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TRANSITION IN URBAN LAKE HEALTH: SEASONAL DYNAMICS OF LIMNOLOGY AND ECOTOXICOLOGY FROM THREE LAKES IN BANGALORE NORTH, INDIA

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ABSTRACT:

This study evaluates the seasonal dynamics of limnological and ecotoxicological parameters in three urban lakes—Ullal, Herohalli, and Lingadheeranahalli—located in Bangalore North. The research spanned over a year (2022-2023) and involved monitoring physical, chemical, and biological parameters across the lakes to assess water quality, pollution levels, and ecological impacts. Water samples were analyzed following standard protocols (APHA 2017), and zebrafish (*Danio rerio*) embryos were used to gauge the ecotoxicological effects. The results highlighted significant seasonal fluctuations in physico-chemical parameters. The lakes showed high organic pollution, particularly during monsoons, indicating poor water quality. Overall, Ullal Lake showed better water quality than Herohalli and Lingadheeranahalli. Ecotoxicological assessments showed reduced heart rates in zebrafish embryos exposed to lake water, suggesting ecological stress. The research emphasizes the need for strict pollution regulation and sustainable water management strategies to protect urban lakes.

KEYWORDS: Limnology, Ecotoxicology, Urban Lakes, Seasonal Dynamics, Water Quality, Zebrafish

INTRODUCTION:

Bengaluru, renowned as India's garden city and silicon hub, enjoys a mild tropical climate that draws people across the country. Unfortunately, this influx has led to unplanned urban development, disrupting its natural environment, biodiversity, and landscapes. One of the most affected ecosystems has been its wetlands, especially lakes, which play a diverse role in supplying water for drinking and irrigation, recharging groundwater, serving as a source for pisciculture, and playing a pivotal role in mitigating natural calamities (Gurunathan, 2006). However, rapid industrialization transforms these lakes into cesspools, functioning as discharge grounds for sewage and effluents (Ramachandra *et al.,* 2008).

This continuous chemical flow increases sedimentation and reduced mobility, contributing to high microbial activity within these wetlands (Chakrapani, 2002). Moreover, rock weathering adds ions to the water, increasing pollution in the catchment areas (Anshumali, 2007). These organic and inorganic pollutants quickly accumulate in aquatic organisms, leading to structural abnormalities (Tilak *et al.,* 2007) while disrupting water percolation, thus hampering groundwater recharge (Ravikumar *et al.,* 2013). Additionally, microplastics have diminished soil-microbe interactions and reduced water-holding capacity, further degrading the ecosystem (Namasivayam *et al.,* 2023).

A delicate balance between the physical, chemical, and biological parameters maintains the water quality within the lakes (Yu *et al.,* 2010). Nevertheless, population outbursts, sewage disposal, and agricultural practices have disrupted this natural balance, causing significant lake pollution (Choudary *et al.,* 2010). The declining water quality within the lakes has increased waterborne diseases, causing ecosystem damage (Ramachandra *et al.,* 2018). Oxygen-dependent assessment and growth of aquatic weeds like *Eichhornia crassipes* have been pollution indicators over these wetlands (Kolo *et al.,* 2010; Raj & Panicker, 2014). In addition, the most probable number (MPN) emphasizes microbial health (Rao *et al.,* 2019).

Urbanization and its impact on limnological variables within the lakes help researchers provide insights into their health and the potential to withstand further changes (Gupta *et al.,* 2017). Consequently, these findings call for immediate conservation efforts (Cai *et al.,* 2008). Genetic models like *Danio rerio* help evaluate the ecological dynamics of urban water bodies (Raj *et al.,* 2015). Transparent embryos and 70% similarity to human genes have enhanced the usage of *D. rerio* (Gerlai *et al.,* 2014). The embryo's sensitivity to water changes provides comprehensive data on their neurotransmission, physiology and behavior (Truong *et al.,* 2017). Seasons alter the lake's health and ecological characteristics (Raj & Philip, 2024). Research on urban lakes like Mallathahalli, Iblur and Ullal highlights the immediate need for conservation through limnological and ecological modeling. This study aims to compare three lakes in northern Bangalore regarding limnology and ecotoxicology, focusing on the seasonal impacts on their health and ecological characteristics.

MATERIALS AND METHODS:

Study area:

The study was conducted on three lakes in Bangalore North—Ullal, Herohalli, and Lingadheeranahalli. Ullal Lake is a large urban lake subject to runoff from nearby residential areas. Situated at coordinates 12.9609° N latitude and 77.4807° E longitude. Herohalli Lake, which is exposed to sewage inflows and sediment accumulation with coordinates 12.9891°N, 77.4896°E and Lingadheeranahalli Lake, a relatively small lake subject to eutrophication surrounded by residential zones located at 13.0035° N latitude and 77.4827° E longitude.

Limnological Assessments:

Water samples were collected from three sampling stations marked as open surface water, deposit water and inlet water from each lake in sterilized bottles at five different seasons: monsoon, autumn, winter, spring, and summer between June 2022 and July 2023. The samples were analyzed for physical and chemical parameters using the prescribed protocols outlined by the American Public Health Association (APHA 2017). Physical parameters analyzed were pH, temperature, atmospheric humidity, turbidity, and conductivity. Chemical Parameters included dissolved oxygen (DO), biochemical oxygen demand (BOD), chemical oxygen demand COD, total dissolved solids (TDS), alkalinity, total hardness, calcium, magnesium, sodium, potassium, nitrates, phosphates, and chlorides.

Ecotoxicological Assessment:

Healthy *Danio rerio* was grown in well-aerated aquarium tanks. Spawning was induced during the early morning hours, with one male fish and three female fish within small breeding tanks fitted with mesh (Rahman *et al.,* 2021). Freshly harvested embryos were introduced into small tanks containing RO and lake water samples. (Brand & Granato, 1999). Microscopic examination was conducted to observe developmental abnormalities (Engerer *et al.,* 2016) and heart rates were measured during the torpedo stage following the protocol of (Truong *et al.,* 2011).

