International Journal for Multidisciplinary Research (IJFMR)
E-ISSN: 2582-2160 ● Website: www.ijfmr.com ● Email: editor@ijfmr.com

Spatiotemporal Evaluation of Water Quality and Pollution Characteristics of Selected Lakes in the Nilgiris District, Western Ghats, India

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Abstract

This study investigates seasonal changes in water quality and the partitioning of trace metals across the water–sediment–fish continuum in selected freshwater lakes of the Nilgiris, Western Ghats, India. Physicochemical parameters, nutrients and Cu, Ni and Pb were evaluated in water, sediments and fish muscle of Cyprinus carpio from Pykara, Emerald and Kattery lakes and Carassius gibelio from Wellington Lake. Water Quality Index (WQI) values increased from 48.2–68.5 during the pre-monsoon period to 62.5–74.9 post-monsoon, indicating seasonal deterioration in water quality. Wellington exhibited the strongest dissolved-ion and organic-loading signal, with elevated BOD and TDS, while phosphate concentrations reached 4.23 mg/L across the study lakes. Dissolved Pb concentrations (27.19–72.5 µg/L) exceeded the adopted water-quality guideline across the study lakes, whereas sediment Cu (50.15–69.74 µg/g) and Ni (61.26–85.82 µg/g) exceeded the adopted 50 µg/g guideline at multiple sites. Fish-muscle Ni concentrations (0.70–0.80 µg/g) were elevated despite comparatively low dissolved Ni concentrations, suggesting that water-column measurements alone may not fully capture biological exposure. Sediment-to-fish concentration ratios for Cu, Ni and Pb were consistently below unity (0.0056–0.0124), with Ni showing the highest ratio among the three metals. Dietary exposure assessment indicated low non-carcinogenic risk, with Hazard Index values ranging from 0.0504–0.0621 for adults and 0.1196–0.1476 for children. Overall, the contrasting distribution of Pb, Cu and Ni among water, sediment and fish indicates compartment-specific contamination patterns and highlights the value of integrated water–sediment–biota assessment for characterizing contaminant persistence and biological exposure in mountain freshwater ecosystems.

Keywords: Fresh water; Heavy metals; WQI -Water Quality Index; R_{sf} - sediment-to-fish concentration ratio, Human Health Risk Assessment; Nickel bioaccumulation; Nilgiris UNESCO Biosphere reserve.

Introduction

Freshwater ecosystems are vital for maintaining ecological balance, conserving biodiversity and supporting human activities such as drinking water supply, irrigation, fisheries and tourism. Mountain lakes are particularly vulnerable to environmental degradation because of their limited self-purification capacity and sensitivity to changes in hydrology and anthropogenic activities. The Nilgiris, located in the Western Ghats and recognized as part of the UNESCO Biosphere Reserve network, contains ecologically important freshwater systems that are increasingly influenced by urbanization, tourism, agricultural

runoff, untreated sewage and seasonal climatic variability [1], [2]. Increasing tourism and residential development have further raised concerns regarding the ecological integrity of Nilgiris lakes [3].
Trace metals are of particular concern because of their persistence and ability to accumulate in aquatic environments. Natural weathering of mafic and ultramafic rocks can contribute to the release of elements such as nickel into aquatic ecosystems, while anthropogenic activities may introduce additional metal inputs. Copper (Cu), nickel (Ni) and lead (Pb) can become associated with sediments and aquatic organisms, with potential implications for ecosystem health and human exposure through fish consumption. Sediments can function as important reservoirs and secondary sources of metals, whereas fish can integrate contaminant exposure over time through waterborne and dietary pathways. Consequently, concentrations measured only in the water column may not adequately represent the distribution of metals or the potential for biological exposure.
Because water, sediment and fish differ in their capacity to retain, mobilize and accumulate trace metals, assessment across these interconnected compartments provides a more comprehensive understanding of aquatic contamination. The Water Quality Index (WQI) is widely used to integrate multiple physicochemical parameters into a single indicator of overall water quality [4], while evaluation of metal distribution in sediment and fish provides additional information on environmental persistence and biological exposure.
Although several studies have investigated water quality or metal contamination in the Western Ghats, integrated assessments linking seasonal water quality with metal distribution in water, sediment and fish, together with potential human health risks, remain limited for the lakes of the Nilgiris. Therefore, the present study investigated seasonal variations in physicochemical water quality and WQI and determined the concentrations of Cu, Ni and Pb in water, sediment and fish muscle from Pykara, Emerald, Kattery and Wellington lakes. The study further evaluated the sediment-to-fish concentration ratio (Rsf) and estimated dietary exposure risks using estimated daily intake (EDI), target hazard quotient (THQ) and hazard index (HI) for adults and children following the USEPA risk-assessment framework [5]. By integrating water, sediment and fish compartments, the study provides a comprehensive assessment of metal distribution, biological exposure and potential human health implications in mountain freshwater ecosystems of the Western Ghats.

Objectives

1. To evaluate the seasonal variation in the physicochemical characteristics and Water Quality Index (WQI) of selected lakes in the Nilgiris.
2. To determine the distribution of copper (Cu), nickel (Ni) and lead (Pb) in water, sediment and fish muscle.
3. To assess the distribution of metals between sediment and fish using the sediment-to-fish concentration ratio (Rsf).
4. To evaluate the potential human health risks associated with fish consumption using estimated daily intake (EDI), target hazard quotient (THQ) and hazard index (HI).

Figure 1: Map showing the area of study

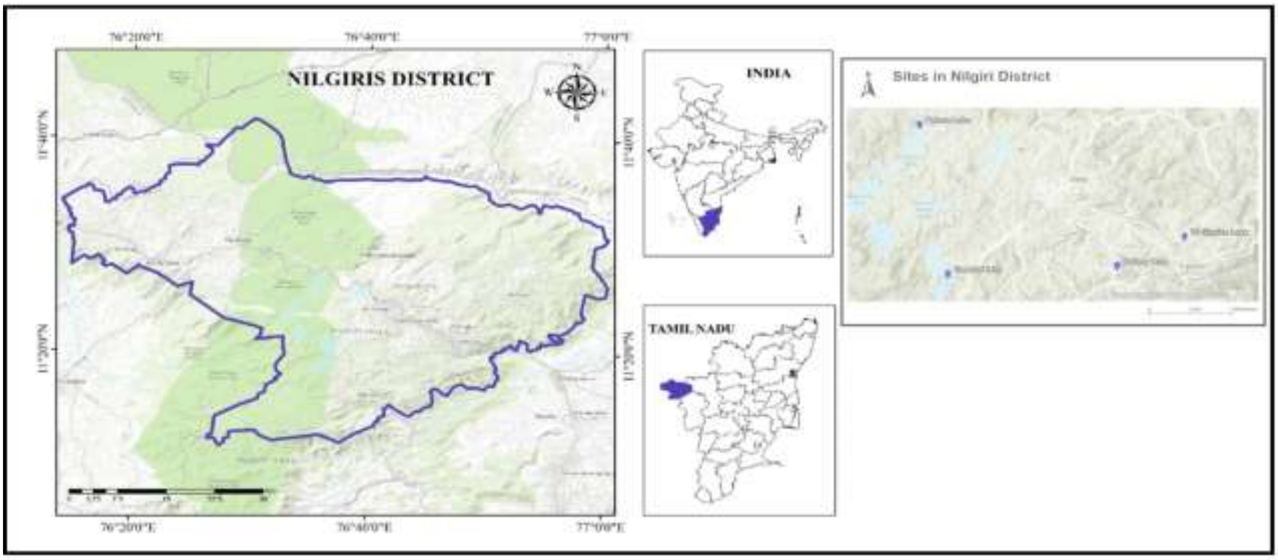


Figure 2: Selected Lakes for study in Nilgiris District

Table 1: Sampling schedules

S. No	Season	Phase	Month of sampling	Season duration
1.	Pre-monsoon	I	April	March to May
2.	Post-monsoon	II	January	November to February

