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Integrated Assessment of Seasonal Hydrochemical Dynamics and Ecological Integrity in the Upper Catchment of the Sankh River, Jharkhand

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Abstract Headwater streams are the backbone of healthy, functioning river systems, but many tropical plateau rivers in Eastern India have been less studied. Here, we provide an integrated assessment of seasonal water quality, ichthyofaunal diversity, ecological status, and human-environment interactions in the upper catchment of a lateritic headwater basin of the Sankh River within India's Chotanagpur Plateau. Multivariate analyses revealed distinct seasonal hydrochemical patterns, with PCA explaining 91.65% of the total variance (PC1 = 60.05%, PC2 = 31.60%), MANOVA confirming highly significant seasonal differences (Pillai's Trace = 1.963, $F = 159.8$, $P = 2.697 \times 10^{-10}$), hierarchical clustering separating samples into three season-specific groups, and Water Quality Index (WQI) values of 22.1, 25.6, and 23.4 for summer, monsoon, and winter, respectively, consistently classified the upper Sankh River as having excellent water quality, suggesting limited anthropogenic influence in the upper catchment. Rainy periods are accompanied by greater surface runoff, which moves nutrients and dissolved solids into the water at high intensities. In winter conditions, the temperatures are cooler, more stable, and have higher levels of dissolved oxygen. Fish diversity was moderate, species were evenly distributed, and rheophilic fishes predominated, suggesting the presence of well-oxygenated, structurally stable habitats. Field observations also showed how protected Sal forests, indigenous livelihoods, and riverine ecosystems together form an integrated socio-ecological landscape that promotes hydrological stability as well as biodiversity conservation. Overall, the study provides a baseline for long-term conservation and shows that the observed hydrochemical patterns and ecological characteristics are consistent with an important influence of natural environmental controls. By integrating seasonal hydrochemical variability, ecological integrity, and socio-ecological characteristics, this first-ever study on river Sankh establishes a scientific baseline to support long-term monitoring, ecological conservation, and sustainable management of tropical plateau headwater river systems.
Keywords Headwater streams; WQI; Rheophilic fishes; Multivariate analysis; Chotanagpur plateau

1 Introduction

Headwater streams are the source zones of river networks and play a critical role in establishing the hydrological, geomorphological, and biological integrity of downstream systems (Lowe and Likens, 2005; Freeman et al., 2007). Although headwater streams occupy a relatively small spatial area, they play a critical role in regulating sediment transport, nutrient cycling, habitat diversity, and basin-scale ecosystem functioning (Allan and Castillo, 2007; Colvin et al., 2019). These processes are especially dynamic in tropical regions, where the pronounced seasonality of precipitation and discharge generates considerable variation in physicochemical conditions and ecosystem structure (Bunn and Arthington, 2002; Boyero et al., 2011). Despite their ecological importance, tropical plateau headwater systems remain comparatively understudied, particularly with respect to the interactions among hydrogeomorphic setting, seasonal hydrochemical variability, and ecological condition.

Several headwater systems in eastern India arise from the lateritic plateau landscapes of Chotanagpur (Kale, 2014; Valdiya, 2016), which are characterized by strong weathering, denudation, and fluvial incisions. The unique arrangement of these geomorphic features has important implications for channel gradient, substrate composition, and hydrological connectivity, as well as regulating flow regimes, sediment dynamics, and hydrochemical characteristics through interrelated hydrogeomorphic processes (Buffington and Montgomery, 1997; Montgomery, 1999; Allan, 2004). This variability is exacerbated by the effects of monsoonal rainfall, which alters discharge patterns, lateral connectivity, and solute transport pathways (Poff et al., 1997; Bunn and Arthington, 2002) and therefore causes marked seasonal variation in water quality and habitat conditions. These hydrogeomorphic characteristics influence not only seasonal water chemistry but also habitat availability and ecological processes, making headwater rivers suitable natural systems for integrated environmental assessment.

Headwater stream hydrochemical properties reflect the integration of lithology, land cover, and flow pathways operating at a range of spatial and temporal scales (Wetzel, 2001; Meybeck, 2003). Multivariate statistical techniques, especially Principal Component Analysis (PCA), are widely used for detecting the main environmental gradients and reducing the complexity that is normally associated with hydrochemical data sets (Singh et al., 2004; Shrestha and Kazama, 2007). These approaches are particularly useful in relatively undisturbed catchments, where hydrochemistry and ecological dynamics are mainly governed by natural geogenic and hydrological factors (Meybeck, 2003; Li et al., 2008). Consequently, evaluating seasonal hydrochemical variability provides an important means of understanding the environmental processes that regulate ecological integrity in relatively undisturbed headwater systems.

Fish assemblages in headwater systems are especially susceptible to alterations of physicochemical conditions, flow regimes, and substrate composition that make them meaningful indicators of ecological integrity and environmental change (Vannote et al., 1980; Matthews, 1998). However, these relationships between hydrochemical gradients and fish community structure remain largely unexplored in the tropical plateau river systems of India (Lakra et al., 2010; Sarkar et al., 2011), particularly in minimally disturbed headwater catchments. Recent studies emphasize that fish assemblage structure and richness of Indian river systems are influenced by several environmental variables and water quality parameters (Gupta et al., 2022; Narasimmarajan et al., 2025).

Moreover, the headwater catchments of Chotanagpur Plateau are complex socio-ecological systems reflecting the linkage between forest-based livelihoods and land use practices with ecological processes that affect river health and biodiversity patterns (Millennium Ecosystem Assessment, 2005; Berkes, 2012). Forest cover in headwater areas is critical for regulating runoff and reducing erosion as well as maintaining water quality and aquatic biodiversity, highlighting the ecological importance of these headwater landscapes (Allan, 2004; Foley et al., 2005).

Although previous investigations have addressed hydrochemistry, geomorphology, or aquatic biodiversity independently, studies integrating these components to evaluate ecological integrity remain limited for tropical plateau headwater rivers of eastern India (Meybeck, 2003; Allan, 2004; Lakra et al., 2010; Sarkar et al., 2011). Therefore, the present study aims to evaluate the ecological integrity of the upper Sankh River headwater system through an integrated assessment of its hydrogeomorphic characteristics, seasonal hydrochemical variability, and socio-ecological setting. The study further identifies the natural environmental factors governing ecosystem functioning and provides a scientific baseline for the conservation and long-term monitoring of tropical plateau headwater systems.

2 Materials and Methods

2.1 Study area

The present investigation focuses on the upper reaches (upper catchment) of the Sankh River, extending from its perennial source near Besnapath village (1006 m above mean sea level) to Chainpur (715 m above mean sea level) in Gumla District, Jharkhand, covering a 52 km stretch. The study area represents a plateau-origin headwater system characterized by lateritic uplands, undulating terrain, and Sal-dominated Forest cover typical of the Chota Nagpur Plateau (Figure 1).

2.2 Sampling design

Seasonal water samples were collected during summer, monsoon, and winter in 2023-2024. Three representative composite samples were obtained per season, giving nine observations (n = 9). Composite sampling was used to reduce short-term spatial variability and represent overall seasonal hydrochemical conditions.

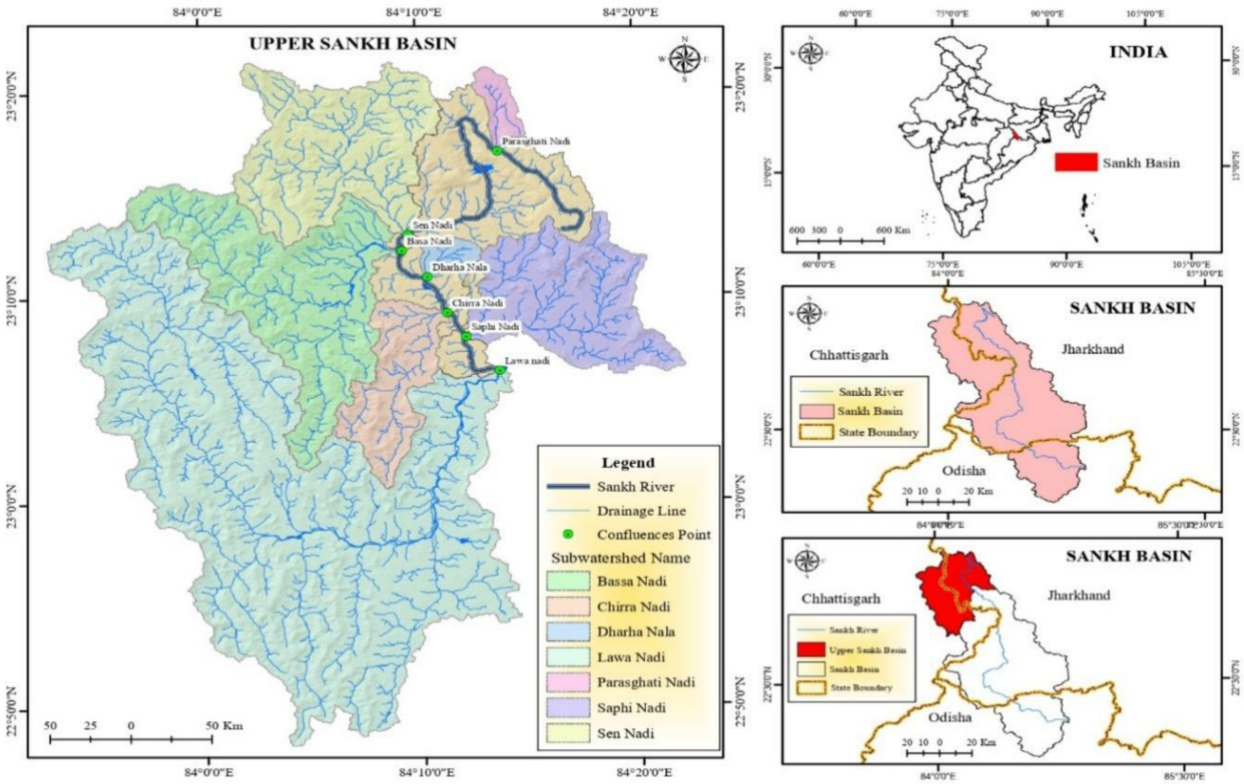

Figure 1 GIS-based map of the upper catchment showing the study area with the tributary network