Statistical Analysis:

Jamove software version 2.4.14 was used for statistical analysis of the data. Descriptive statistics was presented as mean ± SD. Statistical tests, including Shapiro-Wilk and Kruskal-Wallis, examined differences across seasons and lakes. Post-hoc analysis was conducted using Dwass-Steel-Critchlow-Fligner comparisons.

RESULTS:

The study's findings are presented as physical and chemical parameters of lake water, statistical analysis of seasonal and spatial variations and ecotoxicological assessments using zebrafish embryos. Figures 1- 6 depict the limnological characteristics of Ullal, Herohalli, and Lingadheeranahalli Lakes, which revealed significant spatial and seasonal variations over the study period from June 2022 to July 2023. Figures 7 and 8 illustrate the principal component analysis with variance and the correlation matrix heat map. Figures 9 and 10 depict the ecotoxicological characters. Tables 1 and 2 illustrate the Kruskal Wallis statistics over the limnological parameters. Table 3 represents the somite development stage observed in zebrafish.

Physicochemical Parameters

pH, Temperature, and Humidity

Seasonal fluctuations in pH were evident across all lakes (Fig. 1). Ullal recorded the lowest pH in spring (3.92 ± 0.11), while the highest pH was observed in summer (7.43 ± 0.26). Herohalli displayed mildly alkaline conditions in summer (7.31 ± 0.47), whereas Lingadheeranahalli remained acidic throughout. Temperature peaked during summer (30.33°C) and was lowest in winter (22.01°C). Humidity was highest in monsoon (59.21%) and lowest during winter (39.17%).

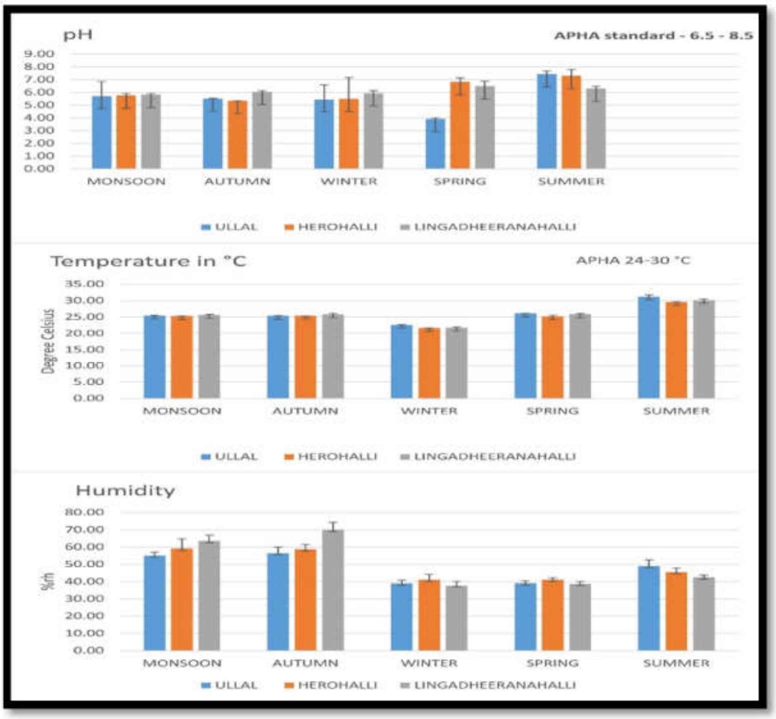

Figure 1 - Indicating pH, temperature and humidity across seasons sampled between June 2022 and July 2023

Turbidity, Conductivity, and Total Dissolved Solids

Herohalli exhibited the highest turbidity values (33.47 ± 32.21 NTU), followed by Lingadheeranahalli (13.17 ± 21.37 NTU) and Ullal (10.67 ± 11.65 NTU) (Fig. 2). Conductivity was highest in Ullal Lake during spring (3901 ± 245 µS/cm). Seasonal conductivity values significantly varied, with Ullal again showing the highest total dissolved solids (TDS) in spring (1966.33 ± 137.17 mg/L) (Fig. 2).

