

Multivariate Assessment of Seasonal Water Quality Dynamics in the Tuivawl River, Mizoram, Northeast India: Implications for Sustainable Water Resource Management

R. Laldinthari¹, Kulendra C. Das^{2*}

¹PhD Scholar, Department of Environmental Science, Pachhunga University College, Aizawl, Mizoram, India – 796005. Contact: 8732853862; E-mail: dinthari2@gmail.com ORCID: 0009-0002-2421-2588

²Associate Professor, Department of Environmental Science, Pachhunga University College, Aizawl, Mizoram, India – 796005. Contact: 7005799862; E-mail: drkulendra.das@gmail.com ORCID: 00000002-7982-3629

*Corresponding author: Kulendra C. Das

Abstract

Rivers of NE India are undercharacterised and lie within the Indo-Burma Biodiversity Hotspot. This study established the first multivariate baseline of surface water quality of the Tuivawl River, Saitual District, Mizoram, and determined whether water quality is under the primary control of season or longitudinal position along the river channel. Seventy-two site-month observations were collected from three stations over a ~25 km reach from November 2022 to December 2024, spanning winter, summer and rainy seasons. Fifteen physico-chemical and bacteriological parameters were measured following APHA standard methods and analysed using Kruskal-Wallis H tests, Pearson correlation, PCA, weighted arithmetic WQI and K-means clustering. Eleven of the 13 physico-chemical parameters differed significantly among seasons ($p < 0.05$), with none differing among sites, indicating that season exerts greater control on water quality than longitudinal position in this reach. PCA extracted three components explaining 68.01% of total variance: mineralisation-ionic enrichment (PC1: 42.01%), thermal transport (PC2: 14.50%) and nutrient-biological activity (PC3: 11.49%). Mean WQI was 94.59 ± 59.48 ("Very Poor") in winter, rising to 222.75 ± 198.61 ("Unsuitable") in summer and 385.83 ± 239.46 ("Wastewater") in the rainy season, driven by coliform counts reaching the detection limit at all three stations. K-means clustering ($k = 3$) reproduced the seasonal structure without any site signal. Health risk in this river is not adequately captured by physico-chemical monitoring alone, and the dataset provides a pre-degradation baseline to guide sanitation planning, riparian protection and sustainable water resource management in Mizoram.

Keywords: Water quality index; principal component analysis; faecal coliform; monsoon; Tuivawl River; Mizoram; Northeast India.

1. INTRODUCTION

Freshwater ecosystems are among the most ecologically valuable and most threatened ecosystems globally (Reid et al., 2018). Despite their small surface area, rivers harbour around one-third of all described vertebrate species and an estimated 10% of all Earth's described species, yet face mounting threats from population expansion, agricultural intensification, urbanisation, climate variability and extractive industry, all of which degrade water quality and imperil aquatic biota (Bogárdi et al., 2020; Leal et al., 2020).

The state of Northeast India is a part of Indo-Burma Biodiversity Hotspot, one of the most species-rich and threatened hotspots globally (Borah and Das, 2022). Mizoram retains 85.41% forest cover (Sati, 2023) and a dense network of hill streams sustaining aquatic life and rural livelihoods, yet these catchments are undergoing land-use change driven by shifting cultivation and infrastructure development, altering soil carbon and nutrient pools in ways transmissible to adjacent streams (Vishwambhar and Khawlhing, 2026; Sahoo et al., 2019).

The Tuivawl River is a headstream of the Barak basin in Saitual District. It carries water from boulder-dominated upstream reaches to alluvial floodplain substrata, providing communities with domestic water supply, irrigation and fishing. Despite this ecological and social importance, no long-term water quality data analysed in a multivariate framework has been published for this river.

In Mizoram, systematic river water quality studies have focused on two systems draining the area around the state capital. The Tlawng has been characterised along its Aizawl reach (Lalchhingpuii et al., 2011); its treatment plant has been evaluated (Ngente, 2024); and land-use effects on adjacent stream water at Sairang examined (Lianngura et al., 2025). The Tuirial has been evaluated near the Tuirial Hydel Project (Lalparmawii and Mishra, 2014), along an upstream-downstream gradient in successive annual cycles (Monica and Mishra, 2023, 2024), and adjacent to the Tuirial landfill (Laskar et al., 2022). The present study differs in three ways: it addresses the eastern Barak basin on a river not previously studied systematically; it analyses parameters jointly in a multivariate framework; and it incorporates faecal and total coliform into the Water Quality Index, quantifying bacteriological risk alongside physico-chemical status.

