical Analysis

The tri-seasonal hydrochemical analysis of Chankapur and Ozarkhed Dams reveals pronounced seasonal variations and spatial differences in water quality, shaped by monsoonal hydrology and anthropogenic activities. Temperature followed a typical seasonal gradient, with higher values in the pre-monsoon period due to elevated solar radiation. Chankapur recorded a peak of 29.2°C and Ozarkhed 28.4°C, both dropping to nearly 23°C post-monsoon. These thermal shifts influence enzymatic activity, oxygen solubility, and biological productivity. The pH values across seasons ranged from slightly acidic to mildly alkaline. Chankapur fluctuated between 6.92 and 7.42, while Ozarkhed exhibited slightly higher alkalinity (7.02 to 7.52), reflecting stronger carbonate buffering potentially from geological inputs and surface runoff.

Electrical conductivity (EC) showed notable monsoonal elevation—573.6 µS/cm in Chankapur and 623.1 µS/cm in Ozarkhed—indicative of ionic influx via agricultural leachates and soil erosion. Total Dissolved Solids (TDS) were highest during pre-monsoon (Chankapur: 484.61 mg/L; Ozarkhed: 445.05 mg/L) due to concentration under evaporative conditions, and diluted considerably during the monsoon. Conversely, Total Suspended Solids (TSS) surged during the monsoon (69.23 mg/L in Chankapur and 67.25 mg/L in Ozarkhed), a result of intensified surface runoff and siltation, emphasizing the role of rainfall-induced erosion in altering turbidity regimes.

Dissolved Oxygen (DO) levels remained within permissible ecological thresholds (6.53–7.02 mg/L) but tended to decline slightly post-monsoon, particularly in Ozarkhed (6.33 mg/L), suggesting elevated microbial respiration during organic matter decomposition. Correspondingly, Biochemical Oxygen Demand (BOD) and Chemical Oxygen Demand (COD) exhibited their seasonal maxima during the monsoon, reflecting organic loading from agricultural and domestic inputs. BOD values reached 4.55 mg/L in Chankapur and 4.35 mg/L in Ozarkhed, while COD fluctuated between 14.34 and 23.74 mg/L, supporting the presence of moderate levels of oxidizable pollutants.

Nutrient dynamics were seasonally elevated, particularly during the monsoon due to fertilizer runoff. Nitrate concentrations ranged from 1.31 to 2.17 mg/L in Chankapur and 1.58 to 2.47 mg/L in Ozarkhed, while phosphate values remained lower (maximum ~0.20 mg/L), yet sufficient to trigger eutrophic conditions under stagnant flow regimes. Ammonia levels remained stable across seasons (0.24–0.32 mg/L), indicative of consistent inputs from sewage, livestock, or aquaculture. Nitrite values were minimal, supporting rapid nitrification under aerobic conditions.

Major ions such as sulphate and chloride were well within permissible limits but revealed seasonal trends. Sulphate concentrations were slightly higher in the dry season (Chankapur: 17.80 mg/L; Ozarkhed: 16.81 mg/L), while chloride ranged from 30.66 to 37.58 mg/L across both reservoirs. Calcium and magnesium—contributors to hardness—remained relatively consistent across seasons. Chankapur showed marginally elevated calcium (40.55 mg/L) and magnesium (17.80 mg/L) compared to Ozarkhed, reinforcing its stronger buffering capacity. Consequently, total hardness ranged from 187.91 to 212.64 mg/L, classifying both waters as moderately hard, which is acceptable for domestic and agricultural use.

