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Spatiotemporal Analysis of Physiochemical Properties and Trophic State Index of Upper Lake, a Ramsar site, Bhopal, India Using in-situ Observation Data

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Abstract:
Upper Lake, designated as a Ramsar site in Bhopal, India, plays a major role in sustaining ecological balance and ensuring water security in the region. This study provides an extensive spatiotemporal analysis of the lake's water quality by assessing essential physiochemical parameters and calculating the Trophic State Index (TSI) through systematic in-situ observations. Field data were collected from spatially distributed sampling sites during the pre- and post-monsoon seasons of 2022. Key water quality indicators, including Secchi disk transparency (SDT), dissolved oxygen (DO), pH, water surface temperature (WST), total alkalinity, turbidity, TDS, conductivity, and total hardness, were quantified and subjected to statistical evaluation. Various spatial interpolation techniques were employed, and the most effective one was selected to create two-dimensional images of lake water quality. The TSI, derived using Carlson's method, indicated that the northeastern side of the lake consistently experienced eutrophic to hypereutrophic conditions. During the post-monsoon period, observations indicate that the western side exhibits hypereutrophic conditions in the lake water. The results indicated significant spatiotemporal fluctuations in water quality parameters, with anthropogenic activities and climatic factors influencing trophic dynamics. This study highlights the necessity for sustainable management strategies to reduce eutrophication risks and to maintain the ecological integrity of lakes.
Keywords: *Trophic State Index; Secchi disk transparency; Turbidity; Upper Lake*

1. INTRODUCTION

Lakes are essential freshwater ecosystems that sustain human livelihoods, provide drinking water, and support biodiversity. However, increasing anthropogenic pressures, rapid urbanization, industrialization, and climate change, have led to a significant deterioration in water quality (Schindler, 2006; Smith et al., 2019). One of the major concerns is eutrophication, a process driven by excessive nutrient enrichment that leads to algal blooms, oxygen depletion, and extinction of aquatic biodiversity (Dodds & Smith, 2016). Eutrophication not only disrupts aquatic ecosystems but also poses serious health risks and economic burdens on surrounding communities. The proliferation of harmful algal blooms (HABs), often resulting from nutrient over-enrichment, can produce toxins detrimental to both human and animal health, contaminate drinking water supplies, and lead to increased treatment costs (Paerl et al., 2016). Additionally, the loss of aquatic biodiversity and decline in fish populations can impact local fisheries and reduce the recreational and aesthetic value of lakes. These multifaceted consequences underscore the urgent need for proactive nutrient management and pollution control strategies to safeguard the ecological integrity and ecosystem services of freshwater lakes (Heisler et al., 2008). Developing successful conservation and management plans for lake ecosystems also requires an understanding of the spatiotemporal variations in water quality parameters (Wetzel, 2001).

The Upper Lake (Bhojtal) in Bhopal, India, is among the largest artificial lakes in the country, and has immense ecological, socioeconomic, and cultural significance (Tare et al., 2013). Constructed in the 11th century, it provides the majority of the drinking water for the city and plays an important part in sustaining the regional hydrological balance. Recognizing its ecological importance, the lake is designated a Ramsar site in 2002. However, in recent years, degradation in water quality has been observed due to untreated sewage discharge, agricultural runoff, and urban expansion (Patel et al., 2018). These factors contribute to increased nutrient loading, leading to eutrophication and a fall in quality of water (Singh et al., 2021). A thorough and interdisciplinary management strategy that incorporates scientific monitoring, community involvement, and policy enforcement is needed to address the Upper Lake water quality deterioration. Understanding the level and dynamics of pollution requires regular assessment of water quality parameters, like nutrient concentrations, DO levels, and biological oxygen demand (BOD) (Kumar & Rai, 2020). In addition, the implementation of best management practices, including the construction of sewage treatment plants, promotion of sustainable agricultural practices, and the creation of buffer zones, can significantly reduce pollutant inflows into the lake (Sharma et al., 2019). Additionally, conservation efforts and public awareness may boost the long-term sustainability of restoration initiatives. Without immediate and sustained action, the ecological and socioeconomic services provided by the Upper Lake may continue to decline, threatening the well-being of the local population and the biodiversity it supports.