2.3 Identification and classification of tributaries

Tributary analysis was conducted using Survey of India (SOI) topographical sheets. These toposheets were georeferenced in ArcGIS, and a mosaic was generated to create a continuous spatial framework. Basin and tributary delineation were then carried out using GIS-based tools. Primarily, tributaries were classified as major where the catchment area exceeded 100 km², and as minor where the catchment area was less than 100 km², and secondly based on drainage area, channel width, and perennial or intermittent flow type, consistent with widely accepted basin morphometry approaches (Horton, 1945; Strahler, 1952; Schumm, 1956).

2.4 Socio-ecological survey of river-adjoining communities

Socio-ecological information was collected through structured field visits, household-level interactions, and participatory discussions with residents. Data on livelihood practices, forest dependency, cropping patterns, and resource use were collected through direct observation and community consultations. The participatory ecological knowledge approach adopted in this study is widely recognized for its ability to understand human-environment interactions in data-limited landscapes (Millennium Ecosystem Assessment, 2005; Berkes, 2012).

2.5 Forest type and wildlife assessment

Forest types along the upper catchment were identified through field surveys and visual classification, supported by standard Indian forest type descriptions (Champion and Seth, 1968), and reconfirmed using Survey of India toposheets in ArcGIS. Wildlife presence in adjacent forest tracts was documented through guided field observations, supplemented by local ecological knowledge from multiple respondents, to minimize reporting bias. Such community-supported approaches are considered effective for biodiversity documentation in data-deficient regions (Berkes, 2012).

2.6 Ichthyofaunal identification, their diversity index, and functional structure

Fish species were recorded through direct observation of catches and interaction with local fishers during seasonal surveys. Specimens were counted and identified at the collection sites whenever possible; otherwise, they were brought back to the laboratory for full taxonomic accounting. Small fishes were directly fixed in 5% aqueous formalin solution, and the bigger ones in 10% aqueous formalin solution (v/v), following a small incision in the abdominal wall to ensure the preservative adequately penetrated the internal organs of the fish. Taxonomic identification followed standard ichthyological references (Talwar and Jhingran, 1991; Daniels, 2002), and current scientific nomenclature was verified using Eschmeyer's Catalog of Fishes (Fricke et al., 2024).

Species abundance data (N = 140) were used to estimate the following diversity metrics: Shannon-Wiener index ($H' = -\sum p_i \ln p_i$), maximum diversity ($H_{max} = \ln S$), and Pielou's evenness ($J' = H'/H_{max}$), where p_i is the proportional abundance of each species, and S is total species richness (Shannon and Weaver, 1949; Pielou, 1966). Relative contributions of species were assigned as the total abundance (%) of functional guilds based on their cross-flow, habitat use, and substrate preferences (Root, 1967). The resulting assemblage structure was assessed across flow regime, substrate complexity, and anthropogenic disturbance along the headwater reach (Naiman et al., 2005).

2.7 Water quality analysis and WQI calculation

Physico-chemical parameters, including temperature, pH, Dissolved Oxygen (DO), Biochemical Oxygen Demand (BOD), Chemical Oxygen Demand (COD), Total Dissolved Solids (TDS), total hardness, total alkalinity, chloride, nitrate, and phosphate, were analysed following standard methods prescribed by the American Public Health Association (APHA), 2017. All measurements were conducted seasonally (summer, monsoon, and winter) during 2023-2024.

Water Quality Index was computed using the weighted arithmetic index method (Horton, 1965; Brown et al., 1973):

$$WQI=\frac{\sum_{i=1}^{d} Q_i W_i}{\sum_{i=1}^{d} W_i}$$

where $Q_i = 100 \times \frac{V_i - V_{ideal}}{S_i - V_{ideal}}$, and $W_i = \frac{1}{\left(\sum \frac{1}{S_j}\right) S_i}$ calculated based on observed values of each physico-chemical factor (V_i), the standard BIS/WHO permissible values for each of the corresponding (S_i) and ideal values (V_{ideal}).

2.8 Statistical methodology

Seasonal water quality patterns were evaluated using a stepwise multivariate statistical approach. Principal Component Analysis (PCA) was first used to reduce dimensionality and identify major environmental gradients (Jolliffe, 2002; Hair et al., 2019). In the first step, correlated physical and chemical parameters were transformed into orthogonal Principal Components (PCs), isolating key variance drivers and filtering out extra noise (Legendre and Legendre, 2012). Subsequently, Multivariate Analysis of Variance (MANOVA) was conducted on scores for the first two PCs as dependent variables. This methodology was specifically employed to overcome any potential rank deficiency concerns due to small sample sizes (n=9), where the number of parameters outnumbers the observations and statistical confidence in differentiating seasonal groups was required, ensuring a sound statistical identification of meaningful differences across all three seasons (Rencher and Christensen, 2012; Hair et al., 2019).

The relationships between specific parameters (loadings) and seasonal clusters (scores) were visualized by a PCA Biplot, presenting a spatial representation of the hydrochemical niche for each season (Gabriel, 1971; Legendre and Legendre, 2012). Then, a Pearson correlation heatmap was used to evaluate the linear dependencies between variables, including the inverse dependency that exists between temperature and dissolved oxygen (Benesty et al., 2009), in order to help support the internal validity of the data.

Finally, a Hierarchical Cluster Analysis (HCA) generated a dendrogram, using the Ward's method to determine intraspecific similarities and detect potential sampling outliers (Ward, 1963; Murtagh and Legendre, 2014). Execution of PCA followed by MANOVA allows for assessing the overall covariability on a global level, which provides insights into the more general patterns of environmental relevance; specific component pairwise interactions can be assessed through correlation analysis and, in turn, treated at the sample level via HCA: from patterns to molecules, featuring high-dimensional coherence. Statistical analyses were performed in RStudio 2025.05.1.

3 Results

3.1 Course of the Sankh River

The perennial source of this river is between the Besnapath and Dokapath villages in Chainpur Block of Gumla District, Jharkhand, at an elevation of approximately 1006 meters above mean sea level, with coordinates 23°13'13.0"N 84°17'20.4"E (Figure 2).

Figure 2 Field view of the origin of the Sankh River

The river flows approximately 172.96 kilometers (km) through Jharkhand before entering Odisha near Barghat. The source region lies on an extensive lateritic plateau locally known as a path, a term used to describe broad, flat-topped upland surfaces characteristic of the Chota Nagpur Plateau. The region features bauxite-laden lateritic soils which have developed from prolonged, intense chemical weathering under tropical conditions, a process termed lateritization (Figure 3).

Figure 3 Bauxite-rich lateritic soil surface near the origin of the Sankh River around Besnapath village

Landforms and soil patterns in the adjacent settlements of Lupungpath and Dokapath show the same pattern, suggesting homogeneity in the landscape in this part of the upper catchment.

From its origin, the Sankh River flows predominantly through Jharkhand, traversing highland plateaus, undulating forested tracts, and gently sloping valleys. From its origin up to Chainpur, it covers 52.71 km and is considered the upper catchment, based on its geomorphology.

3.2 Tributary network of upper catchment

Seven tributaries have reported in the upper catchment of the Sankh River, which includes four major rivers (Basa Nadi, Saphi Nadi, Sen Nadi, and Lawa Nadi) and three minor streams (Parasghati Nadi, Dharha Dala, and Chirra Nadi) as mentioned in Table 1. There is an identifiable spatial gradient: the northern sector depends on small tributaries that deliver only seasonal runoff during the monsoon. In contrast, large tributaries with broader basins and more stable discharge in the central and southern sectors maintain continuous upstream flow in the river.

Settlement is invariably located close to the confluence of these tributaries, reflecting a strong relationship between habitation and water availability. These regions act as socio-ecological hubs that enable domestic water supply, seasonal agriculture, small-scale fisheries, and forest-related livelihoods.