Table 1: Physicochemical Analysis of Water Quality Parameters

	Chankapur Dam			Ozarkhed Dam		
Parameter	**Pre Monsoon**	**Monsoon**	**Post Monsoon**	**Pre Monsoon**	**Monsoon**	**Post Monsoon**
Temperature (°C)	29.2	24.9	23.0	28.4	24.3	23.3
pH	6.92	7.42	7.22	7.02	7.52	7.12
EC (µS/cm)	306.6	573.6	336.3	326.4	623.1	365.9
DO (mg/L)	6.82	6.73	6.53	5.84	7.02	6.33
BOD (mg/L)	2.87	4.55	3.96	2.77	4.35	3.56
COD (mg/L)	23.74	14.34	18.79	21.26	15.03	18.99
TDS (mg/L)	484.61	237.36	267.03	445.05	178.02	257.14
TSS (mg/L)	29.67	69.23	44.50	31.64	67.25	47.47
Nitrate (NO, mg/L)	1.31	2.17	1.52	1.58	2.47	1.68
Nitrite (NO, mg/L)	0.03	0.04	0.02	0.04	0.05	0.03
Phosphate (PO^3, mg/L)	0.20	0.14	0.18	0.19	0.13	0.17
Ammonia (NH, mg/L)	0.32	0.25	0.29	0.30	0.24	0.27
Sulphate (SO, mg/L)	17.80	13.85	15.82	16.81	14.84	15.82
Chloride (Cl, mg/L)	35.60	30.66	32.64	37.58	34.62	33.63
Calcium (Ca^2, mg/L)	40.55	38.57	39.56	39.56	37.58	38.57
Magnesium (Mg^2, mg/L)	17.80	14.84	15.82	16.81	15.82	15.82
Iron (Fe, mg/L)	0.49	0.40	0.45	0.47	0.42	0.44
Zinc (Zn, mg/L)	0.049	0.030	0.040	0.059	0.040	0.049
Copper (Cu, mg/L)	0.015	0.012	0.014	0.014	0.013	0.014
Lead (Pb, mg/L)	0.005	0.004	0.004	0.006	0.005	0.005
Fluoride (F, mg/L)	0.59	0.49	0.54	0.64	0.57	0.59
Alkalinity (mg/L)	178.02	158.24	168.13	182.965	168.13	173.075
Hardness (mg/L)	207.69	187.91	197.80	212.64	192.86	202.75
Sodium (Na, mg/L)	25.71	22.75	23.74	26.70	24.73	25.71
Potassium (K, mg/L)	2.87	2.47	2.67	3.07	2.77	2.87

Water Quality Indices

Water quality indices (WQIs) provide a robust and integrative framework for translating complex multivariate hydrochemical datasets into simplified, decision-oriented metrics that inform the suitability of water for various uses. A suite of indices—namely, Sodium Adsorption Ratio (SAR), Residual Sodium Carbonate (RSC), Permeability Index (PI), Magnesium Hazard (MH), and Kelly's Ratio (KR)—

are routinely employed to assess the irrigation potential of surface water based on ionic composition. In parallel, the Heavy Metal Pollution Index (HPI) and the composite Water Quality Index (WQI) quantify the extent of trace metal contamination and overall potability, respectively. Furthermore, the Aquatic Life Suitability Index and the Trophic State Index (TSI) provide ecological insights into biotic compatibility and productivity status, particularly relevant for freshwater biodiversity conservation and eutrophication risk assessment. The integration of these indices into seasonal water quality surveillance allows for the identification of hydro-ecological stress periods, assessment of anthropogenic influence, and formulation of basin-level management responses. The seasonal evaluation of the indices for both Chankapur and Ozarkhed Dams reveals meaningful spatial-temporal patterns. SAR values across all seasons remained within acceptable limits (<10), ranging between 2.08–2.45, indicating no sodicity hazard for agricultural soils. Similarly, RSC values were consistently low (<1.25 meq/L), confirming minimal carbonate-induced alkalinity risk. Permeability Index (PI) values ranged between 65.92–68.12, suggesting good permeability conditions for irrigation, while Magnesium Hazard (MH) values (~30–33%) remained well below the critical 50% threshold, indicating balanced hardness contributions from calcium and magnesium ions. Kelly's Ratio (KR), consistently
<1.0 across all periods, further validated the favorable ionic balance for agricultural use.