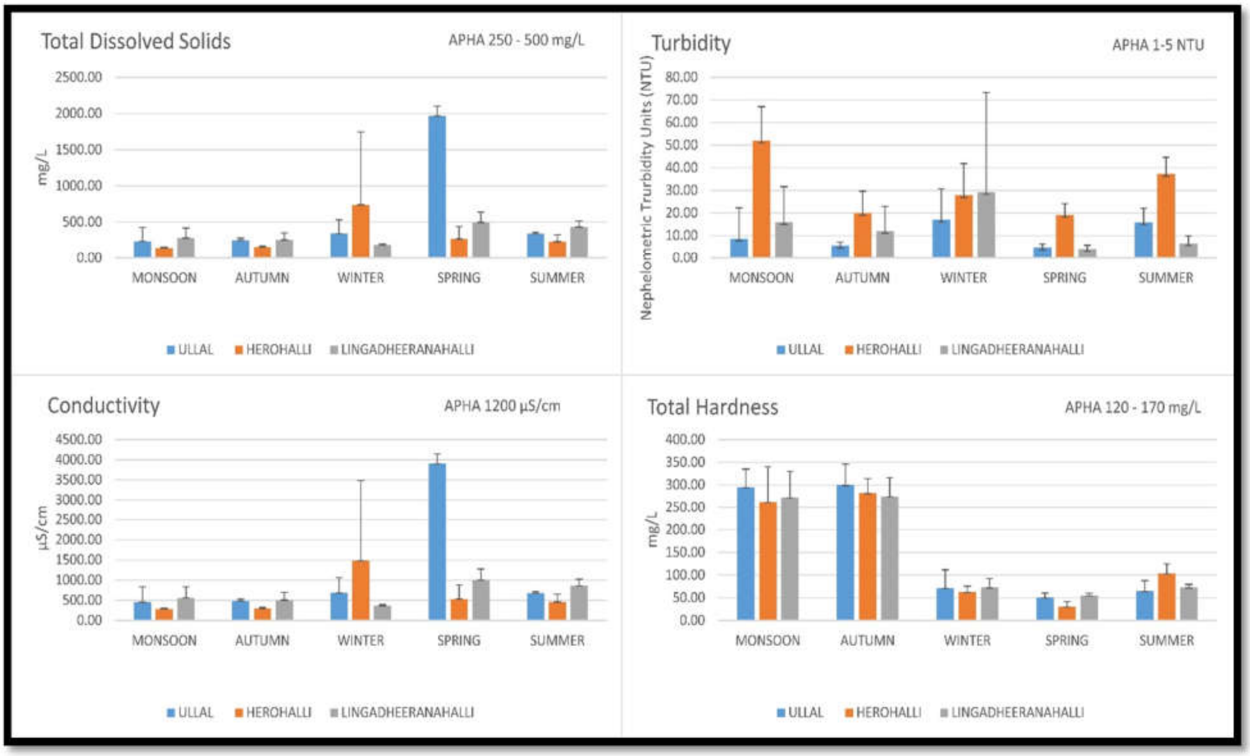

Figure 2 – Indicating total dissolved solids, turbidity, conductivity and total hardness across seasons sampled between June 2022 and July 2023

Dissolved Oxygen (DO), BOD, COD, and Microbial Load

Dissolved oxygen (DO) levels fluctuated seasonally, peaking during the monsoon (Herohalli: 6.09 ± 2.88 mg/L) and declining during autumn (Fig. 3). BOD levels were elevated during summer and monsoon seasons, particularly in Herohalli. Chemical oxygen demand (COD) exceeded permissible limits in all lakes, with the highest value reported in Lingadheeranahalli during spring (282.67 ± 113.51 mg/L) (Fig. 3). MPN values showed high microbial loads during the monsoon, especially in Lingadheeranahalli (1618.56 ± 1353.50) and Herohalli (875.78 ± 1320.52) (Fig. 3).

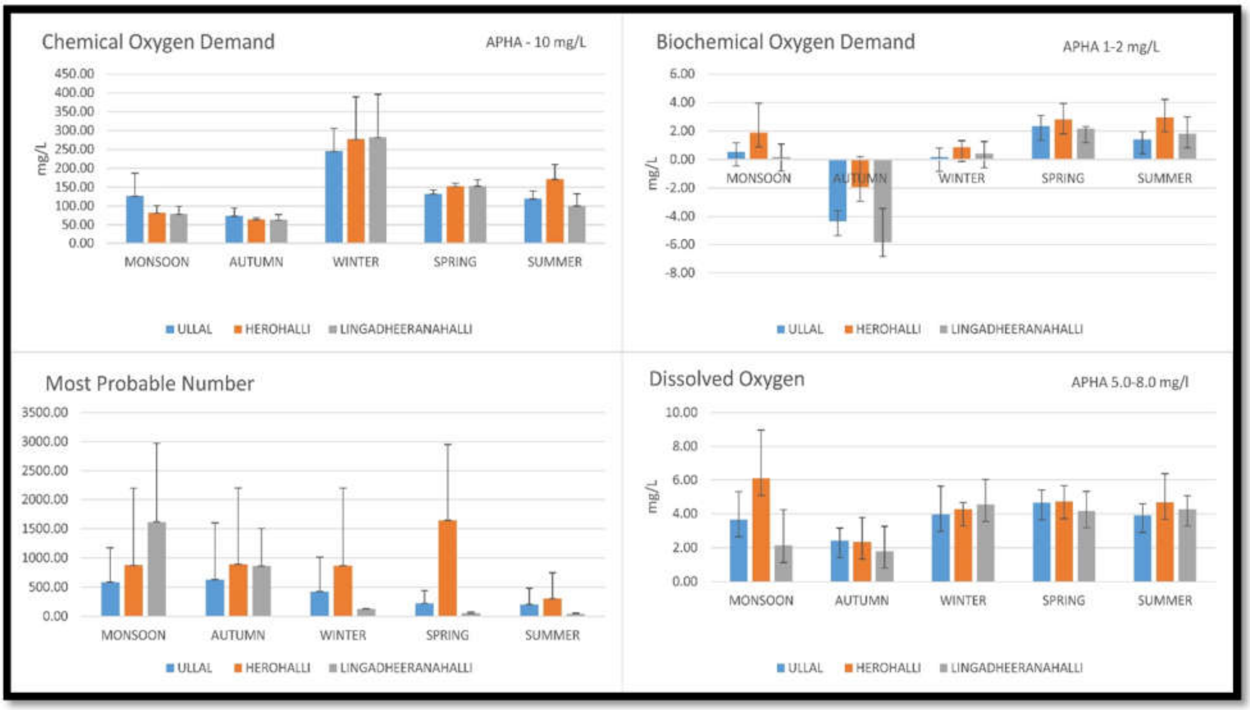

Figure 3 – Indicating total chemical oxygen demand, biochemical oxygen demand, dissolved oxygen and most probable number across seasons sampled between June 2022 and July 2023

Alkalinity and Ionic Composition

Seasonal changes in alkalinity were prominent, with higher bicarbonate content during the monsoon (Fig. 4). Hydroxide alkalinity was elevated in Herohalli (11.67 ± 20.21 mg/L, spring) and Ullal (9.33 ± 8.33 mg/L, summer). Calcium and magnesium levels peaked in Lingadheeranahalli during summer, with values of 78.58 ± 14.17 mg/L and 270 mg/L, respectively (Fig. 5). Sodium and potassium concentrations remained low throughout the year. Chloride, sulphate, phosphate, and nitrate levels exhibited seasonal variation, with phosphate and nitrate peaking during spring (Fig. 6).

