Research Article

Seasonal Dynamics and Ecological Health of Ullal Lake in Bengaluru North, Karnataka, India Introspected through Limnological Perspective and Physiological Response Assessment on Zebrafish (*Danio rerio*)

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ABSTRACT

Aim: Bangalore City in Karnataka is known for its serene environment, landscapes, and IT development. The continuous inflow of people from various states and increased anthropogenic activities have caused stress to lake ecosystems and influenced the seasons. Therefore, the present research investigates the seasonal and spatial variations in the limnological factors of Ullal Lake in Bangalore North to identify environmental stressors and assess its ecological health. **Materials and Methods:** Composite water samples were collected from three sampling stations: an open surface, a deposit, and an inlet. These samples were analyzed for physicochemical factors, including pH, temperature, conductivity, humidity, turbidity, dissolved oxygen, biochemical oxygen demand, chemical oxygen demand, hardness, alkalinity, and the most probable number. Seasonal patterns and developmental stages in Danio rerio were also examined to evaluate the environmental stress. **Results:** Significant fluctuations were observed in the physical parameters. Oxygen-dependent variables also varied, including, hardness, alkalinity, and microbial load. Seasonal patterns showed that environmental factors like temperature, humidity, and biological activity influenced water quality. Specifically, pH and conductivity were most influenced during spring, while autumn significantly affected dissolved oxygen and microbial load. Summer exhibited elevated alkalinity and turbidity. Developmental stages in Danio rerio were unaffected in the open surface and inlet stations, but decreased heart rate indicated environmental stress at the deposit and inlet stations. **Conclusion:** The open surface station demonstrated superior water quality compared to the other two stations. The study highlights the importance of seasonal dynamics in influencing limnological parameters and the ecological health of Ullal Lake. It recommends addressing seasonal variations, continuous monitoring, and the implementation of sustainable management practices for the conservation and sustainability of these wetlands.

Keywords: Ullal Lake, Limnology, Bengaluru North, Heartbeat Count, Zebrafish.

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INTRODUCTION

Bengaluru, the metropolitan city of Karnataka in India, is renowned as the Silicon Valley and the garden city. The city is prone to continuous unplanned urban development, leading to the depletion of its biodiversity and the decline of its lake network, causing an alteration of its natural landscapes. Lakes, essential components of ecosystems, provide habitats for diverse flora and fauna. However, rapid urbanization and industrialization in Bengaluru have resulted in the depletion and degradation of its lakes, transforming them into cesspools due to the discharge of industrial effluents and solid wastes.[1]

Lakes, being fragile ecosystems, readily accumulate pollutants from various sources, such as industrial, urban and agricultural activities, leading to contamination and loss of biodiversity.[2] The pollution of lakes is evident through various indicators, such as the total oxygen demand, which encompasses parameters like DO, BOD and COD.[3] Furthermore, the influx of nutrients from population growth, agricultural practices and sewage discharge has resulted in eutrophication, disrupting the natural balance of these water bodies.[4,5] This deterioration of water quality has severe consequences, including the proliferation of aquatic weeds like *Eichhornia crassipes* (water hyacinth), further exacerbating ecological imbalances and contributing to the gradual decline of lakes.[6] Consequently, the survival of lakes is threatened and needs immediate conservation efforts.[7]

The limnological approach to analyzing physical, chemical and biological variables provides insights into the health and resilience of these water bodies.[8,9] Notably, the use of vertebrate models like *D. rerio* has emerged as a valuable tool in evaluating the ecological health of lakes.[10] Research on specific lakes in Bangalore, such as Mallathahalli Lake, has revealed the physicochemical characteristics and microbial composition, highlighting the urgent need for conservation efforts.[11] In addition, the same studies have emphasized the role of wetlands in sustaining biodiversity and mitigating natural calamities.[12]

The juxtaposition of urbanization and preservation underscores the need for sustainable water management practices.[13] In conclusion, the degradation of lakes due to anthropogenic activities poses significant threats to biodiversity and ecosystem health. Comprehensive assessments combining limnological studies with ecological modelling and vertebrate analysis are essential for understanding and mitigating these challenges.[14,15] Urgent action is required to conserve and restore these vital ecosystems for future generations.[16] In this study, we aim to investigate the associated facets of limnology and the physiological responses of the vertebrate system *D. rerio* within the unique environment of Ullal Lake in Bangalore North with three distinct sampling locations, namely open surface Water (O), Deposit (D) and Inlet (I).

MATERIALS AND METHODS

Study area-Ullal Lake

Ullal Lake is nestled within a residential layout in Bangalore North. Situated at coordinates 12.9609º N latitude and 77.4807º E longitude, it is a tranquil oasis spanning 1.42 km in total distance and with a generous size of 76,166.67 square meters; it offers a serene retreat to the residents and visitors amid urban surroundings. Ullal Lake serves as a vital green space, fostering biodiversity and enhancing the quality of life in the surrounding community. Peacocks and snakes are a common sight in and around the lake.