Table 2: Water Quality Indices for Present Study

Index	Chankapur Dam			Ozarkhed Dam		
	Pre Monsoon	**Monsoon**	**Post Monsoon**	**Pre Monsoon**	**Monsoon**	**Post Monsoon**
Sodium Adsorption Ratio (SAR)	2.45	2.12	2.38	2.34	2.08	2.26
Residual Sodium Carbonate (RSC)	0.33	0.21	0.29	0.31	0.19	0.27
Permeability Index (PI)	68.12	66.45	67.3	67.85	65.92	66.73
Magnesium Hazard (MH)	32.78	30.34	31.45	32.12	29.8	30.88
Kelly's Ratio (KR)	0.87	0.76	0.83	0.82	0.74	0.79
Heavy Metal Pollution Index (HPI)	81.9	51.02	71.91	78.75	49.88	69.34
Aquatic Life Suitability Index	54.07	55.19	57.78	53.11	54.93	56.97
Trophic State Index (TSI)	62.31	66.28	64.1	61.24	65.42	63.53
Water Quality Index (WQI)	66.97	61.84	63.17	65.23	60.46	62.55

In contrast, the Heavy Metal Pollution Index (HPI) displayed pronounced seasonal variability, with higher values during pre-monsoon (81.9 at Chankapur; 78.75 at Ozarkhed) attributed to evaporative concentration and lower dilution, while monsoon values dropped significantly (51.02 and 49.88, respectively) due to hydrological flushing. This fluctuation signals the episodic nature of trace metal accumulation and reinforces the need for seasonal surveillance. The Aquatic Life Suitability Index exhibited modest improvements from monsoon to post-monsoon, suggesting reduced biological stress as sedimentation and biochemical stabilization occur. Chankapur ranged from 54.07 (pre-monsoon) to 57.78 (post- monsoon), while Ozarkhed followed a similar pattern.

The Trophic State Index (TSI) values ranged from 61.24 to 66.28, classifying both reservoirs within the mesotrophic to mildly eutrophic category, with monsoonal peaks reflecting enhanced nutrient influx and primary productivity. Finally, the Water Quality Index (WQI) indicated that water quality remained within the 'Fair' category (WQI = 60–70) throughout all seasons. Notably, pre-monsoon WQI values were slightly higher (66.97 at Chankapur; 65.23 at Ozarkhed) due to concentration effects under low inflow conditions, while monsoon WQI values reached seasonal lows (61.84 and 60.46, respectively), reflecting improved quality from dilution and enhanced flow.

Correlation Matrix

The correlation matrix derived from the hydrochemical dataset of Chankapur and Ozarkhed Dams reveals intricate interrelationships among 25 physicochemical parameters across seasonal regimes. As anticipated, a strong positive correlation ($r \approx 0.91$) was observed between Total Dissolved Solids (TDS) and Electrical Conductivity (EC), underscoring the ionic basis of conductivity in freshwater systems. Similarly, TDS exhibited significant positive correlations with alkalinity ($r \approx 0.72$) and hardness ($r \approx 0.68$), suggesting that increased ionic strength contributes directly to buffering capacity and water hardness, particularly through the presence of divalent cations like Ca^{2+} and Mg^{2+}. Hardness also correlated positively with both calcium ($r \approx 0.75$) and magnesium ($r \approx 0.68$), affirming that these ions are the primary contributors to water hardness and may originate from basaltic weathering in the Deccan catchment geology.

Conversely, a moderate negative correlation ($r \approx -0.39$) was evident between Dissolved Oxygen (DO) and Biochemical Oxygen Demand (BOD), reflecting the classic inverse relationship wherein higher organic load and microbial activity deplete oxygen availability, especially during the monsoon season. Similarly, DO demonstrated slight negative associations with COD, TDS, and temperature, reinforcing its susceptibility to both organic enrichment and thermal stratification. A noteworthy negative correlation between temperature and TDS ($r \approx -0.43$) implies seasonal opposition, with higher solute concentrations in cooler seasons due to reduced dilution and evapotranspiration losses, while temperatures peak during the pre- monsoon period.