Table 1 List of tributaries joining the Sankh River at the upper catchment

Sl. No.	Tributaries Name	Major / Minor	Catchment area (sq km)	Villages near confluences.	Coordinates	District	State
1.	Parasghati nadi	Minor	10.02	Rajadera	23.284101, 84.228785	Gumla	Jharkhand
2.	Sen nadi	Major	171.09	Tati	23.217114, 84.158825	Gumla	Jharkhand
3.	Basa nadi	Major	213.52	Dumardanr	23.204000, 84.154350	Gumla	Jharkhand
4.	Dharha nala	Minor	12.38	Harradipa	23.182178, 84.173955	Gumla	Jharkhand
5.	Chirra nadi	Minor	72.96	Sankhdardih	23.153002, 84.188251	Gumla	Jharkhand
6.	Saphi nadi	Major	138.69	Kunrkel, Chainpur	23.133508, 84.202542	Gumla	Jharkhand
7.	Lawa nadi	Major	755.49	Srinagar	23.105476, 84.228017	Gumla	Jharkhand

3.3 Socio-ecological structure of the upper catchment: human-forest-agriculture-wildlife interactions

The upper catchment of the Sankh River represents a predominantly forested socio-ecological landscape where indigenous settlements, protected Sal forests, rain-fed agriculture, and wildlife occur in close spatial association. Rather than existing as isolated components, these landscape elements function as an integrated system in which natural ecosystems continue to influence settlement distribution, livelihood practices, and resource use. Human habitation throughout the upper catchment has developed largely through coexistence with the surrounding forested environment, resulting in relatively limited anthropogenic modification of the headwater landscape (Table 2).

3.3.1 Indigenous settlements and land use

The catchment is predominantly inhabited by indigenous communities whose livelihoods depend on agriculture, forest resources, and seasonal riverine ecosystems. Agricultural activities remain largely rain-fed and small-scale, while extensive industrial and urban development is absent. Consequently, land-use intensity remains relatively low, reducing pressure on the headwater ecosystem (Table 2).

3.3.2 Forest cover and spatial variation

The upper catchment is predominantly covered by protected Sal (*Shorea robusta*) forests, including the Besna, Dokapat, Rajadera, Akasi, and Kereng forest tracts (Table 2). Reduced forest cover occurs around Basatoli, Bartoli, and parts of Bukma owing to agricultural expansion and settlement development, although remnant patches such as the Bukma Protected Forest persist. The upper catchment is characterized by a forest-agriculture mosaic, with extensive protected forests interspersed with cultivated land and rural settlements.

3.3.3 Wildlife distribution and forest integrity

Wildlife occurrence was closely associated with PF. Villages adjoining these forests reported the presence of bears (*Melursus ursinus*), wild boar (*Sus scrofa*), jungle cats (*Felis chaus*), foxes (*Vulpes benghalensis*), and wild goats. Occasional elephant (*Elephas maximus*) sightings were recorded mainly in the Srinagar Protected Forest, whereas villages lacking adjacent forest cover reported few or no wildlife sightings. Crop depredation by wild boar and elephants near Srinagar further reflects the close interface between forest habitats and agricultural land use (Table 2).

3.3.4 Economic importance of forest products

Forest resources constitute an important component of local livelihoods. The Sal forests provide fuelwood, timber, and a variety of non-timber forest products (NTFPs), including Mahua (*Madhuca longifolia*), Kusum (*Schleichera oleosa*), Chironji (*Buchanania lanzan*), Jamun (*Syzygium cumini*), Mango (*Mangifera indica*), Kathal (*Artocarpus heterophyllus*), Bahera (*Terminalia bellirica*), Haritaki (*Terminalia chebula*), and Karanj (*Pongamia pinnata*). Seasonal edible mushrooms also supplement household nutrition and provide an additional source of income. These forest resources contribute to food security, traditional healthcare, and small-scale household economies (Table 2).

3.3.5 Cropping pattern and agro-ecological constraints

Agriculture in the upper catchment is predominantly rain-fed and seasonal, with dhan (*Oryza sativa*) as the principal crop, along with gehun (*Triticum aestivum*), makai (*Zea mays*), marwa (*Eleusine coracana*), and jatangi (*Guizotia abyssinica*). The cropping pattern reflects dependence on monsoonal rainfall, limited irrigation, low-fertility lateritic soils, and small tribal landholdings. Agricultural land is closely interspersed with forests and river channels, resulting in a heterogeneous land-use mosaic across the upper catchment (Table 2).

3.4 Seasonal variation in physico-chemical characteristics of river water in upper catchment

Seasonal variability in the physicochemical characteristics of the Sankh River in this zone was assessed during the summer, monsoon, and winter periods (2023-2024). The measured parameters, as shown in the following graphs (Figures 4-8), exhibit clear seasonal patterns.

3.4.1 Water Temperature and pH

The changes in temperature of water were also seasonal, with peak summer temperatures (28.10 ± 0.15 °C) decreasing through a monsoon (26.20 ± 0.30 °C) minimum, but down to a winter minimum (24.40 ± 0.25 °C), reflecting the gradual decline from summer to winter typical of plateau-origin headwater systems and confirming the limited thermal buffering capacity associated with shallow channel depths.

During the study period, the pH of river water was near neutral, with a slight alkaline trend (pH 7.12 ± 0.15 during the monsoon to 7.80 ± 0.25 in winter). This indicates that the marginally increased pH values in winter may be related to less dilution and enhanced photosynthetic activity, leading to better conditions for aquatic biota (Figure 4).

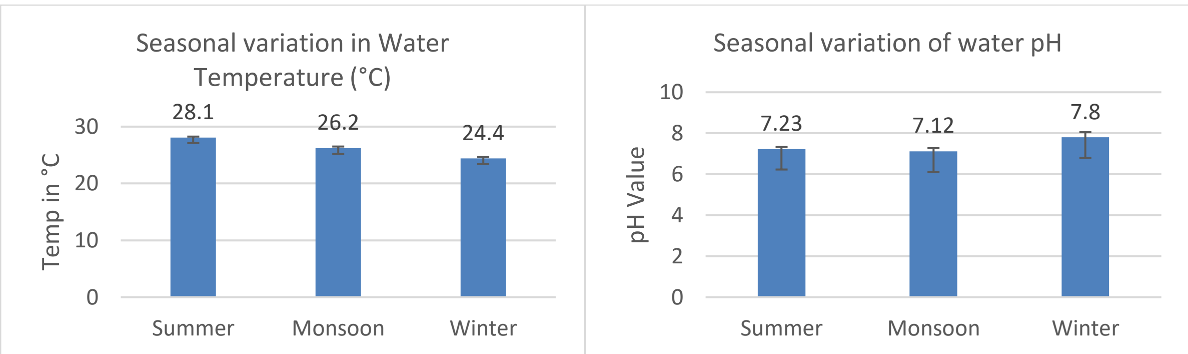

Figure 4 Seasonal variation in water temperature and pH of the Sankh River in the upper catchment

Table 2 Human settlements, forest cover, cropping pattern, and wildlife occurrence in the upper catchment

Nearby villages	Besnapath	Dokapath	Rajadera	Loramba	Akasi pokritoli	Naogaon	Sirsi	Majhgaon	Kereng	Basatoli	Bukma	Dipa Bukma	Bartoli	Srinagar
Major Inhabitants	Lohra, and Oraon community.	Oraon.	Oraon.	Lohra, Asur, Rajput.	Oraon	Turi, and a mixed community	Oraon	Lohra and the Tribal Christian community	Lohra	Oraon	Nagesia- Pahan, Bhagat and Tribal Christian Community	Mallar, Lohra and Bhagat Community	Lohra and Tribal Christian Community	Ghansi, Rautia and Sahu
Types of forest	Besna Protected Sal Forest	Dokapat Protected Sal Forest	Rajadera dense Protected Forest (PF)	Loramba is Sal both open and protected Sal Forest	Akasi Sal PF			Dahkul PF	Kereng PF	No forest area	Bukma PF (5 small forests	No forest area		Shrinagar protected
Wildlife animals found adjacent to the forest	Elephant, Fox, Bear, wild boar, jungle cat, wild goat													
Economically important plants available	*Madhuca longifolia* (Mahua), *Shorea robusta* (Sakhua), *Schleichera oleosa* (Kusum), *Buchanania lanzan* (Chironji) small tree, *Syzigium cumini* (Jamun), *Mangifera indica* (Aam), *Artocarpus heterophyllus* (Kathal), *Terminalia chebula* (Haritaki), *Terminalia bellirica* (Bahera), *Pongamia pinnata* (Karanj)													
Crop cultivated	Dhan (Seasonal), Gehun (Seasonal), Marwa (Seasonal), Jatangi, and Makai													

3.4.2 Dissolved oxygen, biochemical oxygen demand, and chemical oxygen demand

DO levels were generally high throughout the year, reaching their maximum (7.80 ± 0.28 mg L^{-1}) in winter. As dissolved oxygen generally increases with low temperature, the high level in winter can be explained by the water's low temperature. In comparison, the lower values observed in summer reflect higher water temperatures and greater metabolic activity of aquatic organisms.

On the other hand, BOD levels were persistently low across all seasons (0.70-1.00 mg L^{-1}). A low BOD level means there is little organic pollution and that the oxygen needs of aerobic bacteria and animals in water bodies are met, indicating good water quality. During the monsoon season, an increase to 1.00 ± 0.06 mg L^{-1} was detected, which may be due to surface runoff carrying organic matter into the river.