Limnological assessments

Limnological assessments were conducted at Ullal Lake between June 2022 and July 2023, aligning with the seasonal patterns of the Indian subcontinent. Three distinct sampling stations for studying the lake were identified: open surface water, deposit water and inlet water to provide valuable insights into its ecological dynamics. An open surface station is surface water sampled without the interference of plant debris; a deposit is identified as a station where severe plant growth was found, and the Inlet is where treated domestic water was let into the lake. Samples were obtained in triplicates. External temperature, water temperature, humidity and pH levels were recorded at each site. Water samples were carefully collected in freshly sterilized bottles, meeting laboratory requirements for subsequent analysis of chemical and biological factors. Dissolved oxygen levels were fixed at each sampling station. The assessments strictly followed standardized procedures outlined by APHA.[17]

Physical parameters

Onsite measurements of physical parameters, including pH, temperature, humidity, turbidity and conductivity, were conducted using standardized and calibrated instruments such as a pH meter, thermometer, hygrometer, turbidimeter and conductivity meter. Total dissolved solids were assessed using a TDS meter.

Chemical parameters

DO levels were stabilized on-site and measured using a DO meter. BOD was determined via the DO meter and Winkler's method. COD was quantified using the ferrous ammonium sulfate method. Alkalinity, total hardness, calcium and magnesium levels were determined through titration. Sodium and potassium levels were assessed using principles of flame photometry. Chlorides were determined using the silver chloride method, while sulfate was detected using the barium sulfate method. Phosphate levels were analyzed using the Fiske subbarow method and Nitrates were screened using a UV spectrophotometer-all procedures adhered to standard methods outlined in the APHA (2017).

Most Probable Number (MPN) Analysis

MPN analysis was performed to identify the presence of coliforms in the water sample and assess its suitability for drinking, utilizing standardized techniques outlined by Aneja.[18]

Statistical Validation

The physical, chemical and biological parameters analyzed from the three sampling stations underwent descriptive statistics, the Shapiro-Wilk test and the one-way ANOVA, the Kruskal-Wallis test. The Shapiro-Wilk test assessed data distribution, while the Kruskal-Wallis test was a non-parametric analysis. Subsequently, post hoc analysis was done through the Dwass-Steel-Critchlow-Fligner comparison (DSCF).

Zebrafish analysis

Aquaculture and Spawning

Healthy *D. rerios* were kept in well-ventilated aquarium tanks under ideal lighting and temperature and were provided with commercially available nutrient flakes for sustenance.[19] Spawning was stimulated during daylight hours by introducing one male and two female fish into confined breeding tanks equipped with mesh barriers.[20] Embryos collected within a 24 hr window post-spawning were utilized for our experiments. These freshly gathered embryos were placed in small tanks filled with Reverse Osmosis (RO) water alongside tanks containing water samples directly obtained from Ullal Lake. The embryos treated with RO water served as the control group for comparison.

Embryo analysis

The rapid development of embryos in both the control and test setups was examined using a compound microscope (Labomed) at 100x magnification. Key characteristics were assessed, including tube formation, somite development and overall embryo structure.[21] Heartbeat was quantified during the torpedo stage.[22]

RESULTS

The Physicochemical parameters for the three sampling stations are depicted in Tables 1-3, respectively. Ullal Lake water significantly varied limnological parameters across seasons and stations. This seasonal variation is a crucial aspect of our study, highlighting the dynamic nature of Ullal Lake. For instance, pH remained consistently high during the summer season across all stations, with the open surface station recording the highest pH of 7.67±0.44, closely followed by the deposit (7.16±0.85) and the inlet stations (7.48±0.96). The lowest pH of (3.96±5.59) was recorded during the spring in the open station, while in the deposit, it was 3.79±5.36 and 4.01±5.66 in the inlet station. Overall pH remained slightly acidic across all seasons, except during the summer, where pH remained alkaline. The temperature fluctuated as per season, with the lowest recorded during the winter and the highest recorded during the summer, following a seasonal trend across all sampling stations.

The highest humidity was observed in autumn and the lowest in spring. Humidity over the inlet station was 59±2.83%, while the lowest was 37.05±0.64% and was over the open water station. Turbidity fluctuated between the winter and spring for the deposit and the inlet stations, while in summer, it was 12.33±11.06 NTU and monsoon (3.33±3.06 NTU) for the open surface station. The highest turbidity of 31.50±24.75 NTU was seen in the inlet station. Conductivity was influenced during the spring and monsoon. The highest conductivity of 4108.00±4768.73 µS/cm was observed in the inlet station, while the lowest was recorded in the open water station with 455±162.59 µS/cm.

Our findings have significant implications for the health of Ullal Lake. Low DO of 1.70±0.49 mg/L and 2.40±1.13 mg/L was observed during the autumn, while DO increased during the spring in the deposit (4.10±0.14 mg/L) and inlet (4.35±2.05 mg/L) stations respectively. Autumn recorded the lowest DO of 3.17±3.06 mg/L, while the winter season showed a DO of 5.85±2.47 mg/L in the open surface station. Spring and autumn influenced the BOD of Ullal Lake. The Highest BOD, 3.10±0.71 mg/L, was recorded in the inlet station. Negative BOD was recorded in the open and the deposit stations, which could be because microorganisms break down hydrogen peroxide. COD was recorded low in autumn across all seasons, while COD increases during cooler temperatures, especially the winter, with the highest recorded in the inlet station with 272±22.63 mg/L. Hydroxides, carbonates and bicarbonates contributed to the water's alkalinity. Hydroxide and carbonate alkalinity increased during the summer, while bicarbonates were mainly present during the monsoon and low during rising temperatures, as indicated in Tables 1-3. The total hardness of water was high during the monsoon across all stations, while

Table 1: Seasonal variation in physicochemical parameters and most probable number for the sampling station open surface water sampled between June 2022 and July 2023.