Multivariate statistical techniques such as PCA, cluster analysis and non-parametric hypothesis testing can resolve unobserved pollution sources, temporal and spatial structure, and hydrochemical processes that univariate approaches cannot, and yield both mechanistic insight and a policy-actionable output when coupled with a water quality index (Singh et al., 2004; Bramhankar et al., 2026). The objectives of this study were: (i) to describe the water quality seasonal and spatial variation by descriptive statistical and non-parametric testing; (ii) to identify latent hydrochemical factors through PCA; (iii) to classify water quality regimes using WQI and K-means clustering; and (iv) to translate observed water quality patterns into recommendations for sustainable river management in Mizoram.

2. MATERIALS AND METHODS

2.1 Study area

Mizoram occupies 21,087 km² in the south-western part of Northeast India between 21°58'N and 24°35'N and 92°15'E and 93°29'E. The climate is monsoonal, characterised by three seasons: winter (November – February) 11 – 21 °C, summer (March – June) 20 – 29 °C and the rainy season (July – October).

The Tuivawl River originates near Chhawrtui village and runs approximately 72.45 km on a broadly northward course through Saitual District and along the eastern margin of Aizawl District. It joins the trans-boundary Tuivai River (Manipur) at 24°06'46.45"N, 92°58'21.13"E; the combined flow continues to the Barak at Tipaimukh and thence to the Barak-Meghna system. Its well-developed network of first- and second-order seasonal streams responds rapidly to monsoon rainfall, generating the flashy discharge regime reflected in the turbidity and dilution signals reported below.

Twenty-eight settlements lie along the corridor from the source to the Tuivai confluence, across three districts (Khawzawl, Saitual and Aizawl), accommodating approximately 43,600 people in about 8,000-9,000 households. Saitual town is the only settlement exceeding 5,000 residents (27% of the corridor population); twenty-one of the twenty-eight settlements have fewer than 1,300 residents.

Approximately 23,200 people live upstream of Site 2 and 29,600 upstream of Site 3; 13,900 people in eleven settlements downstream of Site 3 have no monitoring data. Livelihoods combine jhum (shifting) cultivation with terrace cultivation. There is no reticulated sewerage; sanitation relies on improvised and well-built latrines, and open defecation persists in some settlements. Sand and gravel are extracted from the lower reaches.

To document land use and riparian condition changes along a longitudinal gradient, three monitoring sites were set up within a ~25 km reach. Site 1 (upstream, Champhai kai) has a boulder bottom, low human presence and domestic and traditional fishing activities. Site 2 (midstream, Saichal kai) has a silt, sand and gravel substratum, is under cultivation pressure and is the first site downstream of Saitual town where the main population influx is to the catchment. Site 3 (downstream, Phullen kai) has sand and gravel substratum, and the discharge is combined domestic and agricultural with a reach also affected by sand extraction.

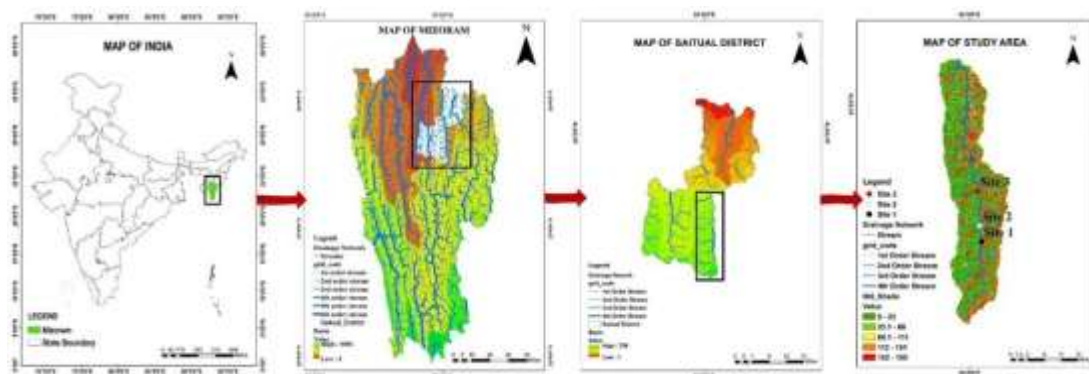


Fig. 1: Study area of the Tuivawl River, Saitual District, Mizoram, Northeast India, showing the three monitoring stations S1 (upstream), S2 (midstream) and S3 (downstream).

2.2 Sampling and analytical methods

Samples were collected monthly from three stations from November 2022 to December 2024, yielding 72 site-month observations (24 per site). These samples were collected in pre-cleaned polyethylene bottles, transported under ice and analysed at Mizoram Pollution Control Board laboratory within 24 hours. The 15 parameters were determined using standard methods (Baird et al., 2017): total dissolved solids – gravimetric, electrical conductivity – Conductivity Meter 306, turbidity – nephelometric, dissolved oxygen, BOD, faecal coliform – Most Probable Number, total coliform – Most Probable Number, total hardness – EDTA titrimetric, calcium – EDTA titrimetric, total alkalinity – titrimetric, nitrogen ammonia, phosphate – stannous chloride colorimetric. The coordinates were recorded using GPS Map Camera 1.5.1 and the study area was mapped in ArcGIS 10.8 using Google Earth imagery.