COD values were characteristically low to moderate and lower during the monsoon, at 8.00 ± 0.40 mg L^{-1}, likely due to dilution effects. In contrast, the summer and winter months showed higher concentrations due to low flow conditions (Figure 5).

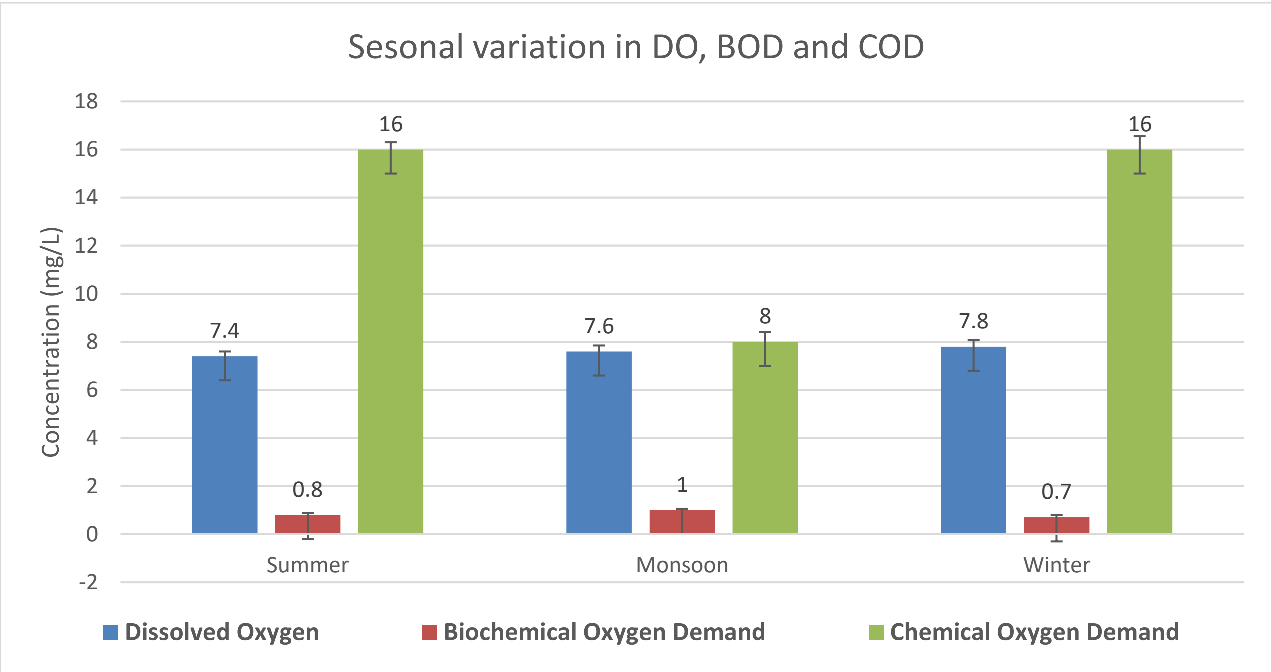

Figure 5 Seasonal variation in DO, BOD, and COD in the upper catchment of the Sankh River

3.4.3 Total dissolved solids, hardness, and alkalinity

The maximum value recorded for TDS was 72.00 ± 0.90 mg L^{-1}, observed in the monsoon season. This increase is likely related to enhanced runoff and soil erosion in the catchment. Summer TDS is lower, suggesting little external input and less surface flow.

Total hardness values during the monsoon season ranged from 44.00 ± 0.70 mg L^{-1} to 54.95 ± 0.60 mg L^{-1} during summer. Rainwater dilution during the monsoon might account for lower hardness, whereas high summer values may be attributed to evaporation concentration of calcium and magnesium ions. Hence, the water is soft to moderately hard.

Total alkalinity (TA) also varied significantly seasonally, with maximum values of 38.30 ± 0.50 mg L^{-1} in summer and minimum values of 31.60 ± 0.60 mg L^{-1} in winter, and a value during the monsoon period at its lowest, around 18.70 ± 0.55 mg L^{-1}, which reflects seasonal variation in bicarbonate concentrations depending on degrees of hydrological dilution and groundwater mixing (Figure 6).

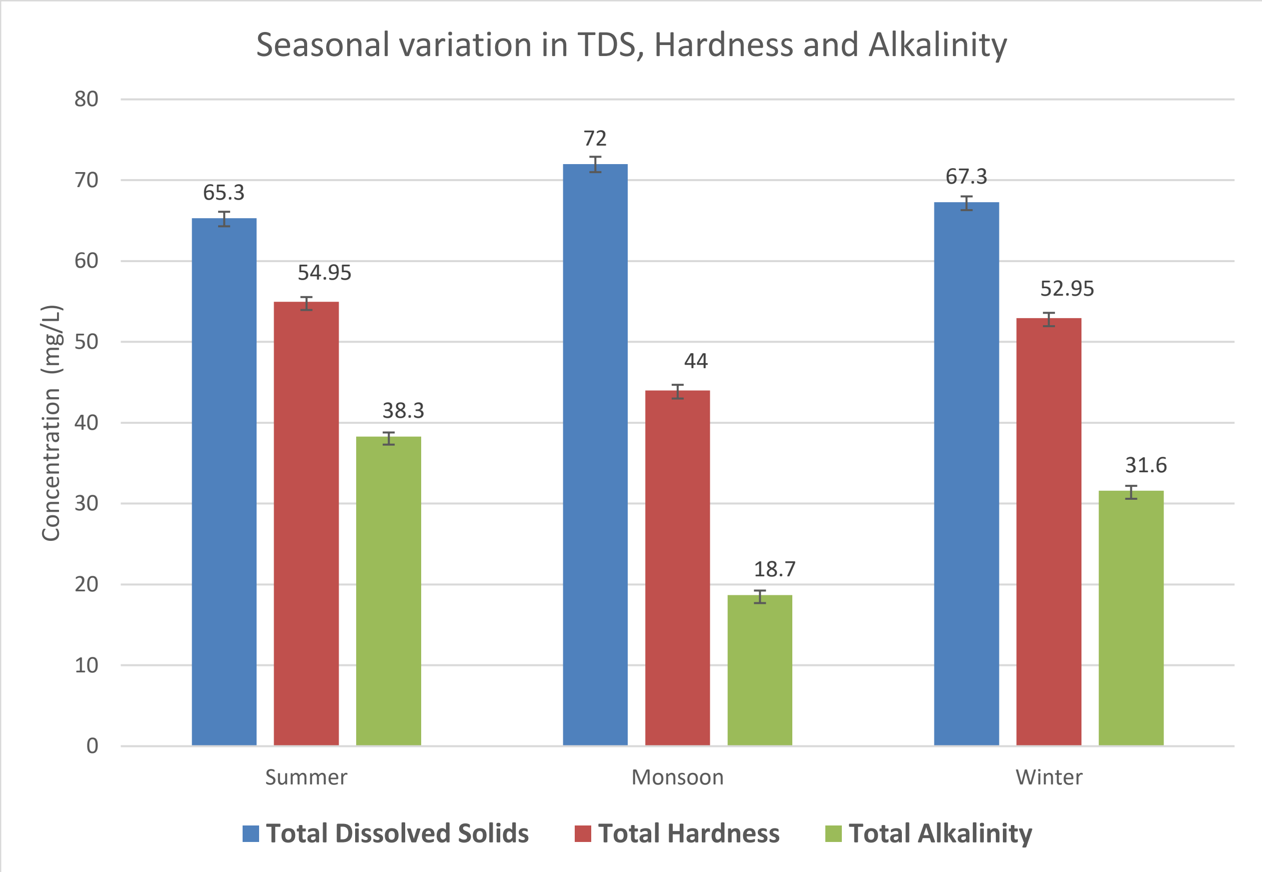

Figure 6 Seasonal variation in Total Dissolved Solids (TDS), Total Hardness (TH), and Total Alkalinity (TA) in the upper catchment of the Sankh River

3.4.4 Major ions and nutrient concentrations

Chloride concentration was uniformly low, recorded at 2.61 ± 0.29 mg L^{-1} in summer and 2.97 ± 0.33 mg L^{-1} during the monsoon season. A marginal increase in the level of these elements during the monsoon season can be associated with runoff from adjacent land use. The low chloride values further indicate drilling east of the basin, where little domestic or industrial salt contamination of surface waters is present.

Winter nitrate-nitrogen concentrations (2.43 ± 0.35 mg L^{-1}) were similar to monsoon levels (2.67 ± 0.20 mg L^{-1}). The high levels during the monsoon are possibly due to agricultural runoff and soil leaching. Nonetheless, these concentrations were under key limits, meaning that dangerous nutrient pollution isn't an issue.

The phosphate concentration showed a strong seasonal variation, with extremely low concentrations in summer (0.0058 ± 0.0010 mg L^{-1}) and higher concentrations during the monsoon (0.0463 ± 0.0013 mg L^{-1}) and winter (0.0580 ± 0.0017 mg L^{-1}). This increase in phosphate concentrations during the monsoon and winter months can most likely be attributed to runoff, sediment release, and reduced biological assimilation. Such factors can increase primary productivity, as shown in Figure 7.