Parameters	Monsoon July-September	Autumn October - November	Winter December-January	Spring February- March	Summer April-June
Sample Station-Open					
pH	5.68±0.82	5.54±0.21	4.12±4.10	3.96±5.59	7.67±0.44
Temperature (ºC)	25.33±0.70	25.17±0.24	22.60±0.57	26.20±0.28	31.30±0.87
Humidity	51.30±1.57	52.50±2.12	37.05±0.64	39.50±1.84	45.67±4.75
Turbidity (NTU)	3.33±3.06	3.67±0.47	4.50±0.71	5±5.66	12.33±11.06
Conductivity (µS/cm)	455±162.59	457.50±3.54	1120.50±1215.52	3964.50±4547.40	642.±181.67
Dissolved Oxygen (DO) (mg/L)	5.33±2.31	3.17±3.06	5.85±2.47	5.50±0.28	4.67±1.36
Biochemical Oxygen Demand (BOD) (mg/L)	1.13±1.03	-4.93±8.58	0.85±2.62	2.35±1.63	1.07±0.47
Chemical Oxygen Demand (COD) (mg/L)	131.20±72.48	73.60±81.46	176±67.88	128±45.25	130.40±70
Phenolphthalein alkalinity (mg/L)	0	0	0	12.50±17.68	20±26
Methyl Orange alkalinity (mg/L)	72±44.54	56±22.63	30±14.14	59.50±21.92	45.33±9.24
Hydroxide alkalinity (mg/L)	0	0	0	0	14.67±25.40
Carbonate alkalinity (mg/L)	0	0	0	0	2.67±12.86
Bicarbonate alkalinity (mg/L)	72±44.54	56±22.63	30±14.14	34.50±13.44	26.67±24.44
Total Hardness (mg/L)	235±115	234.50±0.71	30±14.14	50±42.43	40.67±20.03
Total Dissolved Solids (mg/L)	224.67±73.53	228.33±5.19	561.00±606.70	2042.00±2358.91	322.33±90.72
Calcium Hardness (mg/L)	30.40±11.54	29.20±1.70	22.50±3.54	16±0	37.33±30.29
Magnesium Hardness (mg/L)	204.60±123.28	205.30±0.99	7.50±10.61	34.00±42.43	3.33±33.01
Sodium (mg/L)	0.01±0.01	0	0	0	0
Potassium (mg/L)	0.36±0.55	0.18±0.26	0	0	0.05±0.04
Chlorides (mg/L)	49.70±12.30	45.20±0.28	56.80±20.08	60.44±1.13	29.58±24.80
Sulfates (mg/L)	19.83±15.34	13.26±9.30	21.72±7.42	33.29±12.66	10.47±10.31
Phosphates (mg/L)	0.05±0.05	0.05±0.01	0.32±0.15	0.20±0.11	0.41±0.38
Nitrates (mg/L)	0.89±0.39	1.76±0.28	2.57±0.40	3.44±1.58	0.06±0.10
MPN index	41±29.72	33.50±7.78	23.00	31±11.31	9.67±2.31

it was low during the spring for the deposit and the inlet station and lowest in the open surface station with 30±14.14 mg/L.

During the spring season, they majorly influenced the total dissolved solids of water, with the highest (2049.00±2377.29 mg/L) recorded in the inlet and the lowest recorded in the deposit station (222.33±78.01 mg/L). Calcium ions increased during the summer, while magnesium increased during the monsoon. Low calcium concentrations were found during the spring and summer, indicating low values of magnesium ions. The values for alkaline earth metals Sodium and Potassium were negligible across all seasons and stations. Sodium and potassium were seen during the monsoon. Spring season majorly influenced chlorides, sulfates and nitrates; the deposit station (88.31±8.41 mg/L) and the inlet stations (80.15±2.90 mg/L) recorded high values of chlorides, while the values reduced during the summer. The inlet station recorded the highest sulfate value during the spring (55.40±5.40 mg/ L), while the deposit station recorded the lowest of 10.27±13.74 mg/L. Nitrates recorded high values during the spring and low values during the summer. The highest was recorded in the deposit station (6.06±3.21 mg/L), while the lowest was in the open surface station (0.06±0.10 mg/L). Phosphates were recorded low in the open surface station. MPN was majorly influenced during the monsoon. The inlet station recorded the highest value (1750±919.24).

Kruskal-Wallis test and DSCF pairwise comparisons for dissolved oxygen (**$p<0.01$) and MPN (**$p<0.001$) showing significance amidst sampling stations are recorded in Table 4. Table 5 depicts significant data

Table 2: Seasonal variation in physicochemical parameters and most probable number for the sampling station deposit water sampled between June 2022 and July 2023.