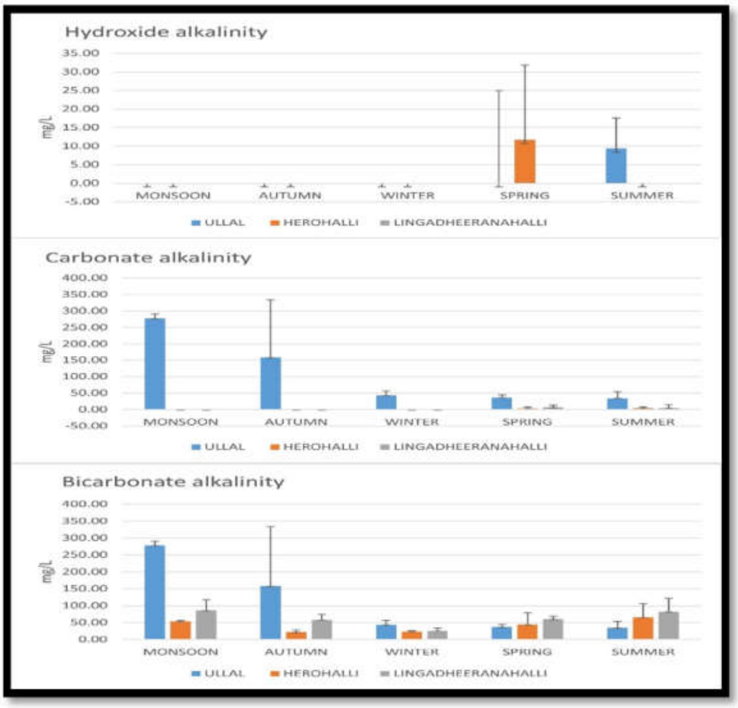

Figure 4 – Indicating alkalinity sampled between June 2022 and July 2023

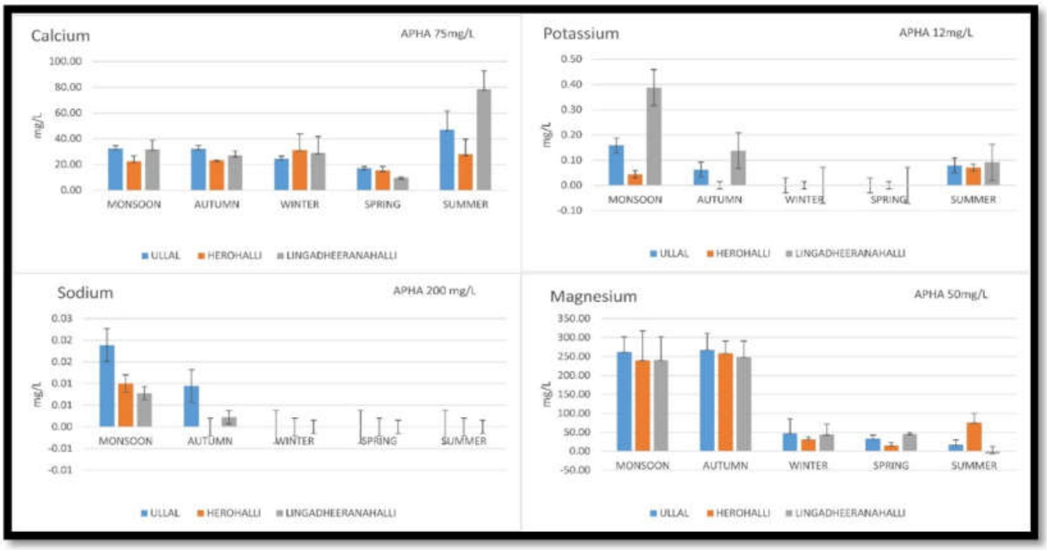

Figure 5 – Indicating calcium, potassium, sodium and magnesium across seasons sampled between June 2022 and July 2023