2. Materials and Methods

2.1 Study Area and Sampling Design

The study was conducted in four selected lakes of the Nilgiris District, Western Ghats, India, namely Pykara, Emerald, Kattery and Wellington (Figure 1). The lakes were selected based on their ecological significance, tourism and agricultural activities, and varying degrees of anthropogenic influence (Figure 2). Sampling locations within each lake were selected to represent areas influenced by tourism and residential activities as well as relatively undisturbed zones, enabling the assessment of spatial variation in water quality and metal distribution [6]. Sampling was carried out during the pre-monsoon (March–May) and post-monsoon (November–February) periods to assess seasonal variations in physicochemical characteristics and trace-metal distribution.

Water Sampling

Surface-water samples were collected in pre-cleaned polypropylene bottles, which were rinsed thoroughly with the respective lake water prior to sampling. For trace-metal analysis, samples were collected in acid-washed bottles and transported to the laboratory under controlled conditions for further analysis. Standard sampling and preservation procedures were followed to maintain sample integrity and minimize contamination during collection and storage [7].

Sediment Sampling

Sediment samples were collected from the selected sampling locations and transported to the laboratory. The samples were air-dried under shade at room temperature, gently ground, homogenized and sieved to obtain a uniform particle fraction. The processed samples were stored in clean polyethylene containers until analysis, following standard procedures for sediment preparation and storage [8].

Fish Sampling

Fish samples were collected from the selected lakes with the assistance of local fishermen using conventional capture methods such as gill nets and cast nets. Cyprinus carpio (common carp) was collected from Pykara, Emerald and Kattery lakes, whereas Carassius gibelio (silver carp) was collected from Wellington Lake. The species were selected based on their availability and local consumption, providing ecological and human-health relevance to the study.

Immediately after collection, fish samples were rinsed with distilled water and transported to the laboratory in ice boxes to minimize tissue degradation. Total length and weight were recorded, after which muscle tissues were dissected using clean stainless-steel instruments to minimize contamination. The tissues were washed with deionized water, oven-dried at 60 °C to constant weight and homogenized prior to elemental analysis following established procedures [9].

2.2 Physicochemical and Nutrient Analysis

Water temperature, pH, electrical conductivity (EC) and total dissolved solids (TDS) were measured in situ using a calibrated PCSTestr 35 Multi-Parameter meter. Dissolved oxygen (DO) was determined by the Winkler titration method, biochemical oxygen demand (BOD_5) by 5-day incubation at 20 °C, and chemical oxygen demand (COD) by the dichromate reflux method. Total hardness, alkalinity and chloride were determined using standard titrimetric methods, while nitrate and phosphate were analysed spectrophotometrically. All analyses followed standard procedures prescribed by APHA (2005).

2.3 Sediment and Fish Digestion and Trace-Metal Analysis

Approximately 1 g of dried, homogenized sediment and fish-muscle samples was subjected to tri-acid digestion using H_2SO_4:HNO_3:$HClO_4$ in a 2:9:1 ratio. The digested samples were filtered and diluted to a known volume with deionized water. Concentrations of Cu, Ni and Pb were determined using a PerkinElmer ICP-MS (NexION™ 300X). Metal concentrations in sediment and fish samples were expressed on a dry-weight basis.

2.4 Major Element Analysis

Sodium (Na), potassium (K) and calcium (Ca) were determined using a flame photometer, while phosphorus was determined by UV spectrophotometry following established analytical procedures [10].

2.5 Quality Assurance and Quality Control

All sampling containers and laboratory glassware were thoroughly cleaned and rinsed with deionized water before use. Reagent blanks, replicate analyses and certified reference materials were used to assess contamination, analytical precision and accuracy. The ICP-MS was calibrated using appropriate standards, with calibration curves showing $R^2 > 0.99$. Analytical recoveries ranged from 90–110%, while relative standard deviations (RSD) were <5%. Detection limits were determined using reagent blanks.

2.6 Water Quality Index (WQI)

The Water Quality Index (WQI) was calculated using the weighted arithmetic index method to provide an integrated assessment of overall water quality [4]. The parameters included pH, dissolved oxygen (DO), total dissolved solids (TDS), electrical conductivity (EC), nitrate and phosphate.

The quality rating (Q_i) for each parameter was calculated as:

$$Q_i = \frac{V_i - V_0}{S_i - V_0} \times 100 \quad (1)$$

where V_i is the observed value of the parameter, S_i is the standard permissible value and V_0 is the ideal value. The ideal value was considered 0 for most parameters, 7.0 for pH and 14.6 mg L^{-1} for DO.

The unit weight (W_i) was calculated as:

$$W_i = \frac{K}{S_i} \quad (2)$$

where K is the proportionality constant calculated as:

$$K = \frac{1}{\sum_{i=1}^{n} \frac{1}{S_i}} \quad (3)$$

The overall WQI was calculated as:

$$WQI = \frac{\sum_{i=1}^{n} W_i Q_i}{\sum_{i=1}^{n} W_i} \quad (4)$$

The resulting WQI values were used to assess the overall water-quality status of the selected lakes.

2.7 Sediment-to-Fish Concentration Ratio

The sediment-to-fish concentration ratio (Rsf) was calculated for Cu, Ni and Pb to evaluate their relative distribution between sediment and fish muscle. The ratio was calculated as:

$$R_{sf} = \frac{C_{fish}}{C_{sediment}} \quad (5)$$

where C_{fish} represents the concentration of the respective metal in fish muscle and $C_{sediment}$ represents its concentration in sediment. The ratio was interpreted as an indicator of the relative distribution of metals between sediment and fish and was used to support the assessment of metal transfer within the aquatic system.

2.8 Human Health Risk Assessment

The potential non-carcinogenic health risks associated with fish consumption were evaluated using estimated daily intake (EDI), target hazard quotient (THQ) and hazard index (HI), following the USEPA risk-assessment framework [5].

The estimated daily intake was calculated as:

$$EDI = \frac{C_f \times IR_f}{BW} \quad (6)$$

where *Cf* is the metal concentration in fish muscle, IR_f is the daily fish ingestion rate and *BW* is the body weight of the consumer.