Parameters	Monsoon July-September	Autumn October-November	Winter December-January	Spring February- March	Summer April-June
Sample Station-Deposit					
pH	5.67±0.53	5.49±0.13	6.08±0.90	3.79±5.36	7.16±085
Temperature (ºC)	25.50±0.26	25.35±0.11	22.75±0.92	26.05±0.21	30.77±1.39
Humidity	56.30±2.21	58±0	41±1.70	40.20±3.54	52.63±1.40
Turbidity (NTU)	13.33±11.50	6.67±4.71	15±21.21	3±4.24	12.33±17.21
Conductivity (µS/cm)	442.33±152.92	459.17±11.90	455.50±252.44	3630.50±4072.23	666±180.49
Dissolved Oxygen (DO) (mg/L)	2.40±0.80	1.70±0.49	3.35±1.34	4.10±0.14	3.70±0.17
Biochemical Oxygen Demand (BOD) (mg/L)	-0.47±3.14	-4.53±2.88	-0.40±1.41	1.60±0.00	1.13±0.67
Chemical Oxygen Demand (COD) (mg/L)	173.87±224.37	94.93±55.81	288±0	126±42.43	95.73±38.87
Phenolphthalein alkalinity (mg/L)	0	0	0	12.50±17.68	18.67±20.13
Methyl Orange alkalinity (mg/L)	70±43.59	56±9.90	45±21.21	70.50±7.78	35.33±21.57
Hydroxide alkalinity (mg/L)	0	0	0	0	22±33.05
Carbonate alkalinity (mg/L)	0	0	0	25±35.36	6.67±30.55
Bicarbonate alkalinity (mg/L)	70±43.59	56±9.90	45±21.21	45.50±43.13	20.00±34.64
Total Hardness (mg/L)	310±150	296.67±9.43	110±14.14	61±55.15	66.67±28.87
Total Dissolved Solids (mg/L)	222.33±78.01	230.17±5.54	225.50±129.40	1808±2025.15	332±92.05
Calcium Hardness (mg/L)	33.07±16.34	31.67±0.99	24.50±0.71	18.80±1.70	40.53±21.78
Magnesium Hardness (mg/L)	276.93±165.31	264.99±8.44	85.50±14.85	42.20±53.46	26.13±21.32
Sodium (mg/L)	0.04±0.07	0.02±0.01	0	0	0
Potassium (mg/L)	0.01±0.02	0.01±0.00	0	0	0.08±0.07
Chlorides (mg/L)	54.43±10.85	71.60±9.62	75.85±36.98	88.31±8.41	38.58±37.93
Sulfates (mg/L)	25.52±17.63	13.06±8.81	37.99±28.10	34.54±33.28	10.27±13.74
Phosphates (mg/L)	0.04±0.04	0.04±0.00	0.51±0.60	0.41±0.19	0.46±0.32
Nitrates (mg/L)	0.97±0.39	1.77±0.08	2.39±0.05	6.06±3.21	0.33±0.49
MPN index	190±62.45	106.50±9.55	157.50±116.67	180±84.85	83.67±109.41

(*p<0.001) and (**p<0.01) for seasons through the Kruskal-Wallis test for other limnological parameters. Figure 1 represents the geographical location of Ullal Lake; Figure 2 indicates the sampling stations within the lake; Figure 3 depicts the somite developmental stages observed in *D. rerio* embryos, whereas Figure 4 graphically represents the heartbeat changes recorded in *D. rerio*. A notable significant difference (p<0.001) in MPN was recorded amidst the sample stations, indicating variations in microbial contamination. The same is depicted in Table 4. The mean at the deposit station was 142.42±83.08, suggesting low levels of contamination, whereas a high MPN index (1065.58±725.46) was recorded at the inlet. Open surface water station exhibited very low MPN (27.25±18.10). DSCF comparisons recorded in Table 4 show variations in microbial contamination across the sample stations, with wastewater discharge and urban development being the sole reasons for the varying MPN index. Table 5 with the Kruskal-Wallis test data revealed significant differences (p<0.001) across different seasons in several parameters, including temperature, humidity, magnesium, total hardness and nitrates levels. Substantial temperature variation was seen between summer and Monsoon. Humidity also varied significantly, with monsoons and summers showing higher mean humidity values than autumn, winter and spring. Magnesium levels exhibited marked seasonal differences, with monsoon recording the highest mean concentration. Total hardness also displayed significant seasonal variability and nitrates exhibited striking differences, with spring recording the highest mean concentration. These observations underscore the significant seasonal dynamics influencing lake water quality.

Table 3: Seasonal variation in physicochemical parameters and most probable number for the sampling station inlet water sampled between June 2022 and July 2023.