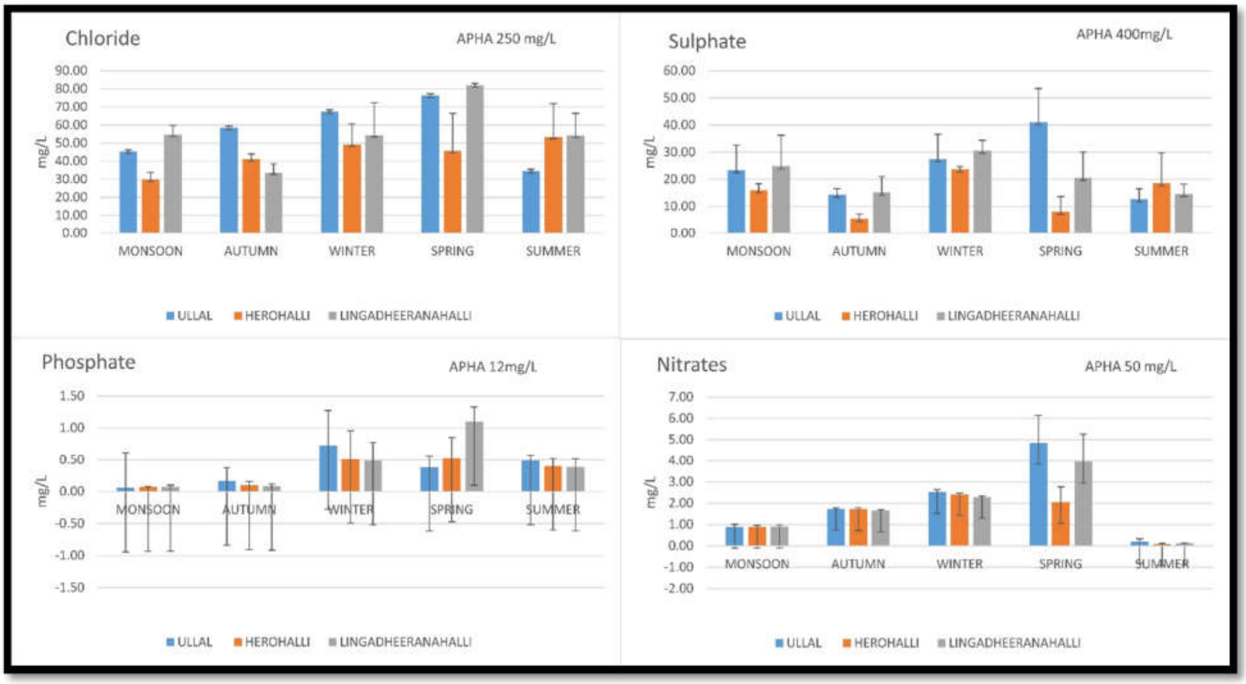

Figure 6 – Indicating chloride, sulphate, phosphate and nitrates across seasons sampled between June 2022 and July 2023

Statistical and Multivariate Analysis

Kruskal-Wallis test showed significant differences ($p<0.001$) across all limnological parameters both seasonally (Table 1) and among the three lakes (Table 2).

Principal component analysis (PCA) (Fig. 7) explained 18.6% (PC1) and 13.0% (PC2) of variance, distinguishing the lakes based on pollution and seasonal variability.

The correlation matrix (Fig. 8) indicated strong positive correlations between TDS, conductivity, magnesium and total hardness.

Table 1: Kruskal Wallis Statistics indicating significance for various limnological parameters among seasons **p<0.001

Limnological Characteristics	Seasons	N	Mean	SD	Kruskal-Wallis	p
ph	Autumn	18	5.63	0.37	36.9	< .001
	Monsoon	27	5.76	0.47		
	Spring	18	5.74	2.78		
	Summer	27	7.01	0.86		
	Winter	18	5.62	1.78		
Temperature	Autumn	18	25.49	0.33	85.24	< .001
	Monsoon	27	25.45	0.53		
	Spring	18	25.74	0.57		
	Summer	27	30.33	1.17		
	Winter	18	22.01	0.63		
Humidity	Autumn	18	61.71	7.79	75.96	< .001
	Monsoon	27	59.21	5.53		
	Spring	18	39.58	2.57		
	Summer	27	45.66	7.12		
	Winter	18	39.17	3.06		
Conductivity	Autumn	18	429.70	150.31	26.65	< .001
	Monsoon	27	432.52	291.87		
	Spring	18	1811.78	2445.16		
	Summer	27	663.89	296.06		
	Winter	18	843.06	1680.14		
DO	Autumn	18	2.19	1.44	19.2	< .001
	Monsoon	27	3.96	4.39		
	Spring	18	4.52	1.23		

	Summer	27	4.29	2.32		
	Winter	18	4.27	1.55		
BOD	Autumn	18	-4.03	5.47	37.58	< .001
	Monsoon	27	0.87	2.34		
	Spring	18	2.44	1.12		
	Summer	27	2.07	2.13		
	Winter	18	0.49	1.12		
COD	Autumn	18	67.36	38.47	41.2	< .001
	Monsoon	27	95.90	85.18		
	Spring	18	146.28	27.67		
	Summer	27	130.80	93.10		
	Winter	18	268.44	97.02		
Total Hardness	Autumn	18	285.87	38.57	77.26	< .001
	Monsoon	27	276.56	110.37		
	Spring	18	45.22	24.41		
	Summer	27	80.15	48.50		
	Winter	18	68.89	24.65		
Total Dissolved Solids	Autumn	18	218.93	73.48	26.39	< .001
	Monsoon	27	218.74	147.20		
	Spring	18	909.94	1235.81		
	Summer	27	332.93	149.47		
	Winter	18	421.50	842.50		
Calcium Hardness	Autumn	18	27.37	5.53	34.2	< .001
	Monsoon	27	28.92	12.07		
	Spring	18	13.96	4.27		
	Summer	27	51.22	39.09		
	Winter	18	28.33	9.44		

Magnesium Hardness	Autumn	18	258.50	38.23	74.47	< .001
	Monsoon	27	247.64	114.30		
	Spring	18	31.27	24.68		
	Summer	27	28.93	61.67		
	Winter	18	40.56	25.96		
Sodium	Autumn	18	0.00	0.01	22.76	< .001
	Monsoon	27	0.01	0.03		
	Spring	18	0.00	0.00		
	Summer	27	0.00	0.00		
	Winter	18	0.00	0.00		
Potassium	Autumn	18	0.07	0.19	31.63	< .001
	Monsoon	27	0.20	0.45		
	Spring	18	0.00	0.00		
	Summer	27	0.08	0.06		
	Winter	18	0.00	0.00		
Chlorides	Autumn	18	44.38	21.40	13.58	0.01
	Monsoon	27	43.20	19.01		
	Spring	18	67.94	20.74		
	Summer	27	47.35	28.50		
	Winter	18	57.02	23.22		
Sulphates	Autumn	18	11.65	10.74	16.98	< .001
	Monsoon	27	21.43	15.95		
	Spring	18	23.28	18.82		
	Summer	27	15.29	13.96		
	Winter	18	27.23	12.63		
Phosphates	Autumn	18	0.11	0.16	47.97	< .001
	Monsoon	27	0.07	0.05		

	Spring	18	0.67	0.48		
	Summer	27	0.42	0.35		
	Winter	18	0.57	0.69		
Nitrates	Autumn	18	1.71	0.23	91.71	< .001
	Monsoon	27	0.90	0.25		
	Spring	18	3.61	2.19		
	Summer	27	0.13	0.28		
	Winter	18	2.41	0.23		
MPN index	Autumn	18	795.39	1051.74	23.53	< .001
	Monsoon	27	1027.48	1104.88		
	Spring	18	640.89	976.23		
	Summer	27	185.26	495.42		
	Winter	18	475.67	771.99		