These variations in temperature, dissolved oxygen, organic load, total dissolved solids (TDS), hardness, alkalinity, and nutrient levels were observed over time during the physicochemical characterization of Sankh River upper catchment. In all, the deviation of all parameters in this long-duration study from the acceptable range was not notable throughout the seasons and suggests good water quality with the least anthropogenic impact. Understanding chemical dynamics in this catchment has heretofore been limited by the scarcity of time-series data, presenting an important shortcoming given the role of forested headwater landscapes in maintaining lowland (upstream-downstream) land-use practices on the Sankh River seasonally.

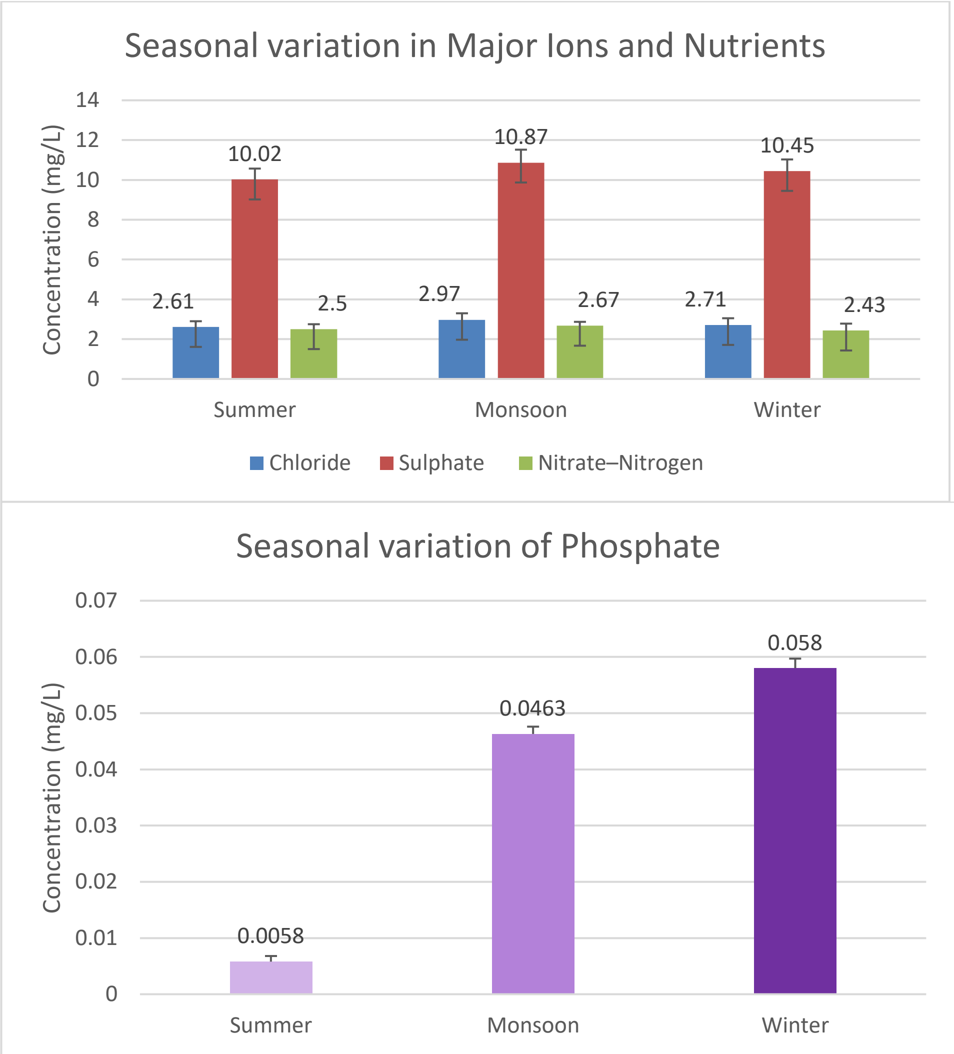

Figure 7 Seasonal variation in major ions and nutrient concentrations (chloride, sulphate, NN) and Phosphate in the upper catchment of the Sankh River

3.5 Statistical analysis of seasonal variability

3.5.1 Seasonal variation in physico-chemical parameters (MANOVA)

PCA is necessary before applying Multivariate Analysis of Variance (MANOVA) when classifying data where the number of parameters equals or outweighs the observations. In this case, even having only nine samples from three seasons and a set of water quality variables is complex enough that a standard MANOVA would produce a rank-deficient variance-covariance matrix. This deficiency would make the test statistically invalid and would forestall the computation of test statistics. By implementing PCA first, this collapses the original correlated parameters into a small number of orthogonal Principal Components (PCs). These factors detect maximal data variance while minimizing the number of variables to a level feasible within the limitations imposed by available degrees of freedom.

However, there are two major justifications for choosing MANOVA over multiple ANOVAs: the inflation of Type I error and keeping correlations between variables. Performing separate ANOVAs increases the possibility of detecting significant differences based on random chance alone, an effect known as multiplicity. More critically, water quality parameters like pH, temperature, and dissolved oxygen are inherently interdependent. MIC calculates the correlation between chemicals, and MANOVA does so across all seasons simultaneously as one big multivariate vector. It allows for the detection of subtle shifts across all parameters at once, information that individual ANOVAs (which would analyze each variable more or less independently) were likely to miss.

3.5.2 PCA dimensionality reduction and variance apportionment

The PCA reduced the detailed water-quality dataset into two orthogonal axes that together contained 91.65% of the total environmental variance. PC1 becomes the first dimension of change extracted, accounting for 60.05% of the observed variation within the data, as noted in the loadings part of Table 3. This component is marked by a clear divide between mineral-based properties and elements associated with organic enrichment. The dominant positive loadings for Total Alkalinity (0.371), Total Hardness (0.367), and Chemical Oxygen Demand (0.354) suggest a defining axis of ionic concentration and chemical oxidation potential. Total Dissolved Solids (-0.371), Sulphate (-0.365), and Chloride (-0.362) have much higher negative loadings than all other variables, which suggests that the first principal component (PC1) captured an important, large gradient in dissolved mineral inputs to Lake Merritt, which may vary with hydrological conditions during sampling periods.

PC2 captures an additional 31.6% of the variance in the system and acts as a primary indicator of physicochemical and thermal seasonality. Additionally, as indicated in Table 3, this component is positively affected by Temperature (0.479) and Nitrate-Nitrogen (0.279); however, it exhibits negative loadings at a notable extent for pH (-0.478), Dissolved Oxygen (-0.466), and Phosphate (-0.420). The significant inverse relationship between Temperature and Dissolved Oxygen on this axis reflects a known theory that higher thermal energy decreases gas solubility. Defaulting Nitrate and Temperature against Dissolved Oxygen and pH extremes, with respect to PC2, suggests that it expresses the biological and physical "pulse" of the waterbody correlated with the variations in nutrient availability as well as lower levels of oxygen in hotter seasons.

Table 3 First two principal components loadings

Parameters	PC1 Loadings	PC2 Loadings
Temperature	0.124	0.479
pH	0.096	-0.478
DO	-0.125	-0.466
BOD	-0.243	0.182
COD	0.354	-0.146
TDS	-0.371	0.003
TH	0.367	-0.068
TA	0.371	0.018
Chloride	-0.362	0.035
Sulphate	-0.365	-0.094
NN	-0.238	0.279
Phosphate	-0.21	-0.42

3.5.3 Multivariate significance of seasonal variation (MANOVA)

To determine if the visual patterns seen in Figure 9 represent statistically significant differences rather than stochastic noise, a Multivariate Analysis of Variance (MANOVA) was performed on the PC scores in Table 4. The analysis showed a Pillai's Trace of 1.9631 with an approximate F-statistic of 159.8 and a p-value of 2.697e-10. These results indicate significant multivariate differences among the sampled seasons. The near-zero p-value gives us the confidence to reject our null hypothesis, which proposes that each season would share the same hydrochemical "fingerprint".

The use of PC scores as the dependent variables in this model was a critical methodological step to ensure the analysis remained statistically identified, given the small sample size ($n=9$) relative to the original number of parameters ($d=12$).

3.5.4 Interpretation of seasonal clustering and biplot analysis

The findings are visually synthesized in Figure 8, which provides a seasonal division of the sampling units into three domains, which is further corroborated by the coordinate values found in the Scores section (Table 4). Samples from the Summer (Points 1-3) appear in the upper-right quadrant of Figure 1 with high positive scores on both PC1 and PC2, coinciding with vectors describing Temperature, Total Alkalinity, and COD. This trend suggests that the warmer months present a period with high organic loads and thermal stress. While the Monsoon samples are all grouped in the upper-left quadrant (Points 4-6) of the plot, and have a strong correlation with TDS, Sulphate, and Chloride vectors. Indicating that the monsoon has an important role in mineral and dissolved solids transport, probably due to the contribution from surface runoff into the aquatic system.