Among nutrient parameters, a positive correlation was observed between nitrate (NO_3^-) and phosphate (PO_4^{3-}) ($r \approx 0.45$), and between nitrate and ammonia (NH_3) ($r \approx 0.41$), indicating common sources such as agricultural runoff and wastewater discharge contributing to nutrient enrichment. These associations point to potential eutrophication threats during monsoonal inflow. Trace metals like zinc and copper showed moderate mutual correlation ($r \approx 0.52$), likely reflecting similar geogenic or agrochemical origins. Iron displayed a negative correlation with pH ($r \approx -0.34$), consistent with its increased solubility under acidic conditions, and further suggesting redox-sensitive behavior.

Lead (Pb) exhibited weak correlations with most parameters, indicating its sporadic distribution and possibly localized anthropogenic origins. Fluoride showed negligible correlation with other variables, reinforcing its primarily lithogenic control rather than biogeochemical coupling.

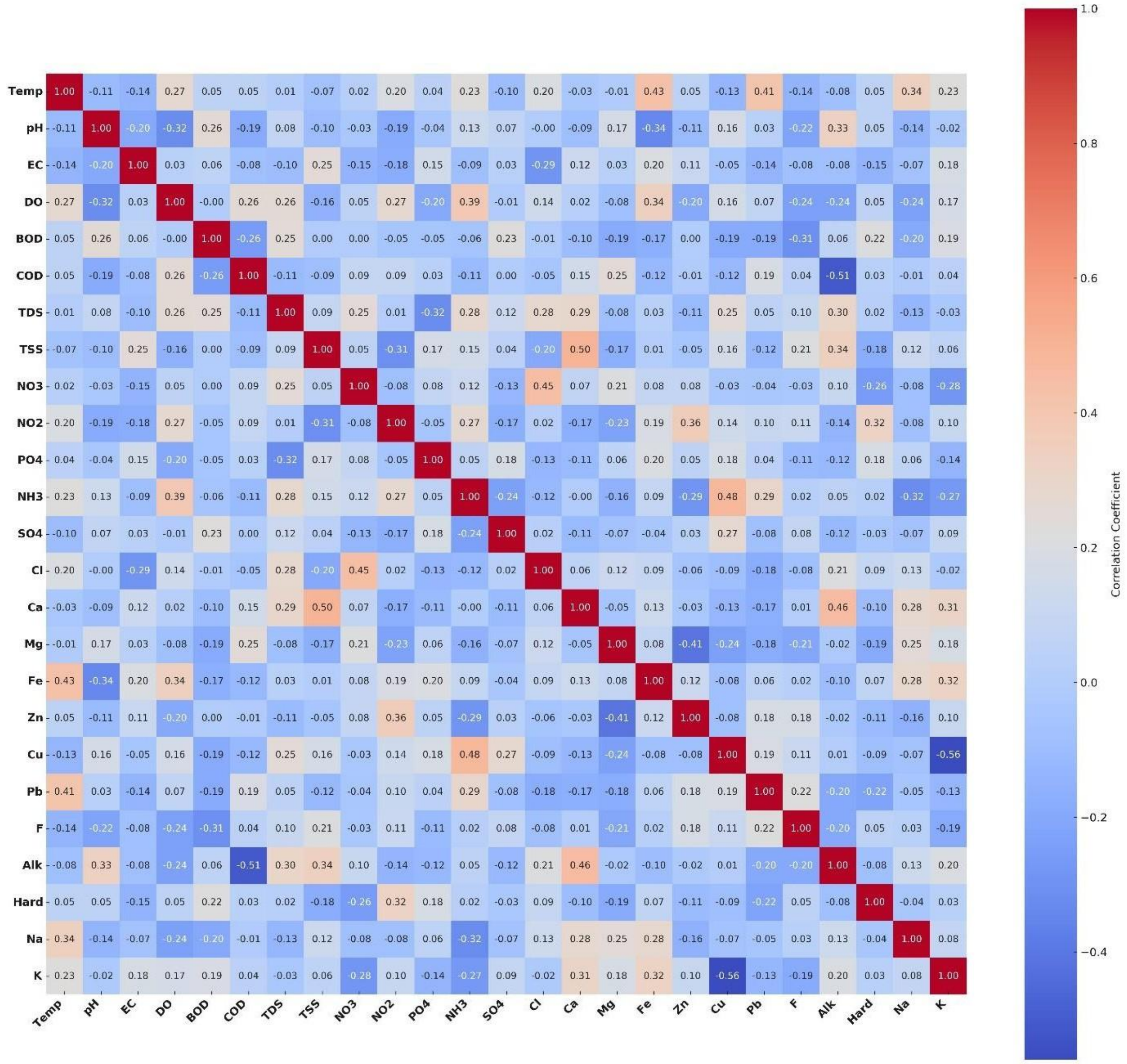

Figure 2: Correlation Matrix Analysis for Present Study

Hierarchical Cluster Analysis (HCA)

The dendrogram generated from HCA using Ward's minimum variance method and Euclidean distance matrix effectively classified the 25 hydrochemical parameters into distinct functional clusters. The clustering pattern revealed a close association between phosphate (PO_4^{3-}), sulphate (SO_4^{2-}), pH, hardness, BOD, and NH_3, suggesting a convergence of nutrient enrichment, buffering mechanisms, and organic pollution stress—typically observed during monsoonal runoff. This reflects strong agro-ecological coupling, where fertilizer residues, livestock waste, and soil leachates concurrently influence water chemistry (Singh et al., 2005). A secondary cluster comprising EC, temperature, Mg^{2+}, COD, DO, and Fe indicates the interconnected dynamics of ionic strength, thermal influence, and redox-sensitive parameters. The third major cluster grouped TDS, TSS, Ca^{2+}, Cl^-, NO_3^-, and alkalinity, reinforcing their role as key contributors to mineralization and salinity gradients in the reservoir system. The spatial segregation of trace metals (Pb, Cu, Zn) into sub-clusters implies localized,