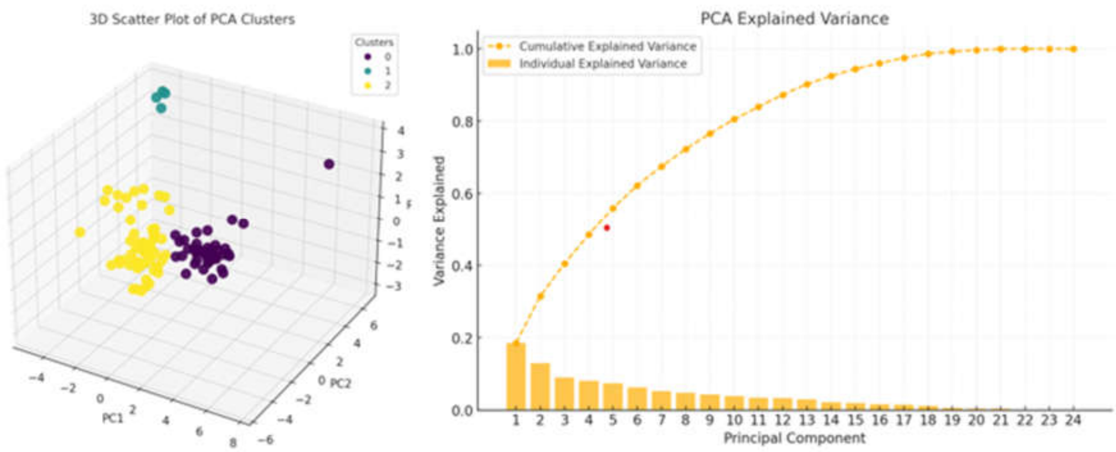

Figure 7: Principal component analysis PC 1 18.6% variance and PC 2 13% variance

Table 2: Kruskal Wallis Statistics indicating significance for various limnological parameters **p<0.001

Limnological Characteristics	Lake Name	N	Mean	SD	Kruskal-Wallis	p
Turbidity	Herohalli Lake	36	33.47	32.21	23.50	< .001
	Lingadheeranahalli Lake	36	13.17	21.37		
	Ullal Lake	36	10.67	11.65		
Conductivity	Herohalli Lake	36	570.58	1190.33	28.86	< .001
	Lingadheeranahalli Lake	36	667.01	382.99		
Total Dissolved Solids	Herohalli Lake	36	286.50	596.66	28.99	< .001
	Lingadheeranahalli Lake	36	333.75	191.69		
	Ullal Lake	36	568.69	928.30		

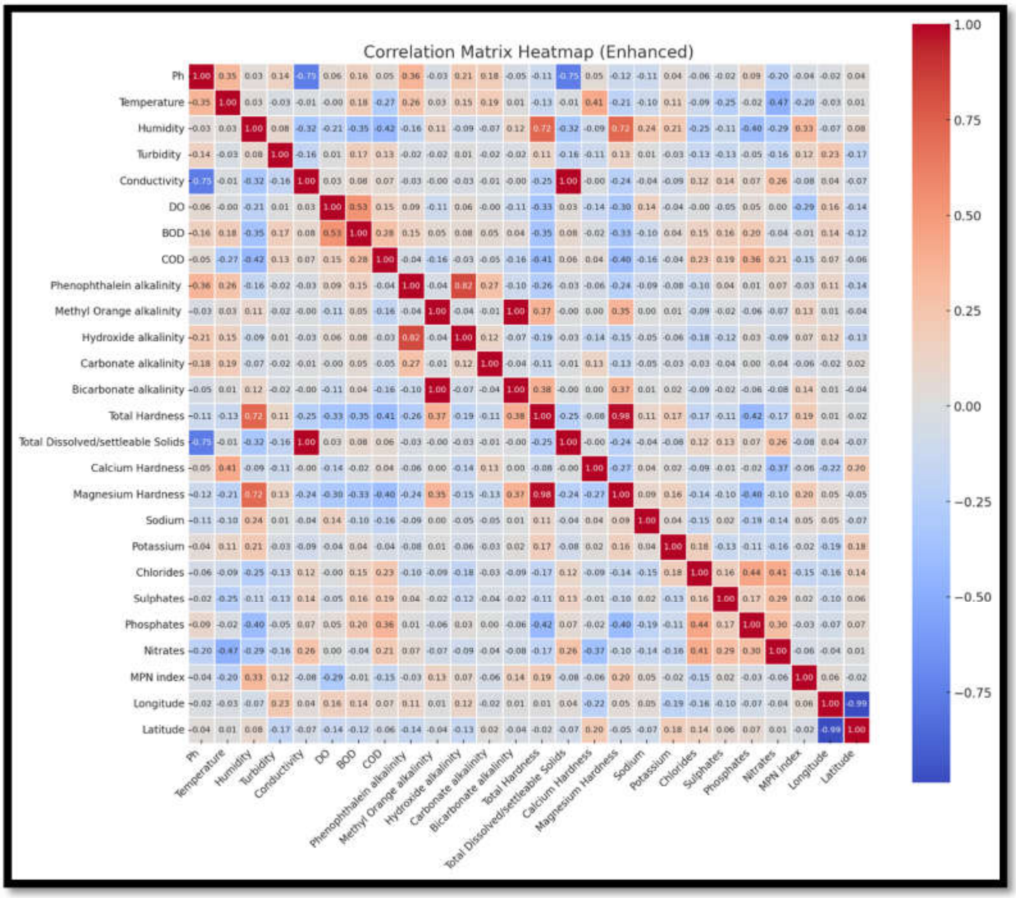

Figure 8: Correlation matrix heat map of limnological parameters

Ecotoxicological Assessment Using Zebrafish

Zebrafish (*Danio rerio*) embryos exposed to lake water exhibited reduced heart rates compared to controls (125 bpm). The most significant reduction was observed in Lingadheeranahalli (99–21 bpm), followed by Ullal (127–92 bpm) and Herohalli (113–112 bpm) (Fig. 9). Somite development analysis (Table 3 and Fig.10) showed Herohalli supporting more advanced embryonic development (14th somite) compared to Ullal and Lingadheeranahalli (10th somite at all stations).