Parameters	Monsoon July-September	Autumn October - November	Winter December-January	Spring February- March	Summer April-June
Sample Station-Inlet					
pH	5.77±0.63	5.52±0.34	6.13±0.10	4.01±5.66	7.48±0.96
Temperature (ºC)	25.47±0.25	25.38±0.12	22.60±0.85	26.05±0.07	31.67±1.10
Humidity	57.47±0.92	59.00±2.83	38.55±1.34	37.15±6.58	48.83±5.09
Turbidity (NTU)	9.33±2.08	6.17±4.48	31.50±24.75	6.00±4.24	23.00±13.08
Conductivity (µS/cm)	465.00±84.59	541.00±107.48	468.50±241.12	4108.00±4768.73	716.67±136.05
Dissolved Oxygen (DO) (mg/L)	3.20±1.60	2.40±1.13	2.70±0.71	4.35±2.05	3.33±0.84
Biochemical Oxygen Demand (BOD) (mg/L)	0.97±0.91	-3.52±6.34	0.05±0.78	3.10±0.71	2.03±1.31
Chemical Oxygen Demand (COD) (mg/L)	74.67±73.90	53.33±30.17	272±22.63	144±22.63	132.67±23.69
Phenolphthalein alkalinity (mg/L)	0	0	0	25±35.36	9.33±16.17
Methyl Orange alkalinity (mg/L)	692.67±1132.24	361.33±468.58	55.00±21.21	55.00±7.07	74.67±40.51
Hydroxide alkalinity (mg/L)	0	0	0	12.50±17.68	0
Carbonate alkalinity (mg/L)	0	0	0	-25.00±35.36	18.67±32.33
Bicarbonate alkalinity (mg/L)	692.67±1132.24	361.33±468.58	55±21.21	30±42.43	56±58.28
Total Hardness (mg/L)	340±220	330±14.14	75±7.07	41±26.87	86.67±15.28
Total Dissolved Solids (mg/L)	254.67±63.07	282.83±39.83	234.50±118.09	2049.00±2377.29	360.67±68.16
Calcium Hardness (mg/L)	33.87±9.61	31.85±2.86	26.50±2.12	16.00±2.26	63.67±48.50
Magnesium Hardness (mg/L)	306.13±225.35	298.14±11.26	48.50±9.19	25.00±29.13	23.00±40.11
Sodium (mg/L)	0.01±0.02	0.01±0.01	0	0	0
Potassium (mg/L)	0.10±0.17	0	0	0	0.10±0.09
Chlorides (mg/L)	31.70±17.76	58.45±37.83	69.55±18.03	80.15±2.90	35.38±25.03
Sulfates (mg/L)	25.01±21.89	16.88±11.51	22.58±22.36	55.40±5.40	17.12±15.25
Phosphates (mg/L)	0.08±0.05	0.41±0.46	1.35±1.60	0.55±0.41	0.58±0.82
Nitrates (mg/L)	0.82±0.30	1.70±0.31	2.61±0.30	5.01±2.09	0.20±0.31
MPN index	1533.33±750.56	1750±919.24	110	460	522.33±549.16

Table 4: Kruskal Wallis Statistics and DSCF pairwise comparisons for Dissolved Oxygen (p<0.01) and Most Probable Number at (MPN) Test (**p<0.001) at sampling stations.**

Variables	Split	N	Mean	SD	Kruskal-Wallis
Dissolved Oxygen (**p<0.01)	Deposit	12	1198.00	1937.07	8.97
Inlet	12	3.05	1.07		
Open Water	12	3.21	1.24		
MPN index (**p<0.001)	Deposit	12	142.42	83.08	21.10
Inlet	12	1065.58	725.46		
Open Water	12	27.25	18.10		

DSCF pairwise comparisons

Pairwise comparisons-DO (*p<0.01)		W	p	MPN Index (*p<0.001)		W	P
Deposit	Inlet	0.0410	1.000	Deposit	Inlet	4.95	0.001
Deposit	Open Water	3.8493	0.018	Deposit	Open Water	-4.51	0.004
Inlet	Open Water	3.4345	0.040	Inlet	Open Water	-4.99	0.001

Table 5: Kruskal Wallis Statistics indicating significance for Physico-chemical parameters at various seasons (*p*<0.001) and (**p*<0.01).**

Physical Parameters	Seasons	N	Mean	SD	Kruskal-Wallis	Physical Parameters	Seasons	N	Mean	SD	Kruskal-Wallis
Temperature (**p<0.001)	Monsoon	9	25.43	0.40	31.52	pH (*p<0.01)	Monsoon	9	5.71	0.58	13.80
	Autumn	6	25.30	0.18			Autumn	6	5.51	0.22	
	Winter	6	22.65	0.62			Winter	6	5.44	2.14	
	Spring	6	26.10	0.18			Spring	6	3.92	4.29	
	Summer	9	31.24	1.06			Summer	9	7.43	0.71	
Humidity (**p<0.001)	Monsoon	9	55.02	3.18	27.15	BOD (*p<0.01)	Monsoon	9	0.54	1.87	13.87
	Autumn	6	56.50	3.51			Autumn	6	-4.33	5.46	
	Winter	6	38.87	2.05			Winter	6	0.17	1.49	
	Spring	6	38.95	3.72			Spring	6	2.35	1.04	
	Summer	9	49.04	4.66			Summer	9	1.41	0.90	
Magnesium (**p<0.001)	Monsoon	9	262.56	159.30	26.02	Total Dissolved Solids (*p<0.01)	Monsoon	9	233.89	64.12	16.44
	Autumn	6	269.34	38.96			Autumn	6	247.11	33.37	
	Winter	6	47.17	36.07			Winter	6	340.33	330.13	
	Spring	6	33.73	34.07			Spring	6	1966.33	1754.56	
	Summer	9	17.49	30.05			Summer	9	338.33	75.07	
Total Hardness (**p<0.001)	Monsoon	9	295.00	152.40	25.67	Conductivity (*p<0.01)	Monsoon	9	454.11	119.75	16.64
	Autumn	6	301.39	40.80			Autumn	6	485.89	65.19	
	Winter	6	71.67	37.10			Winter	6	681.50	659.95	
	Spring	6	50.67	34.54			Spring	6	3901.00	3471.10	
	Summer	9	64.67	27.68			Summer	9	674.89	148.70	
Nitrates (**p<0.001)	Monsoon	9	0.89	0.32	32.08	Phenolphthalein alkalinity (*p<0.01)	Monsoon	9	0.00	0.00	16.20
	Autumn	6	1.74	0.20			Autumn	6	0.00	0.00	
	Winter	6	2.52	0.25			Winter	6	0.00	0.00	
	Spring	6	4.84	2.20			Spring	6	16.67	20.41	
	Summer	9	0.20	0.31			Summer	9	16.00	19.00	
						Phosphates (*p<0.01)	Monsoon	9	0.06	0.04	15.47
							Autumn	6	0.16	0.28	
							Winter	6	0.72	0.91	
							Spring	6	4.84	2.20	
							Summer	9	0.20	0.31	