2.3 Water Quality Index

The multi-parameter dataset was synthesized into a single integrative measure using the weighted arithmetic Water Quality Index as established for rivers of Northeast India (Lkr et al., 2020). Unit weights (W_n) were assigned inversely proportional to WHO permissible standard (S_n) for each parameter where $K = 1/\sum 1/S_n$. The rating for each sub-index was calculated as $Q_n = [(V_n - V_0)/(S_n - V_0)] \times 100$, where V_n is the observed value and V_0 is the value in pure water (0 for most parameters, 7.0 for pH, 14.6 mg/L for DO). The index was calculated as $WQI = \sum (W_n \times Q_n) / \sum W_n$ and was categorised as Excellent (0 – 25), Good (26 – 50), Poor (51 – 75), Very Poor (76 – 100) and Unsuitable for drinking (>100) (Khudhur et al., 2026).

2.4 Statistical analysis

Statistical analyses were performed using RStudio and data was compiled in Microsoft Excel. Most parameters were not normally distributed as indicated by the Shapiro-Wilk test, a common characteristic of environmental water quality data (Helsel, 1987). Differences among seasons and sites were tested by means of the non-parametric Kruskal-Wallis H test. Bivariate associations were tested by means of the Pearson correlation. The variables were standardized to a zero mean and unit variance before ordination. Principal component analysis (PCA) of the 13-parameter physico-chemical data set was carried out retaining components with eigenvalues above 1.0 (average-eigenvalue threshold). Variance and cumulative percentage are shown in Table 2. A K-means cluster analysis ($k = 3$, 10 random starts) was applied to the standardized data to identify discrete water quality regimes. Significance was considered at $\alpha = 0.05$.

3. RESULTS

3.1 Descriptive statistics and seasonal variation

Summary statistics and Kruskal-Wallis results are presented in Table 1 and seasonal distributions in Fig. 2. Significant differences among the seasons were observed for eleven of the thirteen physico-chemical parameters. Temperature ranged between 14 and 29 °C, increasing sharply from the winter through summer and rainy seasons ($H = 41.65$, $p < 0.001$). Dissolved oxygen (5.7-11.1 mg/L) exhibited a reverse

trend, decreasing from 9.13 ± 0.98 mg/L in winter to 6.83 ± 0.61 mg/L in the rainy season ($H = 48.83$, $p < 0.001$), consistent with the temperature dependence of oxygen solubility (Iqbal et al., 2018). Turbidity was the most variable parameter on the relative scale, increasing by approximately an order of magnitude from 6.07 ± 5.79 NTU in winter to 63.29 ± 57.26 NTU in the rainy season ($H = 35.67$, $p < 0.001$), which suggests monsoon-driven suspended sediment and surface runoff loading (Semy and Singh, 2021; Renthlei and Das, 2025). Electrical conductivity showed the opposite trend, decreasing from $117.71 - 120.50$ $\mu\text{S}/\text{cm}$ in dry seasons to 83.21 ± 14.90 $\mu\text{S}/\text{cm}$ in the rainy season ($H = 21.27$, $p < 0.001$). This was caused by dilution by the rainwater and rapid runoff (Pujiindiyati et al., 2020). Total hardness, calcium and total alkalinity followed a similar trend, decreasing by $\sim 40 - 50\%$ in rainy season ($p < 0.001$) consistent with decreased residence time for carbonate dissolution (Khalaf et al., 2021).

Nitrogen-ammonia varied significantly among seasons ($H = 6.84$, $p = 0.033$); the summer season recorded the highest mean (0.096 ± 0.063 mg/L), the rainy season was intermediate (0.196 ± 0.095 mg/L), and winter was lowest (0.096 ± 0.005 mg/L). Total phosphate did not differ significantly among seasons ($H = 2.09$, $p = 0.351$). Total dissolved solids were also not found to be significantly different among the seasons ($H = 14.89$, $p = 0.001$). BOD remained consistently low throughout (mean 1.08 ± 0.68 mg/L), well below the BIS permissible limit of 5 mg/L (Renthlei and Das, 2025; Bhardwaj et al., 2021), and was lowest in the rainy season, most plausibly a dilution effect. No significant difference among the three sampling sites was detected for any physico-chemical parameter ($p > 0.05$); directional trends in turbidity, conductivity and nutrient indicators followed the expected upstream-to-downstream land-use sequence but were homogenised by the steep, turbulent channel flow (Dupas et al., 2021).