The target hazard quotient was calculated as:

$$THQ = \frac{EDI}{RfD}$$

where *RfD* is the oral reference dose of the respective metal. A THQ value below 1 indicates no appreciable non-carcinogenic risk, whereas a value above 1 indicates a potential health concern.

The combined risk from exposure to multiple metals was assessed using:

$$HI = \sum_{i=1}^{n} THQ_i \quad (7)$$

An HI value below 1 indicates a low potential for cumulative non-carcinogenic risk, while an HI above 1 suggests a potential health concern from combined metal exposure through fish consumption.

2.9 Statistical Analysis

The analytical data were subjected to descriptive and inferential statistical analyses to evaluate spatial and seasonal variations in physicochemical parameters and trace-metal concentrations. Results were expressed as mean ± standard deviation. Analysis of variance (ANOVA) was used to assess differences among sampling locations and seasons, with statistical significance considered at $p < 0.05$.

Pearson correlation analysis was performed to examine relationships among physicochemical parameters, nutrients and trace-metal concentrations. Principal component analysis (PCA) was used to identify major patterns and associations among the measured variables and to support interpretation of possible natural and anthropogenic influences. Statistical analyses were performed using IBM SPSS and R software.

3. Results and Discussion

Table 2 - Physicochemical parameters of water – Pre and Post monsoon

Parameter	Limits	Pykara		Emerald		Kattery		Wellington	
		Pre Monsoon	Post Monsoon	Pre Monsoon	Post Monsoon	Pre Monsoon	Post Monsoon	Pre Monsoon	Post Monsoon
Temperature (°C)	30	19.06±0.21^{a}	20.53±0.25^{a}	16.66±0.35^{c}	18.76±0.30^{c}	17.93±0.30^{b}	19.33±0.40^{bc}	16.77±0.25^{c}	20.1±0.26^{ab}
pH	6.5-8.5	8.33±0.058^{b}	8.01±0.05^{c}	9.16±0.23^{a}	8.15±0.08^{a}	8.2±0.001^{b}	8.26±0.06^{c}	7.37±0.06^{c}	8.13±0.06^{b}
EC (µs/Cm)	4000	29.26±1.57^{c}	34.06±1.80^{d}	51.3±1.65^{b}	43.1±0.87^{c}	54.37±1.02^{b}	53.46±1.35^{b}	173.57±3.40^{a}	151.83±1.98^{a}
TDS (Mg/L)	2000	13.13±0.87^{d}	24.16±1.30^{d}	20.13±0.90^{c}	30.60±0.61^{c}	36.45±1.65^{b}	37.96±0.96^{b}	101.86±1.37^{a}	107.80±1.40^{a}
TS (Mg/L)	BDL	20.4±0.7^{c}	29.27±1.06^{d}	36.20±1.22^{b}	40.63±1.02^{c}	37.82±1.71^{b}	50.93±1.05^{b}	121.13±1.75^{a}	261.8±1.87^{a}
TSS (Mg/L)	200	7.26±0.21^{c}	5.1±0.91c	16.06±0.32^{b}	10.03±1.64^{bc}	1.37±0.06^{d}	12.97±1.71^{b}	19.26±0.86^{a}	153.99±3.27^{a}
DO (Mg/L)	6	7.53±0.058^{b}	5.66±0.25^{c}	8.27±0.15^{a}	7.16±0.11^{a}	7.83±0.11^{b}	6.63±0.15^{b}	6.43±0.06^{d}	5.96±0.06^{c}
BOD	3-5	2.8±0.01^{c}	4.2±0.02^{b}	2.9±0.001^{c}	4.2±0.01^{b}	2.2±0.01^{d}	3.7±0.0^{c}	5.5±0.01^{a}	4.9±0.02^{b}
COD	10	5.8±0.02^{d}	9.7±0.03^{cd}	6.1±0.01^{d}	8.7±0.02^{cd}	8.1±0.02^{d}	10.9±0.04^{c}	13.4±0.05^{b}	19.5±0.06^{a}
TH (Mg/L)	500	0.67±0.02^{a}	0.4±0.001^{ab}	0.62±0.01^{a}	0.4±0^{ab}	0.65±0.03^{a}	0.46±0.06^{a}	0.68±0.03^{a}	0.33±0.06^{b}
Calcium (Mg/L)	200	3.49±0.26^{b}	1.10±0.1^{c}	8.16±0.16^{a}	26.2±0.4^{b}	1.13±0.15^{c}	30.46±0.45^{a}	0.13±0.15^{d}	0.05±0.1^{c}

Potassium (Mg/L)	20	3.3 ± 0.1^{c}	13.06 ± 0.25^{b}	4.23 ± 0.15^{b}	6.13 ± 0.15^{d}	8.23 ± 0.15^{a}	8.23 ± 0.25^{c}	3.33 ± 0.11^{c}	16.9 ± 0.26^{a}
Sodium (Mg/L)	200	5.33 ± 0.35^{b}	3.56 ± 0.25^{d}	2.9 ± 0.1^{c}	5.23 ± 0.40^{c}	4 ± 0.001^{bc}	8.03 ± 0.15^{b}	24.96 ± 0.91^{a}	12.5 ± 0.2^{a}
N-Nitrogen (Mg/L)	45-50	0.7 ± 0^{b}	0.87 ± 0.06^{c}	0.83 ± 0.05^{b}	1.13 ± 0.11^{b}	1.36 ± 0.06^{a}	1.73 ± 0.05^{a}	0.43 ± 0.06^{c}	0.5 ± 0.01^{d}
Phosphate (Mg/L)	5	4.23 ± 0.07^{a}	0.54 ± 0.03^{c}	3.92 ± 0.04^{b}	1.25 ± 0.04^{b}	0.75 ± 0.005^{d}	1.24 ± 0.03^{b}	1.99 ± 0.02^{c}	1.87 ± 0.07^{a}
Turbidity (NTU)	5	0.34 ± 0.005^{c}	0.43 ± 0.01^{c}	0.24 ± 0.005^{d}	0.40 ± 0.01^{c}	0.43 ± 0.04^{b}	0.66 ± 0.04^{b}	0.5 ± 0.001^{a}	0.78 ± 0.02^{a}

- BDL - **Below Detection Limit**
- Data were analyzed using one way ANOVA followed by (Duncan's) post-hoc test (SPSS, version at $p<0.05$ significance level: means sharing the same superscript letter are not significantly different.