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possibly anthropogenic sources, such as agrochemical inputs or catchment runoff, corroborating earlier findings from similar monsoon-driven basins (Giri & Singh, 2014).

Principal Component Analysis (PCA)

The PCA biplot of water quality parameters, constructed from standardized datasets, extracted two dominant components (PC1 and PC2), together explaining 21.56% of the total variance. PC1, accounting for 11.21% of variance, is heavily loaded with alkalinity, EC, TDS, chloride, calcium, and sulphate, signifying ionic richness and buffering processes as primary hydrochemical drivers. This is consistent with geological weathering of basaltic terrain and dissolution of carbonate and sulphate minerals (Subba Rao et al., 2012). PC2, contributing 10.35% of variance, is associated with DO, BOD, COD, Fe, NO_2^-, and temperature, suggesting a gradient of oxidative stress and microbial activity, especially prevalent during periods of high organic influx. The compact spatial arrangement of nutrients (NO_3^-, PO_4^{3-}, NH_3) and trace metals (Pb, Zn, Cu) in the multivariate space reflects their shared environmental fate, often linked to catchment-based runoff and particulate association.

The bidirectional vector lengths and angles within the PCA plot illustrate the degree of correlation among variables. For instance, closely aligned vectors of EC and TDS imply strong positive correlation, while orthogonal arrangements such as that of DO and BOD suggest inverse relationships. These visual cues reinforce statistical relationships earlier depicted in the Pearson correlation matrix and help prioritize variables for monitoring or remediation (Reghunath et al., 2002).