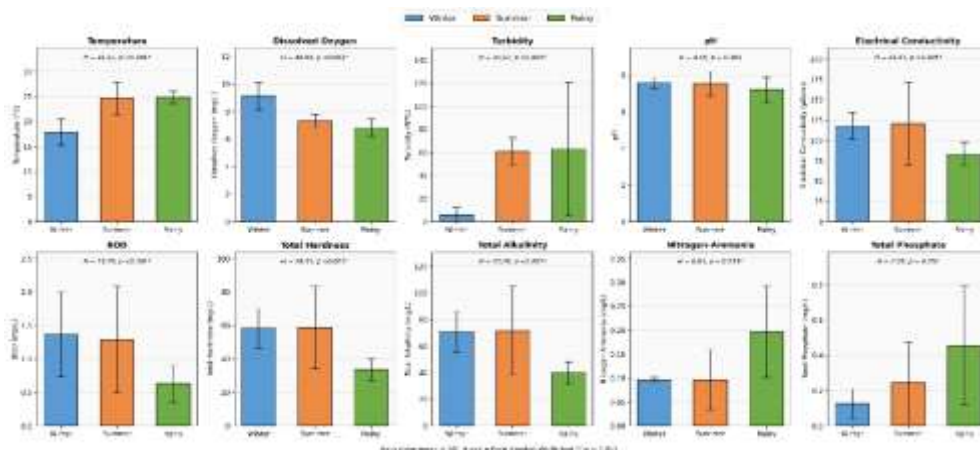


Fig. 2: Seasonal variation of key water quality parameters in the Tuivawl River, 2022-2024.

Table 1. Descriptive statistics and Kruskal-Wallis test results for water quality parameters across seasons (* $p < 0.05$).

Parameter	Unit	Winter (Mean $\pm$ SD)	Summer (Mean $\pm$ SD)	Rainy (Mean $\pm$ SD)	Overall (Mean $\pm$ SD)	H-value	p-value
Temperature	°C	17.79 $\pm$ 2.60	24.62 $\pm$ 3.12	24.74 $\pm$ 1.21	22.25 $\pm$ 4.09	41.65	<0.001*
Electrical Conductivity	$\mu\text{S}/\text{cm}$	117.71 $\pm$ 16.93	120.50 $\pm$ 50.57	83.21 $\pm$ 14.90	107.36 $\pm$ 34.52	21.27	<0.001*
Turbidity	NTU	6.07 $\pm$ 5.79	60.75 $\pm$ 11.97	63.29 $\pm$ 57.26	43.36 $\pm$ 25.06	35.67	<0.001*
Dissolved Oxygen	mg/L	9.13 $\pm$ 0.98	7.32 $\pm$ 0.49	6.83 $\pm$ 0.61	7.85 $\pm$ 1.26	48.83	<0.001*
BOD	mg/L	1.37 $\pm$ 0.63	1.29 $\pm$ 0.79	0.63 $\pm$ 0.27	1.08 $\pm$ 0.68	18.29	<0.001*
Chloride	mg/L	6.31 $\pm$ 2.35	5.63 $\pm$ 1.35	4.47 $\pm$ 0.85	5.50 $\pm$ 1.83	10.78	0.005*

Parameter	Unit	Winter (Mean±SD)	Summer (Mean±SD)	Rainy (Mean±SD)	Overall (Mean±SD)	H- value	p-value
pH	-	7.58±0.28	7.54±0.66	7.21±0.68	7.45±0.57	4.59	0.101
Total Hardness	mg/L	58.44±11.60	58.67±24.54	33.65±6.40	50.48±19.30	28.51	<0.001*
Calcium	mg/L	13.07±3.74	12.30±6.20	6.30±2.72	10.65±5.27	26.13	<0.001*
Total Alkalinity	mg/L	70.88±15.25	71.40±33.30	40.09±8.05	61.06±25.24	30.09	<0.001*
Nitrogen-Ammonia	mg/L	0.096±0.005	0.096±0.063	0.196±0.095	0.129±0.054	6.84	0.033*
Total Phosphate	mg/L	0.125±0.082	0.244±0.230	0.454±0.335	0.274±0.216	2.09	0.351
TDS	mg/L	77.93±15.99	124.00±36.59	111.29±75.81	100.40±50.28	14.89	0.001*

(Source: Authors)

3.2 Principal component analysis

PCA identified three factors with an eigenvalue > 1.0, which collectively account for 68.01% of total variability (Table 2, Fig. 3). Factor 1 (PC1) explained 42.01% of the data set variability with an eigenvalue of 5.567 and had strong correlations to total hardness (+0.404), calcium (+0.397), electrical conductivity (+0.377) and total alkalinity (+0.378), moderate correlation to BOD (+0.370) and negative correlation to turbidity (-0.288). These indicators together reflect the amount of mineral dissolution/chemical weathering occurring within the catchment based on geology, residence time of the water and soil carbonate levels (Hartmann et al., 2013). Therefore, it can be inferred that Factor 1 (PC1) represents the degree of mineralization and ionization, indicating increased interaction between the water and rock due to long residence times at low flow rates throughout both summer and winter. The opposing correlation of turbidity reflects the inverse relationship where high flow events that increase the sediment transport will decrease the ionic strength of the dissolved ions.