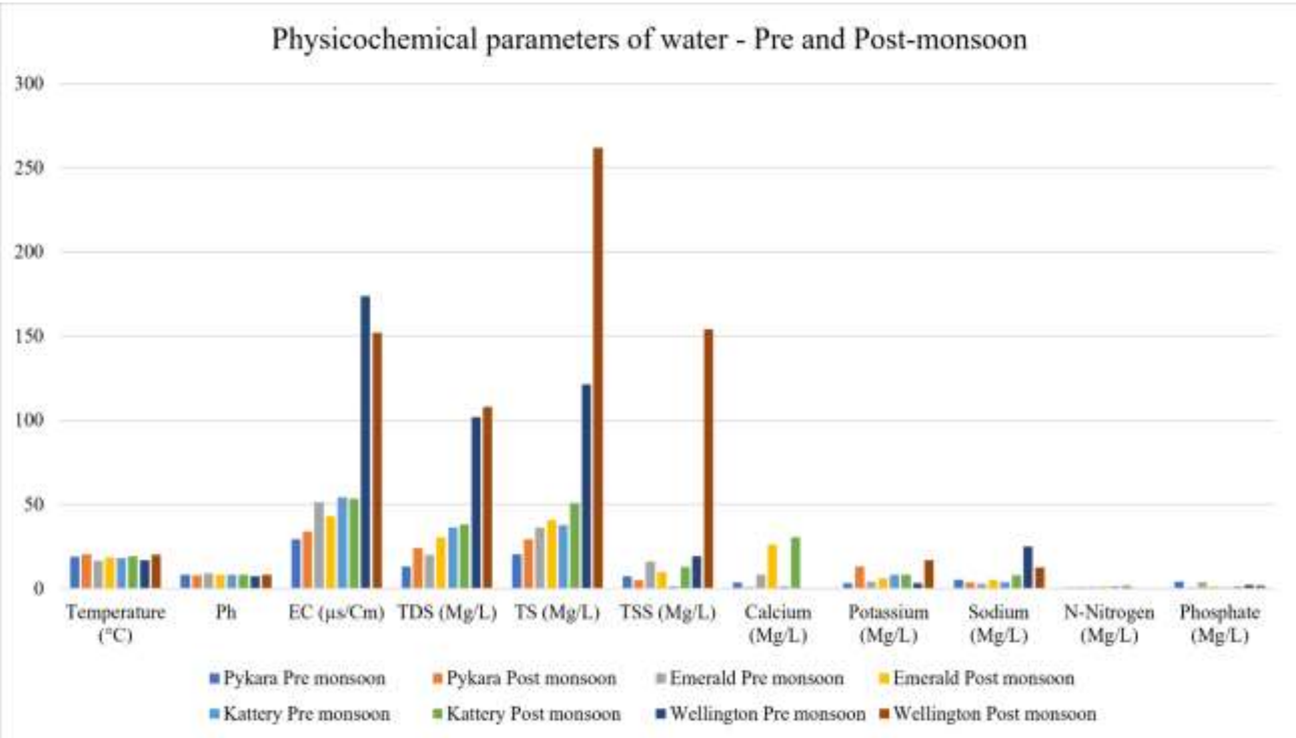


Figure 3 – Physicochemical parameters of water – Pre and Post-monsoon

3.1 Physicochemical Characteristics

The physicochemical parameters showed distinct spatial and seasonal variability among the four lakes (Table 2; Figure 3), reflecting the combined influence of hydrological conditions, catchment characteristics and anthropogenic activities.

Temperature and pH

Water temperature ranged from 16.66 to 20.53 °C, with generally higher values during the post-monsoon period. The maximum temperature was recorded at Pykara (20.53 °C), whereas the minimum occurred at Emerald during pre-monsoon (16.66 °C). The post-monsoon increase may be associated with increased solar radiation and reduced cloud cover following the monsoon [11].

The pH ranged from 7.37 to 9.16, indicating predominantly alkaline conditions. The highest value occurred at Emerald during pre-monsoon, possibly reflecting enhanced photosynthetic activity and carbonate buffering. The relatively lower post-monsoon values may be related to rainfall and dilution effects [12]. Occasional values above the recommended range indicate localized alkaline conditions that may influence aquatic biota.

Electrical Conductivity, TDS and Solids

EC ranged from 29.26 to 173.57 µS/cm, with Wellington consistently recording the highest values. The elevated conductivity suggests greater dissolved ionic inputs associated with domestic wastewater, surface runoff and geogenic sources [13]. TDS ranged from 13.13 to 107.80 mg/L, with the highest values observed at Wellington. TS and TSS were also markedly higher at Wellington, particularly during post-monsoon, indicating increased particulate and dissolved material inputs. These patterns suggest stronger catchment influence and anthropogenic loading at Wellington [14].

Organic Pollution Indicators

DO ranged from 5.66 to 8.27 mg/L. Most lakes maintained relatively favourable oxygen conditions, although Wellington showed comparatively lower values, particularly during post-monsoon. Increased runoff and organic matter decomposition may enhance oxygen consumption during this period [15].

BOD ranged from 2.2 to 5.5 mg/L, with the highest value recorded at Wellington during pre-monsoon. COD ranged from 5.8 to 19.5 mg/L, reaching its maximum at Wellington during post-monsoon. The elevated BOD and COD indicate increased organic and oxidizable pollutant loads, potentially associated with domestic wastewater, tourism and surface runoff [16][17].

Major Ions

Calcium concentrations ranged from below detection limit to 30.46 mg/L, with the highest post-monsoon concentration occurring at Kattery. The variation may reflect differences in catchment lithology, weathering and hydrological inputs [18][19].

Potassium ranged from 3.30 to 16.90 mg/L, with higher concentrations at Pykara and Wellington during post-monsoon. This pattern may reflect runoff-mediated transport of agricultural and organic inputs [20].

Sodium ranged from 2.90 to 24.96 mg/L, with the highest concentration at Wellington during pre-monsoon, suggesting greater influence from domestic and urban sources.

Nutrients

N-nitrogen concentrations ranged from 0.43 to 1.73 mg/L, with the highest value recorded at Kattery during post-monsoon. The seasonal increase may reflect runoff-mediated transport of nitrogenous compounds from surrounding catchments [21].

Phosphate ranged from 0.54 to 4.23 mg/L and showed contrasting seasonal patterns among lakes. Higher concentrations at Kattery and Wellington indicate possible contributions from fertilizers, domestic wastewater and surface runoff, whereas lower post-monsoon values at Pykara and Emerald may reflect dilution [22].

Turbidity and Chloride

Turbidity remained below the prescribed limit of 5 NTU, ranging from 0.24 to 0.78 NTU, although Wellington showed the highest values. The increase may reflect greater suspended material inputs from runoff.

Chloride was below the instrumental detection limit in all lakes during both seasons and was therefore excluded from further statistical analysis. The low chloride concentrations are consistent with observations from freshwater systems of the Nilgiris and other high-altitude lake systems [23] [24].

Water Quality Index

WQI values showed clear spatial and seasonal variation (Table 3). Pre-monsoon values ranged from 48.2 to 68.5, with Pykara classified as good and Emerald, Kattery and Wellington as poor. During post-monsoon, WQI values increased to 62.5–74.9, and all four lakes were classified as poor. Wellington recorded the highest WQI during both seasons (68.5 and 74.9), whereas Pykara recorded the lowest values (48.2 and 62.5). The increase in WQI during post-monsoon suggests greater water-quality stress associated with runoff-mediated inputs of nutrients, dissolved solids and organic matter.