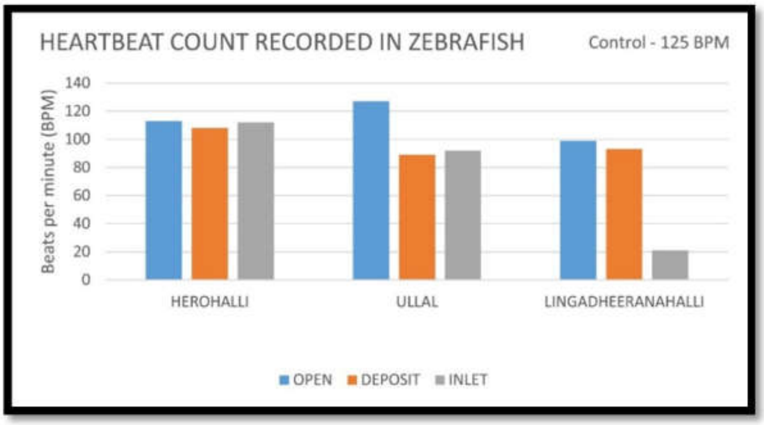

Figure 9: Heartbeat count in Zebrafish (*D. rerio*)

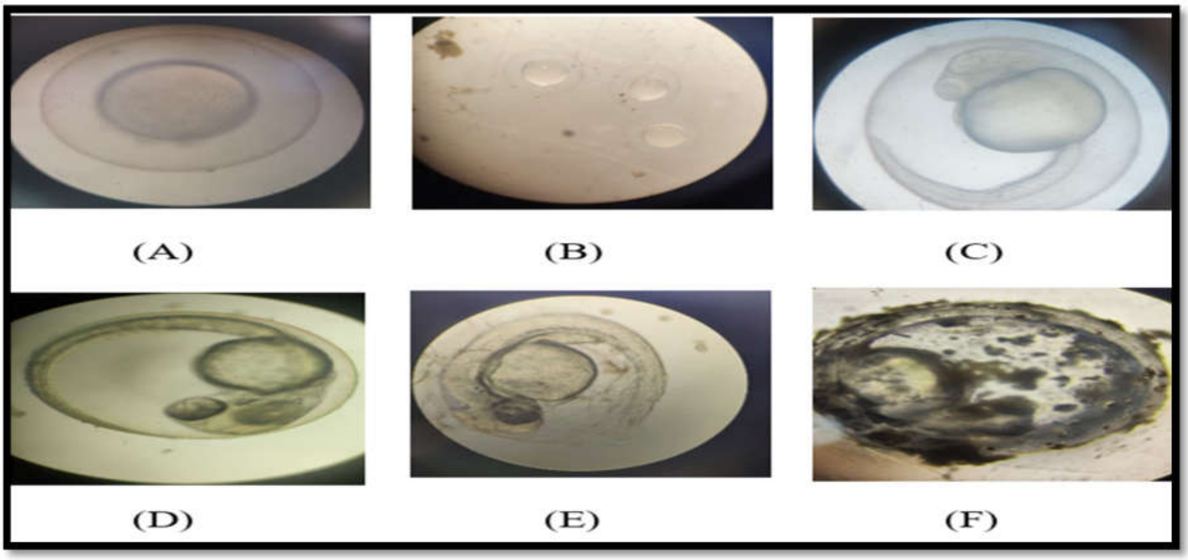

Figure 10: (A, B) Fertilized embryo, (C) 14 Somite stage in control, (D, E, F) Somite stages in Herohalli, Ullal and Lingadheeranahalli lake water samples

Sl. No.	Lake	Somite development stage		
		Open	Deposit	Inlet
1	**Herohalli**	14	14	14
2	**Ullal**	14	10	14
3	**Lingadheeranahalli**	10	10	10

Table 3: Somite development stage in Zebrafish (*D. rerio*)

DISCUSSION

The limnological characteristics of the three urban lakes Ullal, Herohalli, and Lingadheeranahalli—in Bangalore North reflect significant seasonal variation and human impact on water quality. Over a monitoring period between June 2022 and July 2023, pH levels were found to be slightly acidic year-round across all lakes, aligning with APHA standards and also matches with studies by Rawal *et al.,* 2018, who found that urban lake pH variations were heavily influenced by seasonal runoff and pollutants. Such acidic conditions can encourage the leaching of metals and organic compounds, potentially affecting aquatic ecosystems, as supported by Valeria *et al.,* 2024.

Temperature trends also reflected seasonal peaks, with all lakes exceeding 29°C during summer. Ullal Lake maintained a more stable temperature regime, suggesting a healthier aquatic environment than Herohalli and Lingadheeranahalli, which showed higher fluctuations. This trend matches observations by Linghyan *et al.,* 2023, who emphasized the link between stable water temperatures affecting relative humidity and air temperature and better oxygen retention in lakes. Humidity was highest during the monsoon and autumn seasons, correlating with increased total dissolved solids (TDS) levels, especially at Ullal, where TDS peaked at 1966.33±137.17 mg/L in spring, and at Herohalli, where 1006.90±266.67 mg/L was observed during winter. Such high TDS values, influenced by seasonal runoff and urban pollution, are consistent with findings from Sudharshan *et al.,* 2018 where monsoon runoff was a significant TDS contributor in urban (Hebbal Lake in Bangalore) lakes.