Factor 2 (PC2) explained 14.50% of the data set variability with an eigenvalue of 1.922 and had the largest correlation coefficients for temperature (+0.506), chloride (+0.414), TDS (+0.420) and turbidity (+0.323). Correlation between temperature and chlorides/TDS indicates warm temperatures have higher concentrations of ions via evaporative concentration and lower dilution in those same months. This axis is also referred to as a thermal-transport factor.

Factor 3 (PC3) explained 11.49% of the data set variability with an eigenvalue of 1.523 and had strong correlations for nitrogen ammonia (+0.477) and pH (-0.457) along with moderate correlation to DO (+0.416). The combination of nitrogen ammonia and pH is referred to as a nutrient-biological activity factor, illustrating the equilibrium between nitrogen load into streams and biological process in streams.

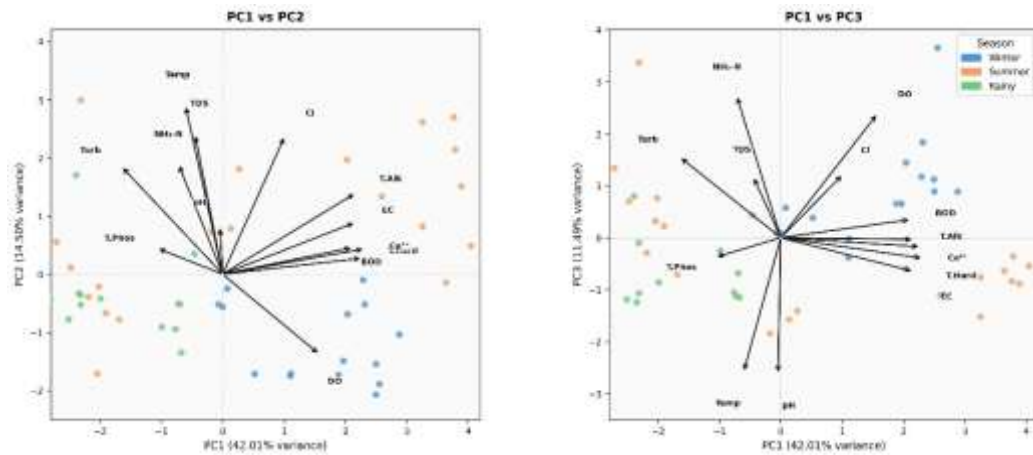


Fig. 3: PCA biplot of water quality parameters in the Tuivawl River (arrows = variable loadings; points = observations coloured by season).

Table 2. PCA loadings for the first three principal components (* loading $\geq |0.38|$).

Parameter	PC1 (42.01%)	PC2 (14.50%)	PC3 (11.49%)
Temperature	-0.106	0.506*	-0.451*
Electrical Conductivity	0.377*	0.155	-0.113
Turbidity	-0.288	0.323	0.271
Dissolved Oxygen	0.275	-0.240	0.416*
BOD	0.370*	0.080	0.061
Chloride	0.177	0.414*	0.213
pH	-0.008	0.144	-0.457*
Total Hardness	0.404*	0.076	-0.069
Calcium	0.397*	0.048	-0.030
Total Alkalinity	0.378*	0.243	-0.006
Nitrogen-Ammonia	-0.126	0.330	0.477*
Total Phosphate	-0.187	0.078	-0.066
TDS	-0.079	0.420*	0.206
Eigenvalue	5.567	1.922	1.523
% Variance	42.01	14.50	11.49
Cumulative %	42.01	56.51	68.01

(Source: Authors)

3.3 Water Quality Index

WQI results are summarised in Table 3 and Fig. 4. On average, based on 71 sampling events with complete data for the parameters considered, the WQI was 234.39 ± 179.47 . This value falls in the “Unsuitable” category as per Piyathilake et al., (2022). In addition to being unsuitable, the results showed significant variability over time. The winter mean WQI (94.59 ± 59.48) fell in the “Very Poor” range, substantially better than summer (222.75 ± 198.61) and the rainy season (385.83 ± 239.46), both “Unsuitable”. Classified individually, 54.9% of 71 observations fell into “Unsuitable for drinking” and only 9.9% into “Good” or “Excellent”, the latter confined to low-flow winter and early pre-monsoon months, demonstrating the river’s capacity to deliver acceptable quality under baseflow conditions. Extreme rainy-season values reaching 2223 at Site 2 were driven by coliform peaks, which exert a disproportionate influence on the WQI through their low permissible standards and correspondingly high unit weights.