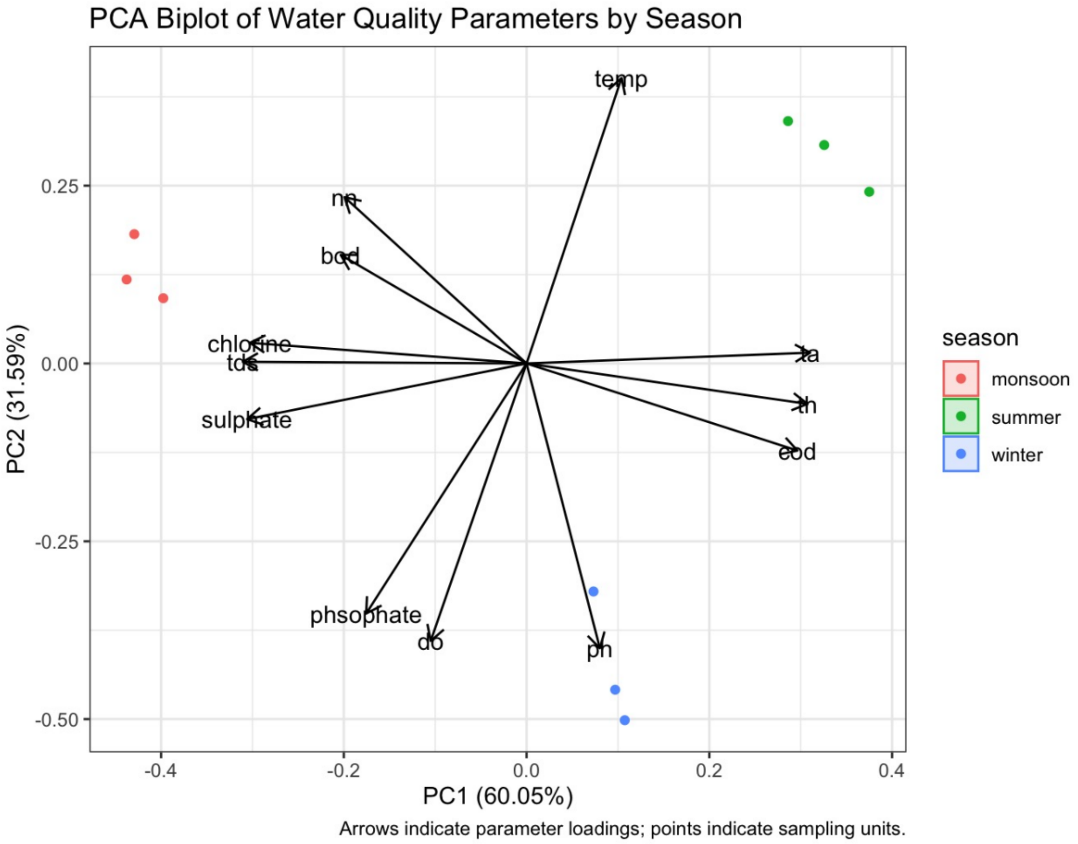

Figure 8 Biplot showing individual sample points along with component loadings

Table 4 Scores or the coordinates of each sampling unit in the PCA space

ID	Season	PC1 Score	PC2 Score
1	Summer	2.623	1.794
2	Summer	3.020	1.410
3	Summer	2.304	1.991
4	Monsoon	-3.457	1.062
5	Monsoon	-3.202	0.536
6	Monsoon	-3.525	0.690
7	Winter	0.781	-2.679
8	Winter	0.590	-1.873
9	Winter	0.866	-2.930

Lastly, the Winter samples, which are (Points 7~9), are located in the lower-right quadrant of Figure 8, showing a strong association with increased Dissolved Oxygen and pH levels, as can be seen from their negative PC2 score in Table 4. Related to this positioning, it shows the oxygen-rich and colder water conditions of winter, which is considered the season with the best physical indicators of quality in aquatic waters over the year. The spatial separation of these clusters in Figure 9 demonstrates that seasonal transitions exert a more profound influence on water chemistry than variations among individual sampling sites, as evidenced by the tight grouping of replicates within each seasonal territory.

3.5.5 Pearson correlation analysis

The Pearson correlation matrix provides a comprehensive quantitative assessment of the linear dependencies between the continuous water quality parameters monitored during this work. One of the matrix features is the expected tight inverse relationship between temperature and dissolved oxygen (DO) with a correlation coefficient r = -0.94. The fact that the solubility anomaly from the dataset agrees with the general principle that a warmer aquatic environment has lower solubility reinforces the physical reliability of this aspect of the study. In addition to that, a very strong positive correlation cluster is also detected between TA, TH, and COD with a high coefficient value of 0.99. This observation suggests geochemical or anthropogenic commonalities in terms of a source for these parameters, and that mineral concentration/organic loading changes in sets.

Conversely, the matrix shows extremely strong negative correlation between alkaline-mineral group (TA, TH) with dissolved solids group (TDS, Sulphate, and Chloride) as seen by correlation values from -0.94 to -1.00. This opposite dynamic implies an essential transformation in the chemical regime of the water, which may oscillate between a mineral-dominant and a runoff-dominated, high-salinity state. The presence of high positive correlations in the dissolved solids group (Chlorine, TDS, and Sulphate; r≥0.94) is interpreted as an inflow mechanism that acts similarly through surface runoff during the monsoon period. Moreover, Phosphate shows a strong positive correlation (r=0.91) with DO and is inversely correlated with Temperature (r=-0.97), reaching peaks in the colder, well-oxygenated winter samples. Such complex interdependencies are reminders that water quality is functionally dependent not on single variables but rather on coupled physicochemical cycles that differ greatly in response to seasonal context (Figure 9).

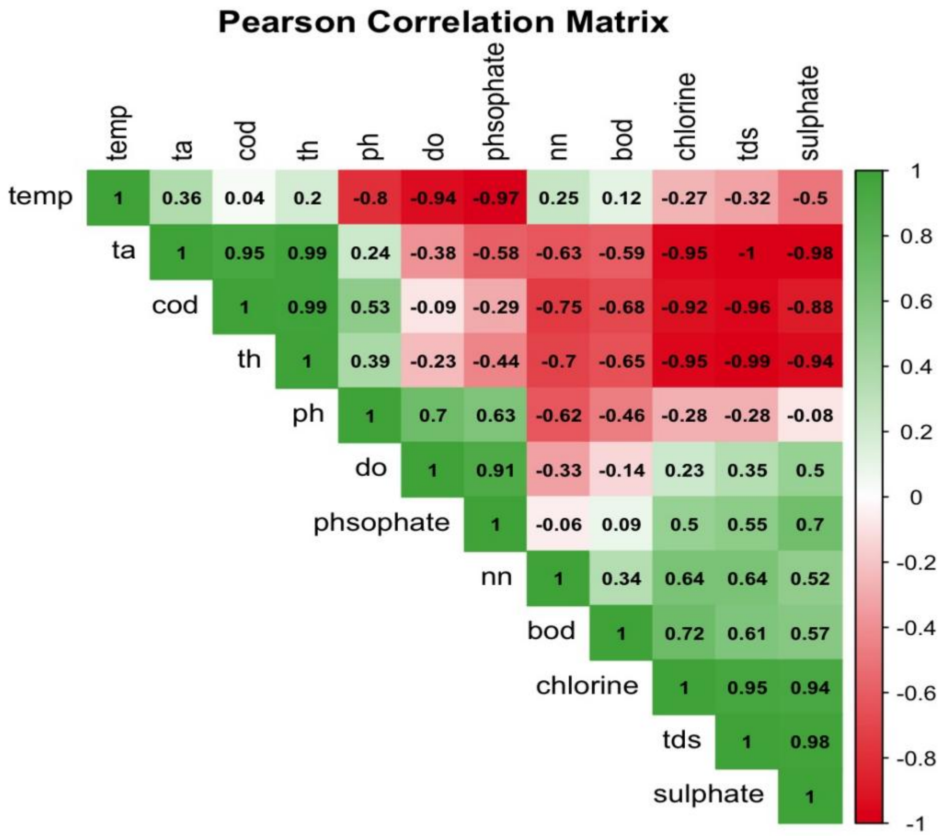

Figure 9 Pearson correlation coefficients among water quality parameters

3.6 Water quality index calculation

Analysis of the calculated water quality index (WQI) values shows that upper catchment, indicating upper Sankh river has good water quality throughout the year with only marginal fluctuations during monsoon season. The modest seasonal differences in WQI may reflect variations in nutrient availability, runoff, and dilution during the sampling periods.; however, these values still remain within excellent range. The consistently low values of WQI indicate its minimal influences by human activities in a forested headwater catchment, which supports the findings from physicochemical analyses (Table 5).

Table 5 Seasonal WQI values for the upper Sankh River (upper catchment) calculated using the weighted arithmetic method, indicating excellent water quality across summer, monsoon, and winter periods (2023~2024)

Season	WQI Value	Water Quality Class
Summer	22.1	Excellent
Monsoon	25.6	Excellent
Winter	23.4	Excellent

3.7 Hierarchical clustering analysis

The natural groupings of the sampling units based on their cumulative physiochemical similarities are displayed in the Global Dendrogram of Seasonal Water Quality (Figure 10). Using Ward's minimum variance method with Euclidean distance, the clustering analysis grouped the nine samples into three distinct clusters that corresponded with the three sampled seasons. The Monsoon (4, 5, and 6) samples occupy a parasitic primary branch that indicates the monsoon cluster showed a distinct chemical pattern that is consistent with increased runoff-related mineral inputs. compared to other seasons.