Table 3 - Water Quality Index of the water samples in selected lakes

Lake	Pre-monsoon WQI	Status	Post-monsoon WQI	Status
Pykara	48.2	Good	62.5	Poor
Emerald	52.8	Poor	66.3	Poor
Kattery	58.6	Poor	71.4	Poor
Wellington	68.5	Poor	74.9	Poor

Correlation Analysis of Water Quality Parameters

Correlation analysis showed significant relationships among selected water-quality parameters. EC was positively correlated with TDS, while BOD and COD showed negative associations with DO, indicating oxygen consumption associated with organic loading. Overall, the correlations reflect the influence of ionic content, nutrients and organic matter on lake water quality.

3.2 Trace Metal Concentrations in Water

Table 4 - Trace Metal Concentrations in Water during Pre and Post monsoon season

Analysis	Permissible Limit (µg/L)	Emerald - pre monsoon (µg/L)	Emerald - post monsoon (µg/L)	Pykara - pre monsoon (µg/L)	Pykara - post monsoon (µg/L)	Kattery - pre monsoon (µg/L)	Kattery - post monsoon (µg/L)	Wellington - pre monsoon (µg/L)	Wellington - post monsoon (µg/L)
Cu (Copper)	2000	22.4±0.33	14.17±0.03	36.7±0.12	17.3±0.08	15.4±0.2	10.3±0.12	51.7±0.4	30.3±0.17
Ni (Nickel)	20	0.84±0.09	0.71±0.05	0.93±0.10	0.89±0.15	1.20±0.10	1.34±0.03	0.85±0.05	0.71±0.05
Pb (Lead)	10	35.5±0.20	27.19±0.02	51.4±0.17	41.32±0.3	60.2±0.08	51.17±0.01	72.5±0.04	54.92±0.71

The concentrations of Cu, Ni and Pb in water showed spatial and seasonal variation (Table 4). Cu ranged from 10.3–51.7 µg/L and remained below the permissible limit of 2000 µg/L. Ni ranged from 0.71–1.34 µg/L, remaining well below the limit of 20 µg/L. In contrast, Pb ranged from 27.19–72.5 µg/L, exceeding the permissible limit of 10 µg/L at all sampling sites. Wellington recorded the highest Cu and Pb concentrations, while Kattery showed the highest Ni concentration. The elevated Pb levels may reflect both natural weathering and anthropogenic inputs [25][26], whereas the low Ni concentrations may be associated with natural geochemical processes [27].

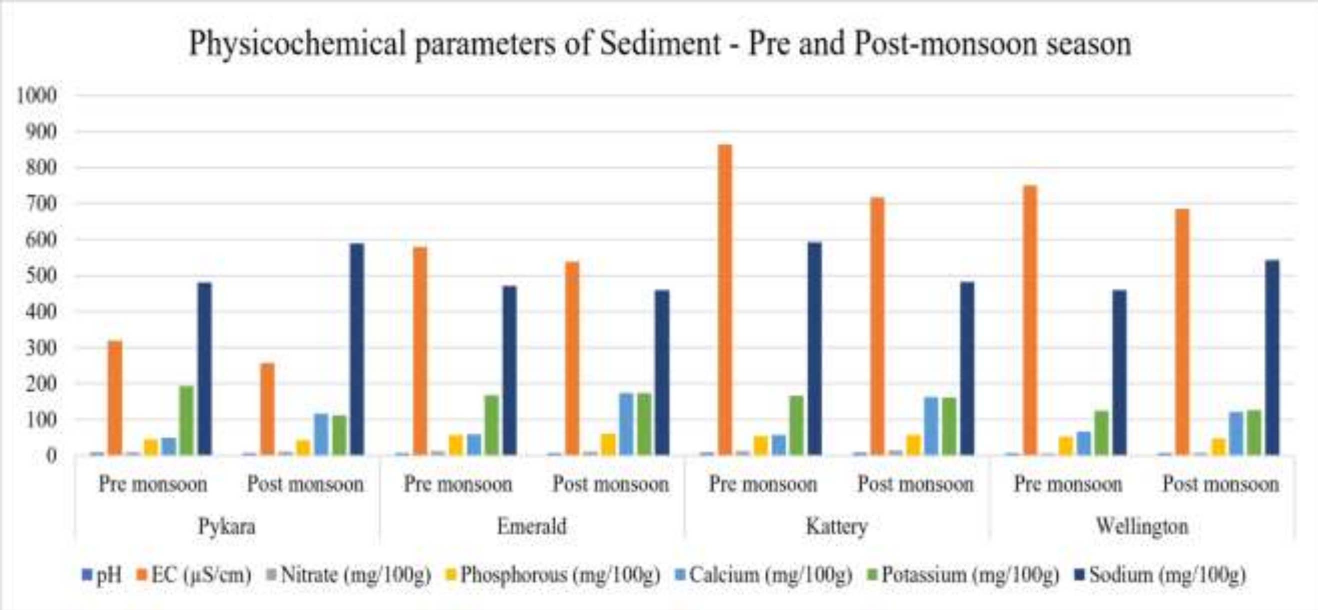
Sediment Physicochemical Characteristics and Nutrient Composition

Table 5 - Sediment Physicochemical Characteristics and Nutrient Composition

Parameter	Pykara		Emerald		Kattery		Wellington	
	Pre monsoon	Post Monsoon	Pre monsoon	Post Monsoon	Pre monsoon	Post Monsoon	Pre monsoon	Post Monsoon
pH	7.56±0.17^{ab}	7.19±0.31^{b}	6.94±0.51^{bc}	7.30±0.21^{ab}	7.89±0.22^{a}	7.86±0.12^{a}	6.3±0.11^{c}	6.97±0.18^{b}
EC (µS/cm)	320±9^{d}	257±9^{c}	580±12^{c}	538±21^{b}	864±14^{a}	717±19^{a}	751±13^{b}	685±14^{a}
Calcium (mg/100 g)	50.37±1.81^{c}	116.70±1.41^{b}	59±1.77^{b}	173.93±1.73^{a}	57±1.09^{b}	163.11±7.12^{a}	67±0.83^{a}	121.34±3.12^{b}
Potassium (mg/100 g)	192.9±3.77^{a}	111.83±3.84^{d}	167.8±7.5^{b}	173.87±4.91^{a}	167.0±9.37^{b}	161.74±5.03^{b}	125.1±4.76^{c}	126.16±0.89^{c}
Sodium (mg/100 g)	480.6±5.61^{b}	590±8.11^{a}	471.6±8.84^{b}	460.29±9.31^{d}	593±7.54^{a}	482.67±6.84^{c}	460±7.71^{b}	543.33±7.66^{b}
Nitrate (mg/100 g)	10.16±0.79^{b}	11.41±0.46^{b}	12.41±0.54^{a}	11.57±0.98^{b}	13.56±1.13^{a}	14.74±0.62^{a}	7.44±0.38^{c}	7.49±0.18^{c}
Phosphorous (mg/100 g)	44.80±0.81^{b}	43±2.21^{b}	57.11±0.69^{a}	60.8±2.71^{a}	54±2.75^{a}	58±1.88^{a}	52.70±5.62^{ab}	48.5±3.71^{b}

The sediment characteristics of the studied lakes exhibited clear spatial and seasonal variability is illustrated in Table 5 and Figure 4 reflecting differences in geochemical composition, organic input, and anthropogenic influence.