Site-by-site variability confirms our Kruskal-Wallis results. Although Site 2 had the largest mean index (324.91) and Site 1 had the smallest (128.97), no two Sites' mean indices were outside of each other's range limits resulting in an overlapping range for all three Sites. Consequently, the variability in WQI values within each Site throughout a year can be greater than differences in WQI values observed among Sites at a single point in time.

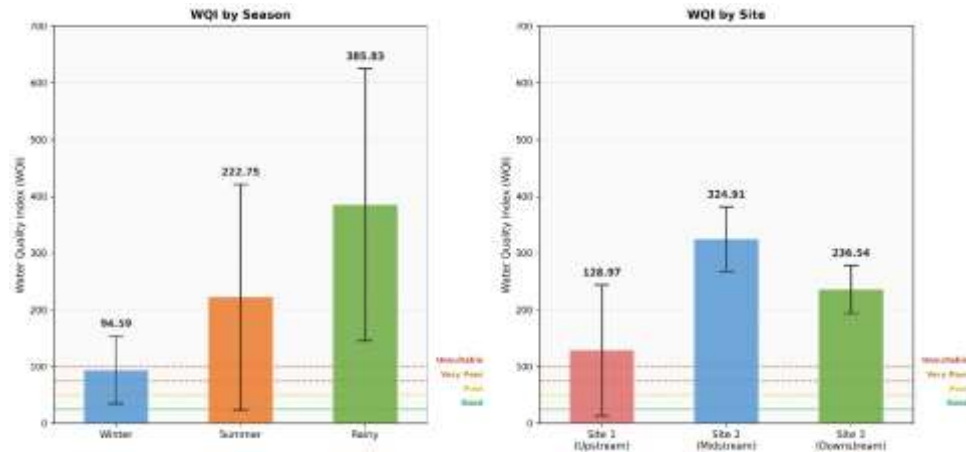


Fig. 4: Water Quality Index scores by sampling site and season (error bars = 95% confidence intervals; dashed lines = WQI classification thresholds).

Table 3. *Water Quality Index by site and season, with observed range and classification.*

Site / Season	WQI Mean±SD	WQI Range	Classification range
Site 1 (Upstream)	128.97±115.29	7.82 – 555.25	Excellent to Unsuitable
Site 2 (Midstream)	324.91±56.72	39.35 – 2223.11	Good to Unsuitable
Site 3 (Downstream)	236.54±42.24	20.73 – 2119.58	Excellent to Unsuitable
Winter	94.59±59.48	10.72 – 236.63	Excellent to Unsuitable
Summer	222.75±198.61	7.82 – 709.68	Excellent to Unsuitable
Rainy	385.83±239.46	49.71 – 2223.11	Good to Unsuitable
Overall	234.39±179.47	7.82 – 2223.11	Unsuitable (54.9%)

(Source: Authors)

The monthly time series for four representative parameters across both hydrological years described a repeating annual cycle with no directional deterioration. The reproducibility of seasonal patterns across two independent years confirms that the contrasts reported above reflect a stable hydrological regime.

3.4 Cluster analysis

The “k-means” selection ($k = 3$) distinguished three internally coherent groups, which show clear seasonal correspondence and no site structure, involving 65 observations for which parameters have been completely covered (Fig. 5). Cluster A ($n = 32$) were mostly rainy and summer (17 rainy, 12 summer, 3 winter), high turbidity, low mineralisation, biologically active regime with monsoon dilution and sediment mobilisation. The cluster B ($n = 12$) observations, with the lowest turbidity and the highest DO, mineralisation and the best water quality of the data set, were all winter observations. The observations in cluster C ($n = 9$) were all in summer, when the turbidity was intermediate, and the temperature as well as the level of nitrogen were also high, as observed during the pre-monsoon period in agriculture. There

was no systematic relationship of cluster membership with any sampling station, thus reinforcing the Kruskal-Wallis result of negligible spatial variation compared to seasonal variation.