The remaining samples are grouped into Summer (1, 2, and 3) and Winter (7, 8, and 9) clades; the Summer cluster shows the shortest internal distance between its members. The high level of internal homogeneity suggests that summer water quality is highly stable across replicates. Moreover, the dendrogram (Figure 10) independently confirms the seasonal clusters from MANOVA and PCA (Figure 8), providing further confidence that transitions between seasons are the key determinants of water quality variance well beyond stochastic sampling noise.

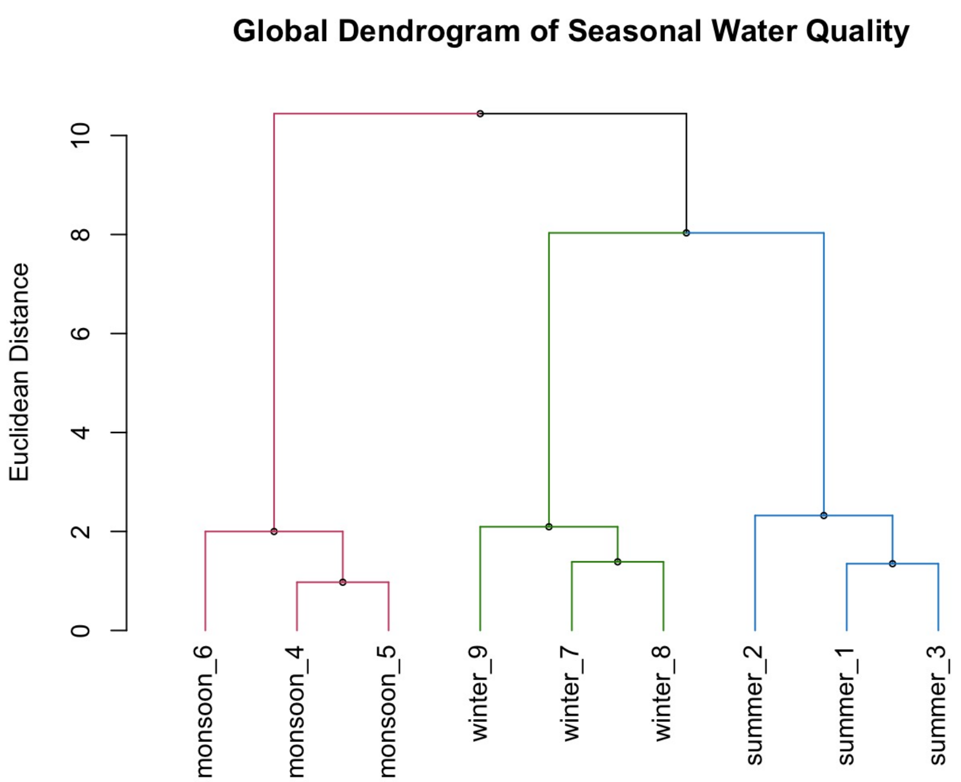

Figure 10 Dendrogram showing hierarchical clustering of sample points

3.8 Ichthyofaunal diversity and functional structure

A total of seven fish species representing six families and four orders were recorded from upper catchment of the Sankh River based on pooled data from all three seasonal surveys. This suggests a low level of species richness, but the assemblage is functionally structured and indicative of a minimally disturbed fluvial system that is sourced from plateau systems (Figure 11).

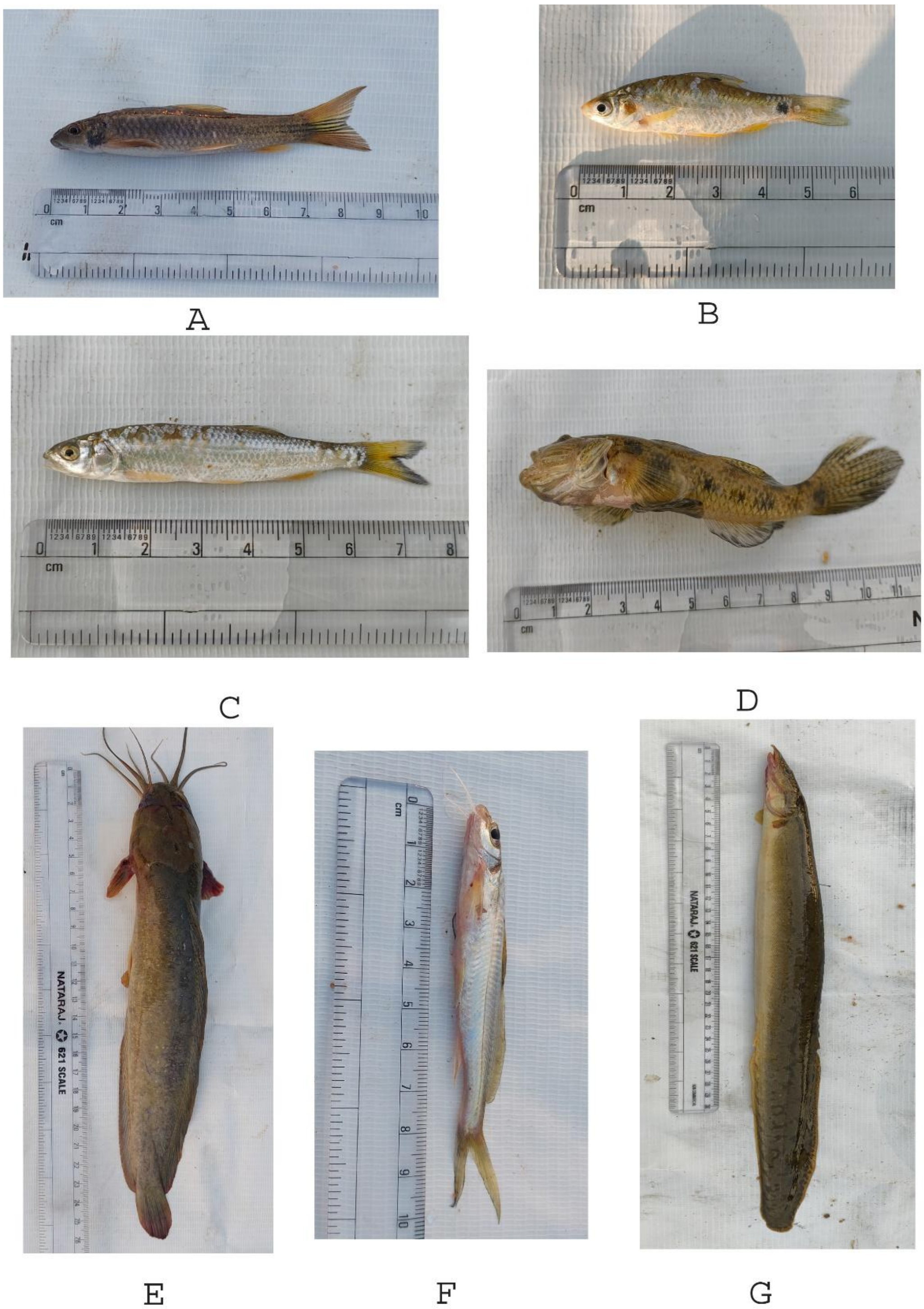

Figure 11 Fish found in the Sankh River in upper catchment
Table notes: A: *Garra mullya*; B: *Puntius sophore*; C: *Cabdio morar*; D: *Glossogobius giuris*; E: *Clarias magur*; F: *Mystus cavasius*; G: *Mastacembelus armatus*

3.8.1 Diversity indices (based on N = 140)
Total species (S) = 7
Total individuals (N) = 140
Species Proportions (pi)
Shannon-Wiener Diversity Index (H′)

$$H' = -\sum p_i \ln p_i$$

H′ = 1.78

Maximum Diversity (Hmax)

$$H_{max} = \ln S = \ln(7) = 1.95$$

Pielou's Evenness (J′)

$$J' = \frac{H'}{H_{max}}$$

J′ = 0.91

The Shannon index value of 1.78 indicated moderate richness of species, resembling the tropical headwater stream with complex structural patterns. The evenness score, which equals 0.91, supports the absence of a dominant species in the community and indicates that habitat resources within the researched areas are stable and available (Table 6).

Table 6 Species composition and relative abundance of fish recorded from the study area, showing the number of individuals (ni) and proportional abundance (pi) for each species

Species	ni	pi
Garra mullya	38	0.271
Puntius sophore	30	0.214
Cabdio morar	22	0.157
Glossogobius giuris	16	0.114
Mystus cavasius	14	0.100
Clarias magur	12	0.086
Mastacembelus armatus	8	0.057

3.8.2 Functional guild classification

The most abundant group was rheophilic taxa at 42.8%, followed by moderate proportions of benthic and pool-associated species. The distribution emphasizes the effect of flow regime and substrate complexity as dominant controls on assemblage structure in upper catchment. These patterns are indicative of the ecohydrological dynamics dominant in a minimally disturbed forested catchment setting (Table 7).