The Kruskal-Wallis test in Table 5 highlights significant differences (p<0.01) across various seasons with parameters such as pH, BOD, total dissolved solids, conductivity, phenolphthalein alkalinity and phosphate levels. pH levels in summer recorded the highest mean value, indicating alkaline conditions, whereas spring displayed the lowest mean pH value, indicating acidic conditions. Spring exhibited the highest value for BOD levels. Total dissolved solids displayed seasonal differences, with winter recording the highest mean value. Conductivity levels varied significantly across seasons, with spring exhibiting the highest mean conductivity. Phenolphthalein alkalinity and phosphate levels also displayed significant seasonal variability.

The development of *D. rerio* embryos in the open surface water and inlet stations was on par with the control, with the embryos reaching the 14th somite stage at 16 hr. In contrast, the deposit station showed the 10th somite stage. The heartbeat was recorded in Beats Per Minute (BPM) and the count in control and the open surface stations was 127 and 125 BPM, respectively, whereas there was a reduced count for the deposit and the inlet stations. The results suggest potential localized environmental stressors or fluctuations in water quality.

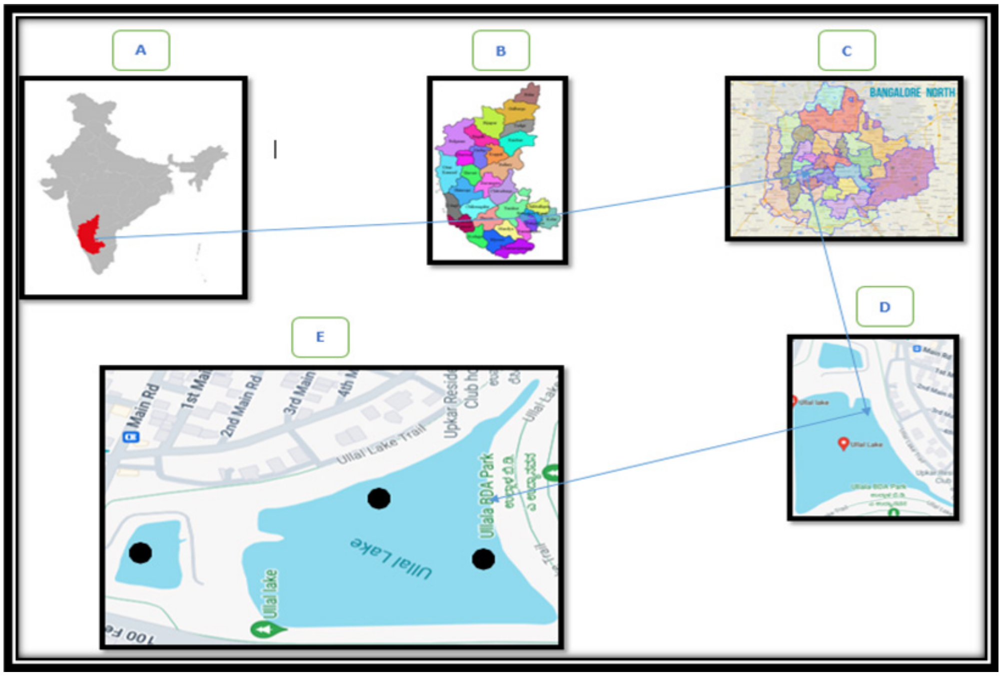

Figure 1: Maps indicating the location of Ullal Lake in Bangalore North and the sampling stations open surface water, deposit and inlet. (A) Map of India highlighting the position of the state of Karnataka[22] (B) Karnataka state with districts;[23] (C)Map of North Bangalore;[24] (D, E) Geographical locations of Lake.[25]