Turbidity consistently exceeded permissible values, with Herohalli recording the highest (52±15.01 NTU), followed by Lingadheeranahalli (29.17±44.11 NTU). Ullal displayed comparatively lower turbidity values, suggesting slightly better water quality than the other two lakes. High turbidity is commonly associated with increased particulate pollution (TDS) from urban activities, as Naik *et al.,* 2019 noted from Hebbal Lake in Bangalore. Conductivity, which mirrored TDS trends, peaked at 3901±245 µS/cm in Ullal during spring, similar to a study on Rudrasagar Lake by Pal *et al.,* 2015 and at 1478.83±2005.44 µS/cm in Herohalli during winter. Conductivity in Lingadheeranahalli remained within permissible limits, indicating reduced dissolved ions. High electrical conductivity affects plant life and the biological food chain (Samal *et al.,* 2011).

The analysis of dissolved oxygen (DO) and biochemical oxygen demand (BOD) further emphasized organic pollution. Herohalli recorded the highest DO during the monsoon (6.09±2.88 mg/L), while the lowest DO (2.33±1 mg/L) occurred in autumn, indicating reduced oxygen availability when the organic load was highest. Lingadheeranahalli showed the least DO across all seasons, with BOD levels surpassing per missible limits during monsoon and summer, highlighting organic load and microbial activity reflecting the septic condition of the lake aligned with previous studies on Bellandur Lake by Samal *et al.,* 2011. Chemical oxygen demand (COD) levels also consistently exceeded APHA limits (10 mg/L), with very high values observed in Lingadheeranahalli (282.67±113.51 mg/L) in spring, underscoring significant organic pollution across all three lakes. High microbial loads were observed in Herohalli (875.78±1320.52 MPN), Lingadheeranahalli (1618.56±1353.50 MPN), and Ullal (588.11±586.85 MPN), particularly during the monsoon, corroborating findings by Li *et al.,* 2017 on microbial contamination from human activities.

Alkalinity, primarily from bicarbonates, was highest in the monsoon, with Ullal Lake displaying additional alkalinity from carbonates and hydroxides. A previous study by Paerl *et al.,* 2016 correlates with the findings suggesting high bicarbonates due to high temperature and increased algal growth. While alkalinity remained within permissible levels, hydroxide presence in Herohalli during spring (11.67±20.21 mg/L) and in Ullal during summer (9.33±8.33 mg/L) highlights seasonal chemical changes. Calcium levels peaked within permissible limits in summer, with Lingadheeranahalli recording the highest (78.58±14.17 mg/L). Ullal showed relatively high calcium levels throughout, suggesting a more significant mineral influx than the other lakes. This is consistent with findings by Vyas & Sawant 2008, suggesting increased calcium and magnesium levels during summer seasons. Magnesium levels were above permissible limits during the monsoon and autumn, with concentrations ranging from 240-270 mg/L, aligning with the high hardness levels recorded during these seasons. This aligns with the studies conducted by Cai *et al.,* 2008 who reported the dissolution of calcite and dolomite during rainfall as the primary reason for increased ions. Concentrations of sodium, potassium, phosphates, and nitrates were minimal, while chloride and sulfate concentrations were within limits, with increased values during spring and summer—patterns also seen in studies by Permulsamy *et al.,* 2012.

According to Table 1, the Kruskal-Wallis statistics indicate significance for various limnological parameters, with **$p<0.001$**. Herohalli Lake showed the highest turbidity, suggesting increased sedimentation, organic matter, or human activity. Ullal Lake exhibited the highest conductivity and elevated TDS levels, indicating the presence of dissolved salts, ionic composition, or pollution. The Kruskal-Wallis statistics among seasons, **$p<0.001$**, as shown in Table 2, suggest that pH levels are higher in the summer due to increased photosynthesis, which reduces CO_2 and raises alkalinity. Temperatures peak in the summer at 30.33°C and drop in winter to 22.01°C, influenced by solar radiation and climate. Humidity affected by rainfall and moisture levels reached its highest in the monsoon season at 59.21% and lowest in the winter season at 39.17%. Lower levels of DO were observed during the summer. The winter and summer seasons recorded elevated BOD and COD levels, while monsoon and autumn exhibited increased hardness due to mineral runoff. MPN values were the highest in the monsoon and the lowest in summer. Total dissolved solids and conductivity exhibit a strong positive correlation, while magnesium and total hardness were nearly identical, showing high interdependence. pH and conductivity are negatively correlated, whereas nitrates and phosphates display an inverse relationship. Like turbidity and BOD, magnesium and conductivity showed a moderate positive correlation, indicating links between organic load and water clarity. Magnesium and calcium strongly influence total Hardness. DO has weak to moderate correlations with temperature and BOD, reflecting complex interactions.

Zebrafish as a bio-indicator, through heart rate monitoring, provided insight into lake toxicity, with a marked reduction in heart rates across all three lakes, especially in Lingadheeranahalli, where heart rates (99-21 bpm) were approximately half of the control group (125 bpm). Herohalli (113-112 bpm) showed better water quality compared to Ullal (127-92 bpm), with the overall low heart rates highlighting physiological stress due to elevated pollution, as demonstrated in Raj *et al.,* 2015. The somite development stage suggests Herohalli (14 at 16 hr.) has better water quality, followed by Ullal and Lingadheeranahalli (10^{th} somite at 16 hr.). This study underscores the pressing need for management efforts to mitigate pollution and restore ecological balance in Bangalore's urban lakes (Raj & Susan, 2024).

CONCLUSION

The limnological assessment of Ullal, Herohalli, and Lingadheeranahalli Lakes in Bangalore highlights significant seasonal variations and anthropogenic impacts. Lingadheeranahalli shows the poorest water quality, with acidic pH, high TDS, turbidity, and COD, while Herohalli exhibits moderate quality with elevated microbial loads and organic contamination. High pH, temperature, COD, and phosphates were observed during the summer; similarly, humidity, DO, MPN, and hardness were high during the winter—monsoon-influenced parameters such as DO, BOD, hardness, and MPN. Ullal Lake fares better overall but still faces pollution challenges. Zebrafish bioindicator studies confirm physiological stress, underscoring the need for sustainable interventions to restore ecological balance.

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