Table 7 Functional guild composition of upper catchment ichthyofauna

Species	Total (ni)	% Contribution	Functional Guild	Habitat Association
Garra mullya	38	27.1	Rheophilic	Rocky riffles, fast flow
Cabdio morar	22	15.7	Rheophilic	Run habitats
Puntius sophore	30	21.4	Riffle-Run Generalist	Moderate flow
Glossogobius giuris	16	11.4	Benthic	Sandy-gravel substrate
Mastacembelus armatus	8	5.7	Benthic-Interstitial	Crevices, roots
Mystus cavasius	14	10.0	Pool-dwelling	Slow-flowing pools
Clarias magur	12	8.6	Pool-Floodplain	Seasonal lentic areas

1 Dominance of rheophilic taxa (42.8%) confirms high dissolved oxygen (>7 mg L^{-1}) and coarse lateritic substrate.
2 Moderate representation of benthic species reflects structural complexity.
3 Pool-associated species indicate seasonal habitat heterogeneity during low-flow conditions.
4 Absence of exotic taxa suggests minimal anthropogenic disturbance.

3.8.3 Functional structure pattern

The dominance of rheophilic taxa and an even distribution between benthic and pool-dwelling guilds support the perspective that flow regime and substrate complexity govern the assemblage structure in the upper Sankh River. Such a finding is consistent with the ecohydrological regulation principles identified among only slightly perturbed tropical headwater systems (Table 8).

Table 8 Functional guild composition (%) of ichthyofauna in upper catchment of the Sankh River

Guild Type	Individuals	% Composition
Rheophilic	60	42.8%
Riffle Run Generalist	30	21.4%
Benthic	24	17.1%
Pool-dwelling	26	18.6%

4 Discussion

The present study demonstrates that the ecological integrity of the upper Sankh River headwater system is primarily regulated by the interaction of hydrogeomorphic setting, seasonal monsoonal hydrology, and extensive forest cover. Although seasonal fluctuations in hydrochemical characteristics were evident, the consistently excellent water quality, distinct multivariate seasonal separation, and structurally stable fish assemblages indicate that the upper catchment remains a minimally disturbed tropical plateau river ecosystem. Similar relationships between catchment geomorphology, hydrological regime, water chemistry, and ecological functioning have been reported for relatively undisturbed headwater rivers worldwide, where natural environmental controls dominate over anthropogenic influences (Poff et al., 1997; Bunn and Arthington, 2002; Meybeck, 2003; Allan, 2004). The present findings therefore reinforce the importance of integrating hydrogeomorphological, hydrochemical, biological, and landscape-level information when evaluating the ecological integrity and long-term conservation of tropical headwater systems.

The hydrochemical characteristics indicate that natural geogenic processes are the dominant factors driving the system, with a minor anthropogenic influence. The key attributes include low ionic strength, near-neutral to weakly alkaline pH, and high dissolved oxygen concentrations. Such characteristics are typical of forested headwater streams, where rock weathering and soil-water interactions control solute proportions (Gibbs, 1970; Wetzel, 2001; Meybeck, 2003). Similar trends have been noted even in relatively pristine catchments, where land cover types play an important role in protecting water quality (Allan, 2004; Li et al., 2008).

Monsoonal hydrology drives dilution, runoff, and solute transport processes resulting in seasonal variation in water chemistry. In the monsoon season, runoff is high with increased dissolved solids and nutrients, while in summer and winter, low-flow conditions cause concentration effects. This seasonal hydrogeochemical behavior has been described in heterogeneous river systems (Singh and Hasnain, 1999; Singh et al., 2004; Shrestha and Kazama, 2007; Setia et al., 2021). Both biological and physical processes drive these dynamics, which affect key parameters such as dissolved oxygen (DO), biochemical oxygen demand (BOD), and major ion concentrations (Pejman et al., 2009; Garizi et al., 2011; Bojarczuk et al., 2018). Therefore, the observed inverse temperature-DO relationship in this study would also show consistency with established physicochemical and biological principles dictating oxygen solubility (Wetzel, 2001).

A multivariate statistical analysis elucidated the dominant factors that are impacting water quality. Application of Principal Component Analysis (PCA) shows that hydrochemical variability is structured along two primary axes: lithogenic and seasonal physicochemical gradients. Nonetheless, caution is needed when interpreting PCA as statistical association does not mean direct causation (Shrestha and Kazama, 2007; Hair et al., 2019). The measured correlations between alkalinity, hardness, COD, and dissolved solids imply that such conditions fluctuate between mineral-dominated pathways versus runoff-influenced pathways as previously described by models of weathering-controlled river chemistry (Meybeck, 2003; Li et al., 2008).

The clear separation of seasonal clusters in PCA space, supported by MANOVA results ($p < 0.001$), further suggests that temporal variance holds greater influence on hydrochemistry than spatial differences within the study area. This concurrent consistency among PCA, correlation analysis, and hierarchical clustering provides strong evidence that seasonal discharge patterns are the major drivers of water quality variation.

The socio-ecological characteristics of the upper catchment further support the observed ecological integrity. Indigenous settlements remain closely associated with protected Sal forests and predominantly rain-fed agriculture, resulting in relatively low land-use intensity. This landscape configuration likely contributes to reduced sediment disturbance, enhanced infiltration, and maintenance of water quality through continued ecosystem functioning. Similar relationships between forest cover, traditional land use, and river ecosystem health have been reported in tropical headwater catchments where intact forests regulate runoff, nutrient retention, and aquatic habitat quality (Allan, 2004; Foley et al., 2005; Berkes, 2012).

Ecological observations support these findings. The ichthyofaunal assemblage was moderately diverse (H′ = 1.78) and highly even (J′ = 0.91), with a dominance of rheophilic species, indicating well-oxygenated, low-disturbance flowing-water conditions (Matthews, 1998; Sarkar et al., 2011). The composition of the assemblage corresponds to the River Continuum Concept, which hypothesizes a functional organization of aquatic communities along many environmental gradients (Vannote et al., 1980).

WQI values were consistently good in all seasons, which further strengthens the very low anthropogenic pressure results of the upper catchment. The comparison of specific physicochemical parameters with WQI also helps in assessing the river's overall health (Tyagi et al., 2020; Ali et al., 2024).

At the catchment scale, forest cover is critical to runoff regulation as well as erosion control and aquatic biodiversity. The sal-pine silvopastoral to forest-agriculture mosaic observed in the upper Sankh basin ensures hydrological stability and promotes nutrient retention which is essential for hydrochemical balance (Allan, 2004; Foley et al., 2005; Rodríguez-Romero et al., 2018). Sustainable land use practices and participatory local resource management are crucial to maintaining the ecological integrity of these headwater systems (Berkes, 2012).

Overall, the upper Sankh River provides a minimally disturbed headwater system dominated by lithogenic processes that work in conjunction with seasonal monsoonal hydrology to shape hydrochemistry and ecology. The insights forged herein can be further illuminated in future work with greater temporal frequency, broader spatial coverage, and long-term monitoring to advance understanding of ecohydrological processes for watershed management.

Study Limitations

There are certain limitations to consider when interpreting this study's findings. The hydrochemical and statistical assessments are based on a small sample size (n = 9) derived from composite seasonal sampling. Although this approach captures some integrated conditions, it limits spatial generalization and the capacity to observe fine-scale heterogeneity. In addition, multivariate methods like PCA and MANOVA identify statistical relationships but not causal connections. Though based on available observational data, the ichthyofaunal assessment is preliminary. Studies with additional spatial replication, higher sampling frequencies, and long-term monitoring would allow a more complete exploration of the dynamics within our system.

5 Conclusion

The upper Sankh River represents an undisturbed lateritic plateau headwater system strongly impacted by lithology and monsoonal hydrology. Hydrochemical variability is seasonal and follows known dilution-concentration models, while changes through time account for more than spatial differences according to multivariate analyses. The combined implementation of Principal Component Analysis (PCA) and Multivariate Analysis of Variance (MANOVA) successfully identified key environmental gradients influencing water quality. The makeup of fish species, in addition, highlights the stability and well-oxygenated state of the ecosystem, a characteristic feature of intact headwater streams. Low values of the Water Quality Index confirmed the good quality of the water and its little anthropogenic impact. The strong association between forest cover and hydrological regulation highlights the ecological importance of this catchment area.

Author Contributions

BB: Conceptualization, field investigation, data collection, socio-ecological surveys, ichthyofaunal assessment, data curation, and manuscript drafting. DG: Statistical analysis, data interpretation, multivariate analysis, visualization, and critical revision of the manuscript. SD: GIS Mapping, socio-ecological surveys. SKV: data interpretation, manuscript review, SG: Supervision, conceptual guidance, methodological oversight, interpretation of findings, manuscript review, and final revision.

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Data availability statement

The datasets analyzed during the current study are available from the corresponding author on reasonable request.

Conflict of Interest Disclosure

The authors affirm that this research was conducted without any commercial or financial relationships that could be construed as a potential conflict of interest.

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