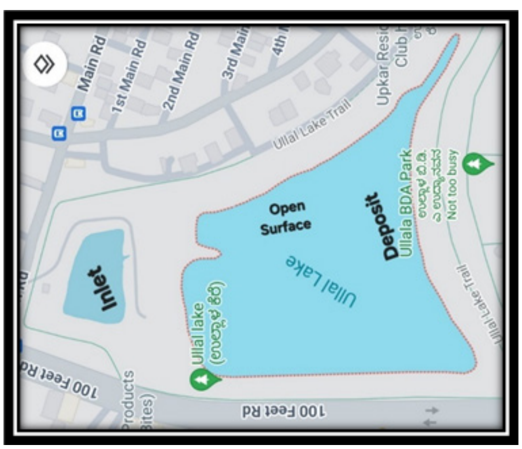

Figure 2: Indicating the Sampling stations within Ullal Lake.[25]

Overall, the open surface water quality appeared superior to that of deposit and inlet stations.

DISCUSSION

The study investigates Ullal Lake's seasonal dynamics and ecological health in Bangalore through limnological perspectives and physiological developmental responses using *D. rerio* embryos. It explains significant seasonal physical, chemical and MPN parameter variations. pH of the lake during the summers is alkaline while slightly acidic during other seasons; the same is consistent with the urban lakes of Bangalore, as suggested by previous findings. Acidic pH may be due to rainfall and mineral

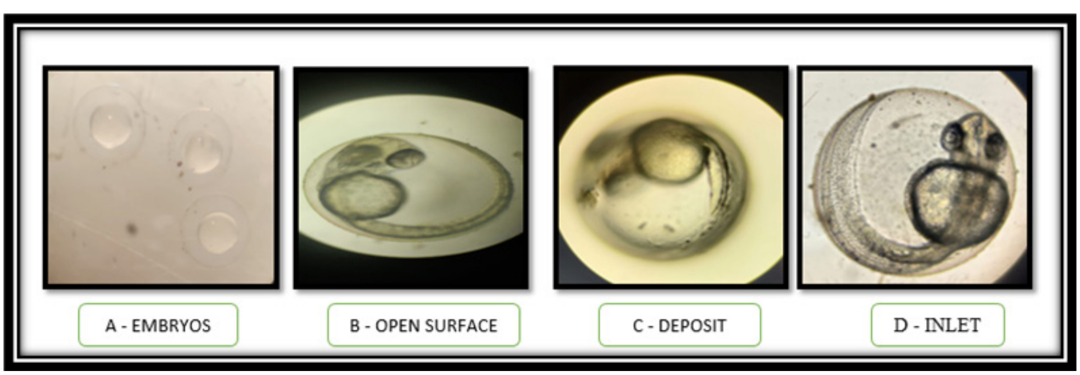

Figure 3: Influence of Ullal Lake water on the somite developmental stage of *D. rerio* embryos (a) fertilized embryo in control setup (b, c, d) somite embryonic developmental stage in open surface, deposit and inlet station.
Note: Deposit indicating 10th somite stage after 16 hr.

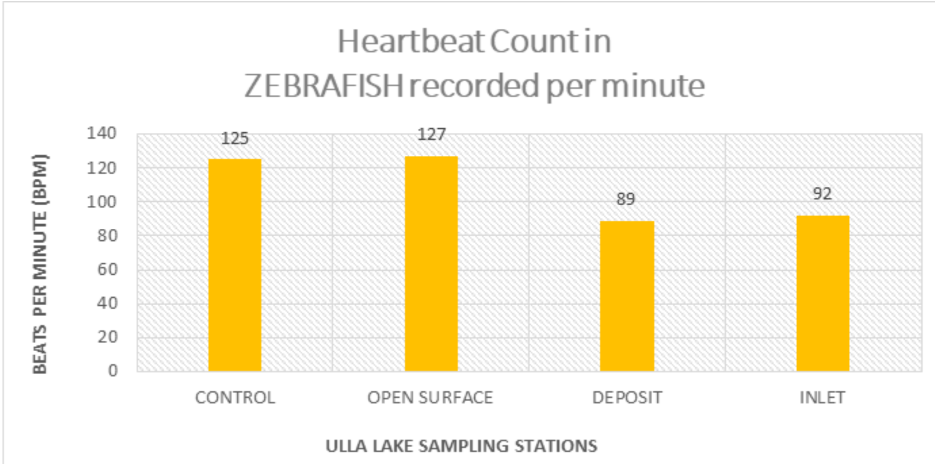

Figure 4: Impact of Ullal Lake water on Heartbeat count in *D. rerio*.