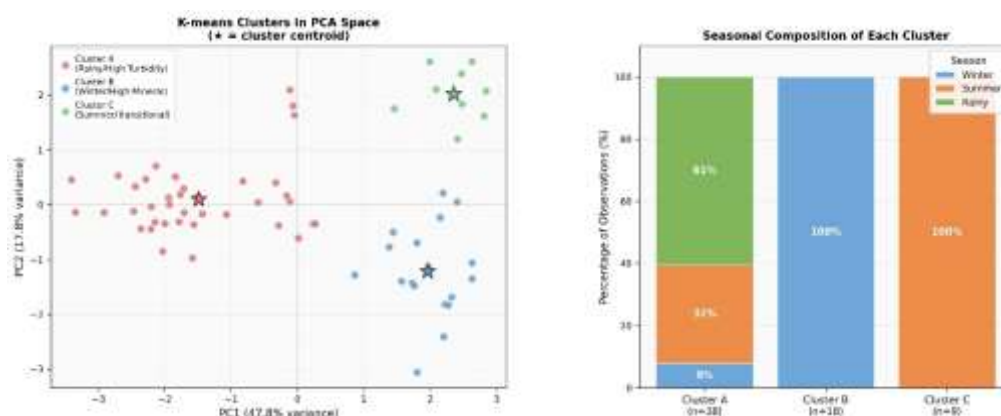


Fig. 5: K-means cluster analysis ($k = 3$) in principal component space, with the seasonal composition of each cluster.

4. Discussion

4.1 Seasonal control and hydrochemical processes

Season was the dominant control on water quality in the Tuivawl, aligning it with the broader class of monsoon-influenced rivers in South and Southeast Asia. The inverse temperature – dissolved oxygen relationship reflects thermodynamics and atmospheric re-aeration at high flow, a pattern shared by the Doyang (Lkr et al., 2020) and Tsurang (Semy and Singh, 2021) rivers, indicating a regional rather than catchment-specific signature.

The PCA structure indicates a system governed by three interacting process domains. The dominant mineralisation factor reflects water-rock interaction and carbonate weathering, intensified during dry seasons when residence times are longer and dilution is absent. This contrasts instructively with lowland Indian rivers such as the Gomti, where the first component is typically dominated by organic and nutrient loading from point sources rather than weathering products (Singh et al., 2004), and parallels PCA results for rivers of the north-western Himalaya where geological controls explain the largest share of variance (Sharma et al., 2021). A weathering-dominated rather than effluent-dominated first axis is itself diagnostic of a catchment in which diffuse natural processes still outweigh concentrated anthropogenic discharge. The thermal-transport factor (PC2), dominated by temperature, chloride and TDS, captures evaporative concentration during summer low flows; chloride is a widely used conservative tracer of domestic wastewater in rural headwaters (Benettin et al., 2015; Withers et al., 2011).

The elevated summer nitrogen-ammonia most plausibly reflects pre-monsoon applications of fertiliser near the riparian corridor, mobilised by the first significant rainfall – consistent with the jhum and terrace cultivation systems prevalent in Saitual District (Mukul et al., 2022). Concentrations remained below the WHO drinking-water guideline of 1.5 mg/L (Mitchell and Frisbie, 2023), but ammonia is a sensitive early indicator of anthropogenic N loading (Edwards et al., 2023) with sub-lethal effects on freshwater organisms well below the human health threshold (Yuan et al., 2026).

4.2 Microbiological contamination and the exposed population

The principal factor driving the WQI into the "Unsuitable" class during the rainy and summer seasons is bacteriological contamination. In several rainy and summer events, in both 2023 and 2024, the total coliform counts exceeded the analytical ceiling of 2400 MPN/100 mL at all three sites, while faecal coliform counts exceeded or approached this ceiling. These magnitudes are consistent with documented

wet-season bacteriological loading in rural rivers across South and Southeast Asia (Boithias et al., 2024), and comparable loads have been reported for the Tuikual River in Aizawl (Ngente and Mishra, 2022). The broader implication is that the Tuivawl may be the least degraded of Mizoram's studied rivers on physico-chemical grounds yet is not potable for roughly two-thirds of the year once bacteriological parameters are considered – a dimension absent from the published literature on the state's rivers. There are around 43,600 people living in the corridor without reticulated sewerage, dumping waste into the narrow steep sided catchment where separation between the latrine and the stream channel is often tens of metres only. The near-simultaneous detection of the coliform signal across the channel network during monsoon rainfall is best explained by shallow subsurface and overland flow connecting sources to the river, rather than progressive downstream accumulation. The population is concentrated at a single moderate node (Saitual town, upstream of Site 2), so source control must be distributed across the corridor. No bacteriological data exist for the 13,900 people living below Site 3; untreated use during the rainy season implies a substantial risk of waterborne gastrointestinal disease, borne disproportionately by children under five (Ranjan et al., 2024).

4.3 Spatial homogeneity in comparative perspective

The absence of any significant longitudinal gradient sets the Tuivawl apart from Mizoram's two better-studied rivers, which share its lithology, climate and hydrological regime but differ in catchment population density and land-use intensity. Both the Tlawng and the Tuirial show distinct downstream pollution intensification (Lianngura et al., 2025; Laskar et al., 2022). Two explanations are plausible: the Aizawl sewage load and the Tuirial solid-waste site generate high-magnitude point sources absent from the Tuivawl; and the steep, turbulent flow of this hill river homogenises the water column over short distances (Bassin et al., 2009; Dupas et al., 2021).