Figure 4 – Physicochemical parameters of Sediment (Pre and Post-monsoon season)



3.3 Physicochemical and Nutrient Characteristics of Sediment

pH and Electrical Conductivity(EC)

Sediment pH ranged from 6.30–7.89, indicating slightly acidic to near-neutral conditions. Kattery recorded the highest pH, while Wellington showed the lowest values. EC ranged from 257–864 µS/cm, with the highest values at Kattery, indicating greater ionic content. EC generally decreased post-monsoon, possibly due to rainfall-driven dilution and leaching [28].

MajorIons(Ca^{2+},K^{+}andNa^{+})

Calcium increased post-monsoon in all lakes, reaching 173.93 mg/100 g at Emerald. Potassium ranged from 111.83–192.90 mg/100 g, with the highest value at Pykara pre-monsoon. Sodium ranged from 460.0–593.0 mg/100 g, with higher values at Pykara and Kattery. These variations may reflect catchment inputs and hydrological conditions [29]

Nutrients (Nitrate and Phosphorus)

Nitrate ranged from 7.44–14.74 mg/100 g, with the highest value at Kattery post-monsoon. Phosphorus ranged from 43.0–60.8 mg/100 g, with higher concentrations at Emerald and Kattery, indicating nutrient accumulation associated with organic matter and anthropogenic inputs [7]. Seasonal variations are shown in Figure 4.

Combined Pearson Correlation Matrix (Water - Sediment Physicochemicals) is discussed in the Table 6.

Table 6 - Combined Pearson Correlation Matrix (Water-Sediment Physicochemicals)

Variables	W-pH	W-EC	W-Calcium	W-Potassium	W-Sodium	W-Nitrate	W-Phosphorus
S-pH	1	0.216	-0.412	0.533	0.284	0.601	0.118
S-EC	0.216	1	**0.744***	-0.482	0.355	**0.689***	0.296
S-Calcium	-0.412	**0.744***	1	**-0.821** **	-0.267	**0.705***	0.438

S-Potassium	0.533	-0.482	**-0.821** **	1	0.312	-0.577	-0.391
S-Sodium	0.284	0.355	-0.267	0.312	1	0.521	0.208
S-Nitrate	0.601	**0.689***	**0.705***	-0.577	0.521	1	0.336
S-Phosphorus	0.118	0.296	0.438	-0.391	0.208	0.336	1

* $p < 0.05$ → Significant, ** $p < 0.01$ → Highly significant

- EC–Calcium (r = 0.744)* → strong geochemical control of ionic composition
- Calcium–Potassium (r = -0.821)** → strong inverse relation, indicating ion competition
- Nitrate–EC (r = 0.689)* and Nitrate–Calcium (r = 0.705)* → nutrient enrichment linked with mineral inputs
- pH–Nitrate (r = 0.601) → moderate relationship indicating biogeochemical influence
- Weak correlations of phosphorus suggest complex cycling behavior

Pearson correlation analysis revealed significant positive relationships among EC, calcium, and nitrate, indicating strong geochemical and nutrient interactions, while a significant negative correlation between calcium and potassium suggests ionic competition within the system.

Heavy metal concentration in sediment sample

Table 7 : Heavy metals in sediments – Pre monsoon and Post monsoon

Analysis	Permissible Limit (µg/g)	Emerald pre monsoon (µg/g)	Emerald post monsoon (µg/g)	Pykara pre monsoon (µg/g)	Pykara post monsoon (µg/g)	Kattery pre monsoon (µg/g)	Kattery post monsoon (µg/g)	Wellington pre monsoon (µg/g)	Wellington post monsoon (µg/g)
Cu (Copper)	50	54.75±0.59	50.15±0.54	66.46±1.20	61.74±1.12	58.05±0.45	54.21±0.41	69.74±0.41	61.28±0.36
Ni (Nickel)	0	78.72±1.59	72.26±1.46	80.51±2.35	79.93±2.34	64.42table 9±0.17	61.26±0.17	85.82±1.63	84.86±1.61
Pb (Lead)	60	11.74±0.19	10.32±0.17	12.50±0.16	12.04±0.16	8.95±0.06	8.84±0.05	12.87±0.34	11.31±0.30

Copper: Copper concentrations range from 50.15-69.74 µg/g, with the highest level at Wellington during the pre-monsoon season. Most sites slightly exceeded the sediment quality guidelines (50 µg/g), indicating moderate Cu enrichment, while lower post-monsoon concentrations suggest dilution by rainfall in Table 7. Sediment Cu, as a bioavailable fraction can be accumulated by aquatic organisms. [30]

Nickel: Nickel concentration (61.26-85.82 µg/g), exceeded the guidelines value (50 µg/g) at sites, with the highest concentration at wellington shown in Table 7. The elevated Ni level is attributed to the

weathering of mafic and ultramafic rocks and its strong affinity for sediment particles. The sediment bound Ni remains bioavailable and can accumulate in aquatic organisms [31].
Lead: Lead concentration ranged from 8.84-12.87 µg/g, remaining below the guidelines value (60 µg/g) at all sites shown in Table 7. Pb concentration was higher in sediment than in water, indicating that sediment act as a reservoir for Pb, where sediment-bound Pb can be transferred to aquatic organisms [32].

Fish Nutrition Analysis

Table 8 - Elemental Composition of Fish Muscle

Parameters	Pykara		Emerald		Kattery		Wellington	
	Pre monsoon	Post Monsoon	Pre monsoon	Post Monsoon	Pre monsoon	Post Monsoon	Pre monsoon	Post Monsoon
Potassium mg/100g	405±0.02^{a}	427±0.1^{ab}	422±0.02^{a}	456±0.03^{ab}	440±0.01^{b}	478±0.4^{a}	418±0.01^{b}	445±0.1^{a}
Phosphate mg/100g	180±0.1^{ab}	210±0.02^{b}	213±0.01^{ab}	252±0.01^{b}	235±0.02^{b}	281±0.02^{a}	242±0.01^{b}	284±0.02^{a}
Sodium mg/100g	62±0.04^{ab}	54±0.01^{b}	71±0.1^{ab}	57±0.02^{b}	80±0.1^{b}	63±0.02^{a}	87±0.2^{b}	73±0.1^{a}
Calcium mg/100g	47±0.02^{ab}	42±0.01^{b}	53±0.02^{ab}	47±0.01^{b}	58±0.01^{b}	50±0.3^{ab}	68±0.01^{b}	53±0.2^{a}

3.4 Elemental Composition of Fish Muscle

The elemental composition of fish muscle showed spatial and seasonal variation among the studied lakes (Tables 8 and 9), reflecting differences in environmental availability and physiological regulation.