leachates;[26] previous studies also indicate pH to have lower values during the monsoon.[27] Temperature peaks in summer and dips in winter and freshwater ecosystems project seasonal trends with temperature.[28,29] High humidity in autumn and low in spring at Ullal Lake reflect seasonal variation; similar observations were made in Bellandur Lake, where humidity peaked post-monsoon. The variation in moisture is to strike a heat balance over a wetland.[30] A previous study indicates that the residence time of water is high during monsoon.[31] Past studies indicate low turbidity during the dry seasons,[32] whereas, in the current study, turbidity varied throughout the year; summers recorded maximum value for all three stations and inlet stations peaked during the winter. Precipitation and wind speed affect sediment resuspension and transportation, affecting turbidity.[33] Freshwater has low conductivity in comparison with saline water.[34] Conductivity was recorded as high across the sampling stations during the spring. Studies indicate conductivity to increase post-monsoon seasons due to the mixing of freshwater.[35] DO levels were lowest in autumn and high during cooler seasons; increased microbial activity and organic matter decomposition consume oxygen during warmer temperatures. Low DO during autumn is suggested by previous findings.[36] BOD is significantly influenced during spring and autumn, indicating organic matter variability. A negative BOD was observed during autumn across all stations. The deposit station also showed a negative BOD during the monsoon and winter seasons. Negative BOD is due to microorganisms that produce hydrogen peroxide, releasing oxygen.[37] Chemical oxygen demand was above the permissible values across all stations during all the seasons. This is indicative of pollutants and oxygen demand. Studies indicate that COD increases linearly with temperature.[38] The trend in COD is comparable to findings of Jakkur Lake in Bangalore, where winter showed high levels of COD due to reduced water volume and pollutant concentrations.[39] Alkalinity predicts the potential of an aquatic system.[40] Phenolphthalein alkalinity remained low throughout all seasons at all sampling stations, indicating minimum low acid content, whereas methyl orange alkalinity showed fluctuations. Past studies suggest that hardness rises during the summer,[41] whereas in the present study on Ullal Lake, the hardness peaked during the monsoon season and autumn in all three stations. The dissolution of minerals like calcite and dolomite during monsoon season might be the reason for the high hardness during monsoon season, as indicated by past studies.[7] Calcium ions were within the permissible limits, whereas magnesium ions during the monsoon and autumn recorded high values with a gradual decrease after autumn; leaching of magnesite and dolomite during rainfall might cause high magnesium levels,[42] but studies also indicate calcium and magnesium to increase during winter.[43] MPN index was maximum during the monsoon season; this increase in MPN can be attributed to the high load of organic matter and sewage carried into the lake. As suggested by previous findings, MPN tends to be high during monsoon.[44] In comparison with the season's parameters, conductivity, BOD, TDS, chlorides, sulfates and nitrates were majorly influenced by spring. Research suggests increased biological activity, temperature fluctuations and precipitation during the spring.[45] Monsoon-influenced variables include bicarbonates, hardness, magnesium, sodium, potassium and MPN. Turbidity, COD and phosphates were significant during the winter. Humidity increased during autumn, while the rise in calcium levels was seen during summer. Organic matter and leaf litter can lead to elevated levels of BOD, influencing alkalinity and hardness.[46] The developmental response and the heartrate count in *D. rerio* imply that open surface water is superior. Previous research suggests no significant impact on the developmental stage of the *D. rerio* embryos despite potential changes in water quality and nutrient levels.[47] Heartbeat count, somite development stage and the limnological parameters suggest that open surface water quality is better than deposit and inlet stations. The choice of limited sampling stations and a one-year study period might be the limitations of the current investigation, while comprehensive data collection and seasonal variation analysis enhance the robustness of the study. The importance of current findings that could be practiced are conservation and pollution control. Seasonal influence on water quality and identification of environmental stressors can also be understood from the findings. The study highlights enforcing water quality standards and sewage discharge limits and promoting sustainable urban practices through a policy regulatory framework. Combining limnological and biological assessments can serve as a model for ecological studies in urban communities, making the study more relevant to policymakers and environmental scientists around the globe.

CONCLUSION

A comprehensive study of limnological parameters at Ullal Lake revealed significant seasonal and spatial variations across sampling stations. Ullal Lake in North Bangalore demonstrates moderate ecological health overall. The study signifies the influence of environmental factors such as temperature, humidity and biological activity on water quality. Spring, monsoon and winter contribute to the seasonal dynamics of limnological parameters. Despite limnological variations, the developmental stages of *D. rerio* embryos were unaffected except for delayed development observed in the deposit station. Heartbeat count suggests potential environmental stressors. Overall, open surface water quality appeared superior to deposit and inlet stations. Continuous water monitoring and management practices ensure the sustainability and health of freshwater ecosystems. The study highlights the intricate relationship between seasonal variations and ecological health. By recognizing and addressing these seasonal dynamics through effective policy regulation, we can sustainably manage and better protect this vital freshwater resource within rapidly urbanizing regions.

CONFLICT OF INTEREST

The authors declare that there is no conflict of interest.

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ABBREVIATIONS

APHA: American Public Health Association; **BPM:** Beats Per Minute; **BOD:** Biochemical Oxygen Demand; **COD:** Chemical Oxygen Demand; **DO:** Dissolved Oxygen; **DSCF:** Dwass-Steel-Critchlow-Fligner; **MPN:** Most Probable Number; **NTU:** Nephelometric Turbidity Units; **RO:** Reverse Osmosis.

SUMMARY

The study investigates Ullal Lake's seasonal dynamics and ecological health by analyzing limnological factors and assessing the physiological responses of D. rerio. The research highlights the influence of seasonal variations on water quality parameters across three sampling stations. The results indicate environmental stressors, particularly in the deposit and inlet stations. The study underscores continuous monitoring and sustainable management for the conservation of lake ecosystems.

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