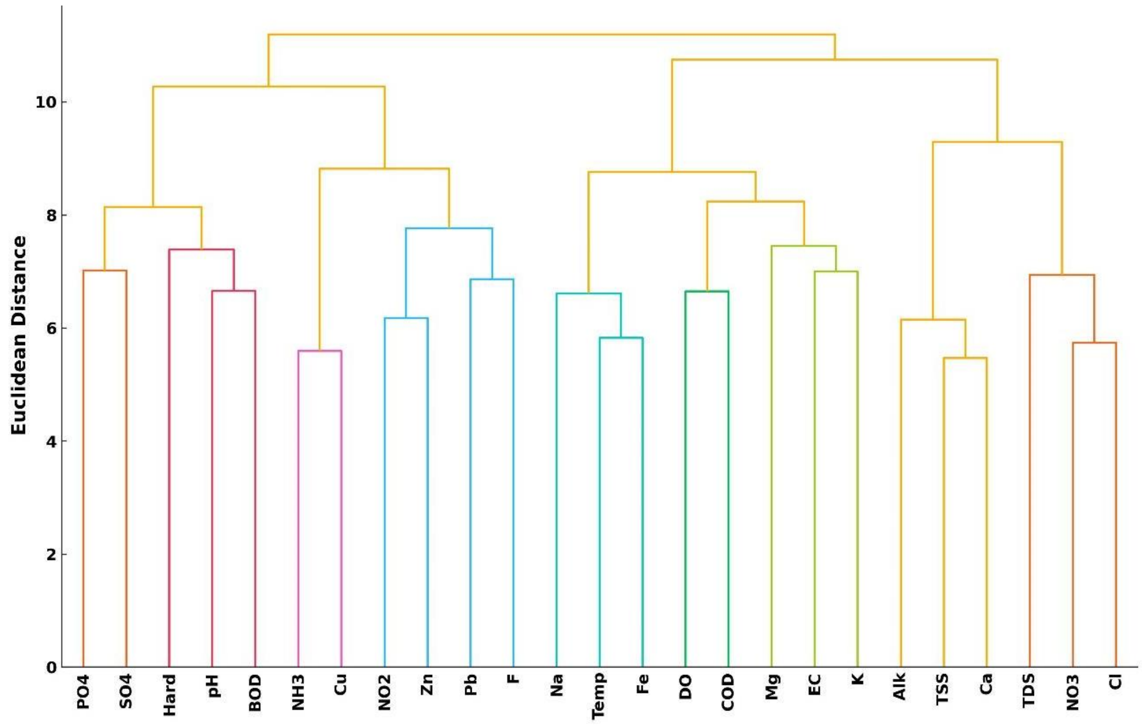

Figure 3: Cluster Dendrogram for Water Quality Parameters

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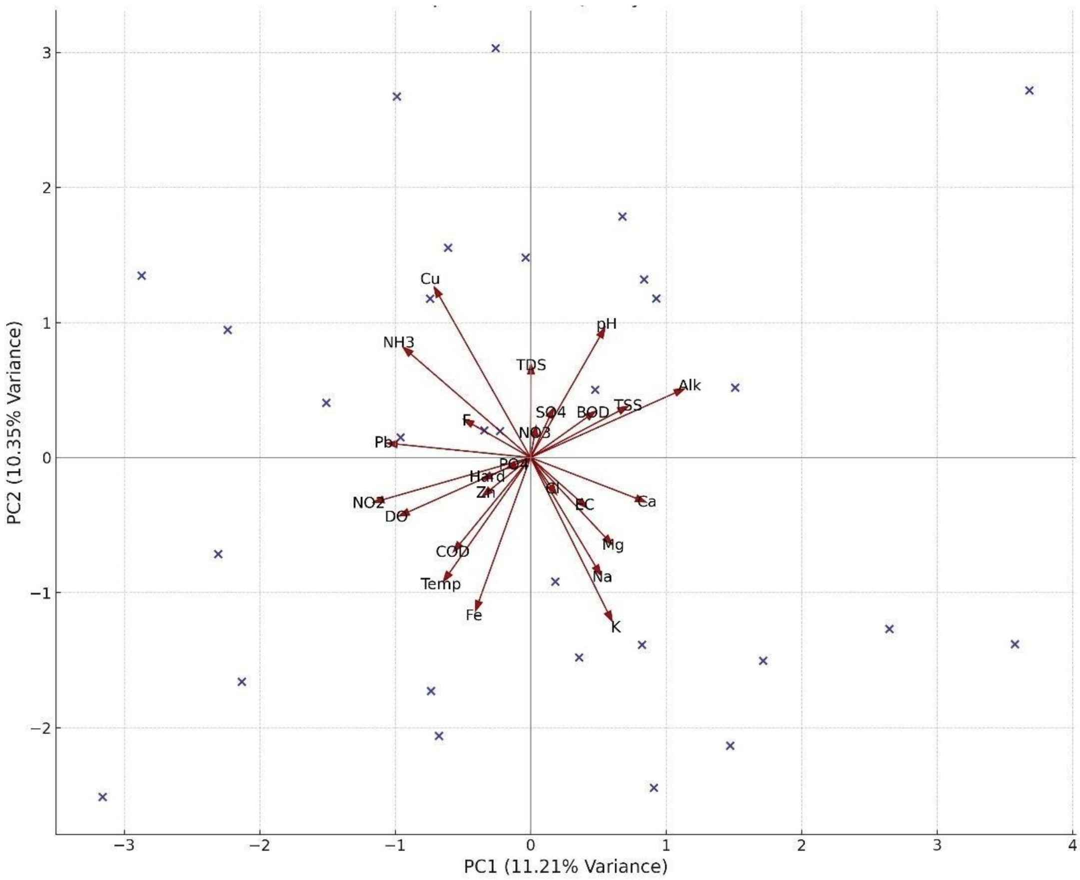

Figure 4: Principal Component Analysis for Water Quality Parameters

Together, HCA and PCA provide a robust framework for interpreting hydrochemical complexity, revealing both natural geogenic influences (e.g., mineral weathering, carbonate buffering) and anthropogenic pressures (e.g., nutrient runoff, organic waste loading) acting on the reservoir systems. Such multivariate analyses are particularly crucial in monsoon-impacted regions, where temporal and spatial variability necessitate adaptive and data-driven water management strategies (Kumar et al., 2021; Dash et al., 2019).

CONCLUSION

The present study elucidates the complex and seasonally modulated hydrochemical dynamics of Chankapur and Ozarkhed Dams, revealing that both reservoirs exhibit distinct temporal trends and inter-reservoir variations driven by monsoonal hydrology, catchment inputs, and land use characteristics. Elevated values of EC, TDS, and alkalinity during the pre- monsoon period reflect concentration of solutes due to evaporative losses and minimal dilution. Conversely, monsoon periods are characterized by increased nutrient influx (NO_3^-, PO_4^{3-}), BOD, and TSS, attributable to runoff from surrounding agricultural and semi-urban landscapes. Post-monsoon phases show signs of recovery in water quality but also signal potential hypoxia due to decomposing organic matter and declining DO.

The statistical correlation analysis confirmed that EC, TDS, hardness, and alkalinity are closely interlinked, suggesting their shared origin in mineral weathering and geogenic processes. Negative correlations between DO and BOD further highlight organic pollution events during high-flow periods.

Multivariate techniques—particularly HCA and PCA— revealed coherent variable clusters and principal components, reinforcing the mechanistic understanding of water quality transformation across hydrological seasons. Notably, PCA distinguished two dominant gradients: one associated with ionic richness and buffering, and another reflecting oxidative stress and nutrient-metal enrichment.

Overall, the findings validate the efficacy of integrated multiseasonal and multivariate hydrochemical surveillance in understanding freshwater reservoir health. They highlight the pressing need for periodic water quality monitoring, especially during monsoon transitions, to prevent eutrophication, trace metal accumulation, and biological stress. The insights from this research serve as a scientific foundation for sustainable water resource governance and adaptive ecological management in the Nashik region and comparable monsoon-influenced landscapes.

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