Potassium (K) and Sodium (Na)

Potassium was the dominant macro-element, ranging from 405–478 mg/100 g, with concentrations increasing during post-monsoon across all lakes. The highest value was recorded at Kattery (478 mg/100 g). Sodium ranged from 54–87 mg/100 g and generally decreased during post-monsoon, with the highest concentration at Wellington during pre-monsoon (87 mg/100 g). These variations may reflect seasonal changes in ionic availability and physiological regulation [33] [34].

Phosphorus (P) and Calcium (Ca)

Phosphorus ranged from 180–284 mg/100 g and increased during post-monsoon in all lakes, with the highest value at Wellington (284 mg/100 g). This may indicate enhanced nutrient availability and biological uptake following runoff.

Calcium ranged from 42–68 mg/100 g and decreased slightly during post-monsoon across all lakes, with the highest pre-monsoon concentration at Wellington (68 mg/100 g). The observed variation may reflect differences in mineral availability and physiological regulation [35].

3.5 Trace Metals in Fish Muscle

Copper (Cu)

Cu concentrations ranged from 0.49–0.58 µg/g, remaining well below the permissible limit of 30 µg/g. Pre-monsoon concentrations were slightly higher than post-monsoon values at all sites, possibly due to seasonal dilution during the rainy period. Overall, Cu accumulation remained low and within the permissible limit [36].

Nickel (Ni)

Ni concentrations ranged from 0.70–0.80 µg/g, with all values exceeding the permissible limit of 0.6 µg/g. The presence of Ni in fish muscle indicates its accumulation from the aquatic environment and supports the use of fish as bioindicators of metal exposure [37].

Lead (Pb)

Pb concentrations ranged from 0.067–0.098 µg/g, remaining below the permissible limit of 0.3 µg/g. Slightly lower concentrations were generally observed during post-monsoon. The detection of Pb in fish muscle indicates uptake from the surrounding aquatic environment, including sediment-associated sources [38].

Table 9 - Heavy metals in fish sample for Pre monsoon and Post monsoon season

Analysis	Permissible Limit (µg/g)	Emerald pre monsoon (µg/g)	Emerald post monsoon (µg/g)	Pykara pre monsoon (µg/g)	Pykara post monsoon (µg/g)	Kattery pre monsoon (µg/g)	Kattery post monsoon (µg/g)	Wellington pre monsoon (µg/g)	Wellington post monsoon (µg/g)
Cu (Copper)	30	0.58±0.05	0.52±0.02	0.57±0.11	0.52±0.01	0.56±0.01	0.53±0.01	0.53±0.01	0.49±0.01
Ni (Nickel)	0.6	0.80±0.07	0.74±0.03	0.75±0.04	0.71±0.01	0.80±0.09	0.76±0.005	0.75±0.08	0.7±0.015
Pb (Lead)	0.3	0.098±0.01	0.093±0.09	0.095±0.001	0.089±0.001	0.098±0.008	0.07±0.0015	0.072±0.002	0.067±0.001

Sediment-to-Fish Concentration Ratio (R_{sf}) for Cu, Ni and Pb

A simplified approach R_{sf} based on concentration ratios of the transfer of elements from sediment to fish muscle using the following equation [39].

Table 10 - Sediment-to-Fish Concentration Ratio (R_{sf}) for Cu, Ni and Pb

Parameters	**Copper µg/g**		**Nickel µg/g**		**Lead µg/g**	
	Pre monsoon	Post monsoon	Pre monsoon	Post monsoon	Pre monsoon	Post monsoon
Emerald	0.0106	0.0104	0.0102	0.0102	0.0083	0.009
Pykara	0.0086	0.0084	0.0093	0.0089	0.0076	0.0074
Kattery	0.0096	0.0098	0.0124	0.0124	0.011	0.0079
Wellington	0.0076	0.008	0.0087	0.0082	0.0056	0.0059

The values for Cu, Ni and Pb remained below 1 across all lakes and seasons (Table 10), indicating relatively low sediment-to-fish concentration ratios. Values ranged from 0.0076–0.0106 for Cu, 0.0082–

0.0124 for Ni and 0.0056–0.0110 for Pb. Ni exhibited the highest ratios, particularly in Kattery, suggesting comparatively greater transfer to fish muscle. Seasonal variation was limited, with slightly lower ratios observed during post-monsoon at most sites. Overall, the results indicate limited relative transfer of the studied metals from sediment to fish muscle.

Estimated Daily Intake of fish (EDI)

The fish intake date for the adult and children specific to the sample collected area were not available, therefore, standard values from the USEPA [40], were used for calculation Adult with the weight of 70 kg and child with the weight of 15 kg as per the standard is taken for calculation, with a fish intake of approximately 55g/ day and 28g/ day for adult and children respectively. Estimated daily Intake (EDI) Where,

Table 11 - EDI

Parameters		**Adult**	**Children**
C medium	concentration of contaminant in medis (mg/L, mg/g)	Fish concentration (mg/kg)	Fish concentration (mg/kg)
IR	Ingestion rate (L/ day, g/day)	55 g /day	28 g/day
BW	Body weight (Kg)	70kg	15kg

Table 12 – EDI for Adult of Cu, Ni and Pb for Pre and Post monsoon season

Site	**Copper**		**Nickel**		**Lead**	
	Pre monsoon	**Post monsoon**	**Pre monsoon**	**Post monsoon**	**Pre monsoon**	**Post monsoon**
Pykara	0.000448	0.000409	0.000589	0.000558	0.000075	0.00007
Emerald	0.000456	0.000409	0.000629	0.000581	0.000077	0.000073
Kattery	0.00044	0.000416	0.000629	0.000597	0.000077	0.000055
Wellington	0.000416	0.000385	0.000589	0.00055	0.000057	0.000053

Figure 5 – EDI of Cu, Ni and Pb for Adult

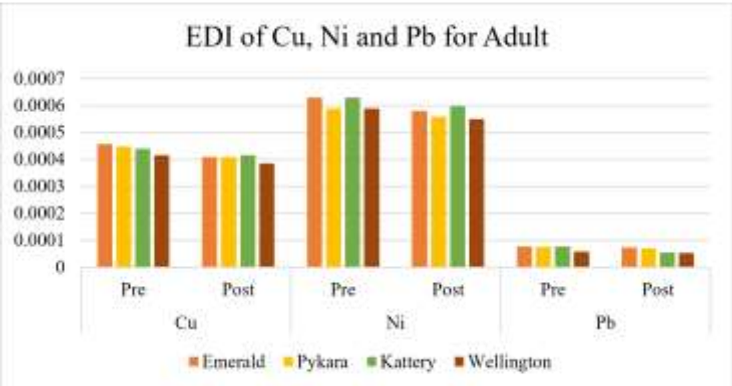
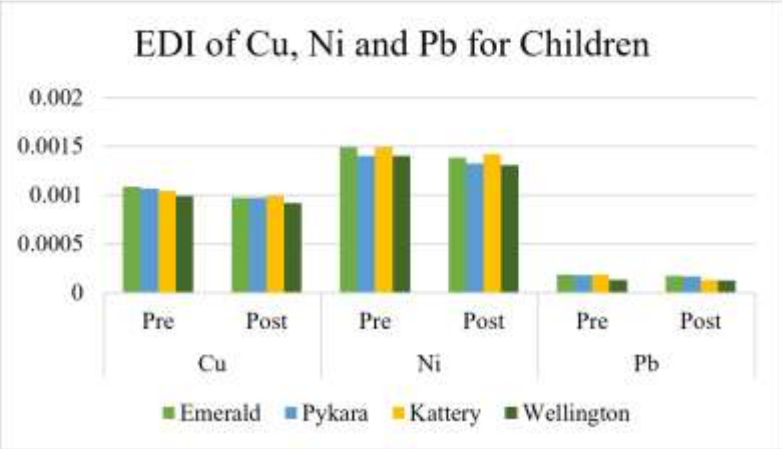