The Tuivawl carries lower chloride and lower overall mineralisation than these comparators, as expected without a city-scale settlement, and its BOD lies well below pre-treatment Tlawng values. Its distinguishing feature is its sediment load, rising tenfold between winter and the rainy season, pointing to catchment-scale erosion from steep-slope cultivation, unmetalled road cuttings and in-channel sand extraction rather than effluent discharge. The Tuivawl is therefore best characterised not as a cleaner river but as a differently stressed one – high in suspended sediment and bacteriological load, low in dissolved and organic pollutants – a signature typical of catchments at an earlier stage of degradation.

4.4 Implications for conservation and management

The study reaches lies within the Indo-Burma Biodiversity Hotspot (Smith et al., 2012), and the Barak-Tuivawl system probably provides connectivity for freshwater-dependent species. The rainy season carries the greatest ecological risk: elevated turbidity disrupts predator-prey interactions (Ortega et al., 2020), while nutrient pulses and extreme bacteriological loads impose additional stress, as documented in comparable Himalayan systems (Tabassum et al., 2024). High ichthyological diversity is expected given the Barak basin context (Kar and Sen, 2007), but no systematic fish or macroinvertebrate survey has been undertaken and should be a priority. Spatial homogeneity is not evidence of pristine conditions; it reflects cumulative stresses distributed uniformly along the entire reach.

Four priority interventions follow. First, household-level water treatment should be promoted corridor-wide, supported by seasonal public health messaging initiated in June (Trent et al., 2018). Second, sanitation investment should be prioritised in proportion to contributing population rather than distributed evenly, with Saitual town, Kawkulh, Phullen, Suangpuilawn and Darlawn bearing the majority of the corridor's faecal load. Third, Village Council programmes should establish riparian buffer zones and regularise sand excavation at Site 3 to limit benthic disturbance; enforcement capacity under existing statutory powers remains a recognised constraint in rural districts (Verma, 2021). Fourth, the unmonitored lower reach between Site 3 and the Tuivawl-Tuivai confluence should be brought into the monitoring network, and coliform enumeration made mandatory in state protocols.

5. CONCLUSION

This study provides the first multivariate assessment of water quality in the Tuivawl River. Eleven of the thirteen physico-chemical parameters differed significantly among seasons while none differed among the three sampling stations, indicating chemical homogeneity along the 25 km study reach. Three factors

were extracted by PCA that accounted for 68.01% of the total variance – mineralisation and ionic enrichment (42.01%), thermal transport (14.50%) and nutrient-biological activity (11.49%) – and represented the interaction between geological weathering, monsoonal hydrology and anthropogenic nutrient input. The rainy season consistently produced the worst water quality, driven by extreme coliform loads and high turbidity, with 54.9% of the observations being classified as "Unsuitable for drinking" by the WQI (Uddin et al., 2020). The seasonal partition was independently reproduced by K-means clustering ($k = 3$) and proved stable across two full hydrological years.

Limitations. Three constraints apply. First, the network covers only the upper 25 km reach; the unmonitored lower stretch between Site 3 and the Tuivawl-Tuivai confluence is not represented. Second, coliform counts exceeding the 2400 MPN/100 mL analytical ceiling were censored, so the high-load tail is underestimated. Third, the absence of discharge, sediment chemistry, heavy metal and biological data limits source apportionment to inference rather than quantification.

Scope for future research. Priority actions are installing monitoring stations at the Tuivawl-Tuivai confluence; quantifying coliform loads via serial dilution or molecular methods beyond the current MPN ceiling to apportion sources; undertaking systematic fish and macroinvertebrate surveys to establish a biological baseline; and conducting heavy metal and sediment sampling in areas affected by sand extraction.

Practical implications. The central practical finding is that health risk in Mizoram's rivers is not adequately captured by physico-chemical monitoring alone; coliform enumeration must be mandatory in state protocols. Interventions should be timed rather than geographically targeted: household treatment promotion and public health messaging scaled up ahead of June, and sanitation investment allocated in proportion to contributing population. The river's ecological integrity remains adequate for diverse aquatic biota, particularly in winter, but is being progressively degraded by agricultural encroachment, inadequate sanitation and sand mining. The dataset provides a pre-degradation baseline against which future land-use change, shifts in monsoon intensity and pollution-control effectiveness can be evaluated.

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Authors' contributions

R. Laldinthari – Sample collection, Formal analysis, Investigation, Methodology, Software, Visualization, Writing (original draft). Kulendra C. Das – Conceptualization, Validation, Supervision, Resources, Writing (review and editing).

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Data availability: The datasets analysed during this study are available from the corresponding author on reasonable request.

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