Table 13 – EDI for Children of Cu, Ni and Pb for Pre and Post monsoon season

Site	Copper		Nickel		Lead	
	Pre monsoon	Post monsoon	Pre monsoon	Post monsoon	Pre monsoon	Post monsoon
Emerald	0.001083	0.000971	0.001493	0.001381	0.000183	0.000174
Pykara	0.001064	0.000971	0.0014	0.001325	0.000177	0.000166
Kattery	0.001045	0.000989	0.001493	0.001419	0.000183	0.000131
Wellington	0.000989	0.000915	0.0014	0.001307	0.000134	0.000125

Figure 6 – EDI of Cu, Ni and Pb for Children



Target Hazard Quotient (THQ)

The calculated THQ values for Cu, Ni and Pb were <1 for both adults and children across all lakes and seasons (Table 14), indicating no appreciable non-carcinogenic risk from individual metal exposure through fish consumption [40]. Children showed relatively higher THQ values than adults, primarily due to their lower body weight.

Table 14 - Target Hazard Quotient of Cu, Ni and Pb through fish consumption for Adult and children

Metal	Population	Emerald (Pre monsoon)	Emerald (Post monsoon)	Pykara (Pre monsoon)	Pykara (Post monsoon)	Kattery (Pre monsoon)	Kattery (Post monsoon)	Wellington (Pre monsoon)	Wellington (Post monsoon)
Cu	Adult	0.0114	0.0102	0.0112	0.0102	0.011	0.0104	0.0104	0.0096
	Children	0.0271	0.0243	0.0266	0.0243	0.0261	0.0247	0.0247	0.0229
Ni	Adult	0.0314	0.0291	0.0295	0.0279	0.0314	0.0299	0.0295	0.0275
	Children	0.0747	0.0691	0.07	0.0663	0.0747	0.071	0.07	0.0654
Pb	Adult	0.0193	0.0183	0.0188	0.0175	0.0193	0.0138	0.0143	0.0133
	Children	0.0458	0.0435	0.0443	0.0415	0.0458	0.0328	0.0335	0.0313

Hazard Index (HI)

The combined HI values for Cu, Ni and Pb ranged from 0.0504–0.0621 in adults and 0.1196–0.1476 in children (Table 15). All values remained below the threshold of 1, indicating no significant combined non-carcinogenic health risk from consumption of the studied fish [40]. The higher HI values in children reflect their greater exposure relative to body weight.

Table 15 – HI of Adult and Children for Cu, Ni and Pb

Population	Season	Emerald	Pykara	Kattery	Wellington	Mean HI
Adult	Pre monsoon	0.0621	0.0595	0.0617	0.0542	0.0594
	Post monsoon	0.0576	0.0556	0.0541	0.0504	0.0544
Children	Pre monsoon	0.1476	0.1409	0.1466	0.1282	0.1408
	Post monsoon	0.1369	0.1321	0.1285	0.1196	0.1293

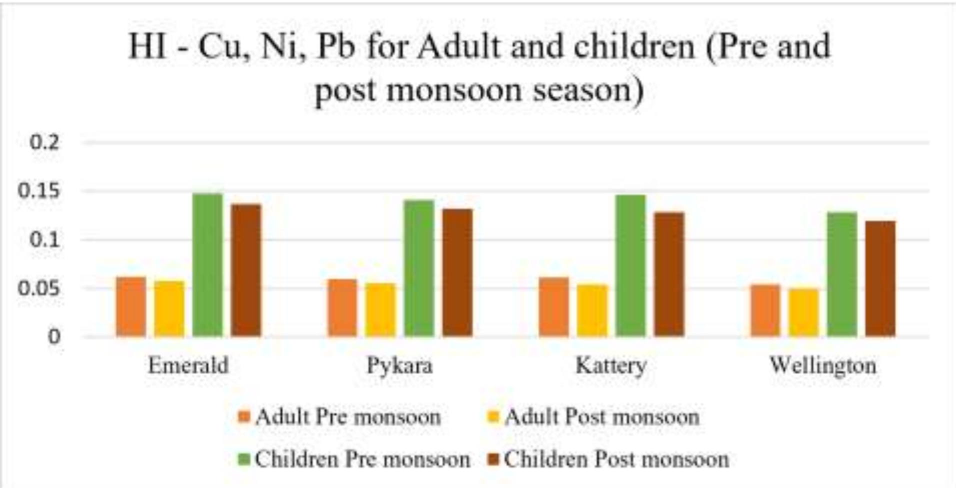


Figure 7 - HI - Cu, Ni, Pb for Adult and children (Pre and post monsoon season)

Conclusion

The study revealed significant spatial and seasonal variations in the water, sediment and fish characteristics of the selected lakes in the Nilgiris. Wellington exhibited comparatively greater physicochemical stress, with higher EC, TDS, TS, TSS, BOD and COD, along with the highest Pb concentration in water. Sediment analysis showed higher nitrate accumulation at Kattery and higher phosphorus concentrations at Emerald and Kattery. Metal distribution was compartment-specific: Pb exceeded the adopted water-quality limit at all sites, whereas Cu and Ni remained within water limits; conversely, Cu and Ni exceeded their adopted sediment limits, while Pb remained below the sediment guideline. In fish muscle, Cu and Pb were within permissible limits, whereas Ni exceeded the selected limit. Rsf values below 1 indicated relatively limited sediment-to-fish transfer. Despite these findings, EDI, THQ and HI values remained below 1 for both adults and chil+dren, indicating no appreciable non-carcinogenic health risk under the assessed exposure conditions. Overall, the findings highlight heterogeneous environmental pressures and emphasize the importance of integrated water–sediment–biota monitoring for sustainable freshwater management.

Recommendations

Regular monitoring of water, sediment and fish should be continued, particularly at Wellington and sites showing elevated Cu and Ni concentrations. Catchment protection and control of domestic, tourism-related and other anthropogenic inputs should be strengthened to reduce nutrient, organic and metal loading. Periodic monitoring of edible fish, particularly for Ni, is recommended to identify changes in dietary exposure. Integrated catchment and lake-management strategies should be implemented to maintain the long-term ecological integrity of freshwater ecosystems in the Western Ghats.

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