For assessing the health of the Upper Lake, it is crucial to examine its physiochemical properties and Trophic State Index (TSI), which are key indicators of water quality and productivity levels (Carlson, 1977). Physiochemical characteristics, like pH, DO, biochemical oxygen demand (BOD), TDS, and chlorophyll-a, are essential in establishing the trophic level of the water body (Boyd, 2015; Qin et al., 2020). The spatial and temporal analyses of these parameters can help identify pollution sources, seasonal variations, and long-term trends, thereby offering critical insights for lake management and conservation (Hakanson & Bryhn, 2008). By understanding the spatiotemporal trends in water quality, this study will contribute to the growing body of research on freshwater ecosystem health and provide critical insights for policymakers, environmental agencies, and local communities to develop effective conservation and restoration strategies for the Upper Lake (Garg et al., 2010). With the advancement of remote sensing technologies and geospatial analysis, it greatly enhanced our capacity to assess water quality across wide regions and timeframes, providing valuable insights into the dynamics of nutrient loading, sedimentation, and temperature fluctuations (Palmer et al., 2015). These tools help researchers and policymakers to identify early signs of degradation, assess the effectiveness of restoration efforts, and prioritize areas for intervention. Incorporating such data-driven approaches into lake management frameworks ensures more adaptive and informed decision-making in the face of ongoing environmental change (Villa et al., 2014). This study emphasizes on the spatiotemporal analysis of the major physiochemical properties and TSI of the Upper Lake using in-situ observation data collected over different locations and time periods. The findings of this study will be instrumental in addressing the growing challenges of eutrophication and preserving the long-term sustainability of this vital water resource.

2. MATERIALS AND METHODS

2.1 Study area

The Upper Lake is a significant freshwater reservoir in Bhopal, Madhya Pradesh (Fig. 1). It is among the country’s largest and oldest manmade freshwater lakes, covering approximately 31 km², with a catchment area of 361 km² (Garg et al., 2010; CPCB, 2019). This lake was built by Raja Bhoj by damming the Kolans River in the eleventh century. It acts as a main source of drinking water for more than 40% of Bhopal's population (Jain et al., 2014). Recognizing its ecological and socio-economic significance, the lake was declared a “Ramsar site” in 2002. Geographically, the Upper Lake is situated latitudinally at 23°13′N and longitude at 77°18′E. The lake is placed an altitude of 527 m above MSL, with an average and maximum depth of 6 m and 11.7 m respectively (Tare et al., 2013; Singh et al., 2021). The lake is fed by the Kolans River and small seasonal streams, with the outflow regulated through a spillway connecting it to the Lower Lake (Patel et al., 2018). Bhopal’s subtropical climate, characterized by an average annual rainfall of 1200 mm, significantly influences seasonal water quality fluctuations (Jain et al., 2014). The Upper Lake supports diverse aquatic flora and fauna, including fish species and serves as habitat for migratory birds and wetland vegetation (Garg et al., 2010). However, eutrophication, urban encroachment, wastewater discharge, and overextraction of water have caused in a significant decline of quality of lake water (Singh et al., 2021). The lake is increasingly threatened due to nutrient loading from sewage and agricultural runoff, which leads to frequent algal blooms and oxygen depletion (Patel et al., 2018). Conservation efforts such as the Bhopal Lake Conservation and Management Plan (BLCMP) and community-driven restoration initiatives have been implemented to mitigate pollution and ensure sustainable water resource management (CPCB, 2019). Given these challenges, spatiotemporal monitoring of physiochemical parameters and trophic status is essential for evaluating water quality trends and guiding effective conservation strategies for this ecologically significant Ramsar site (Tare et al., 2013; Singh et al., 2021).

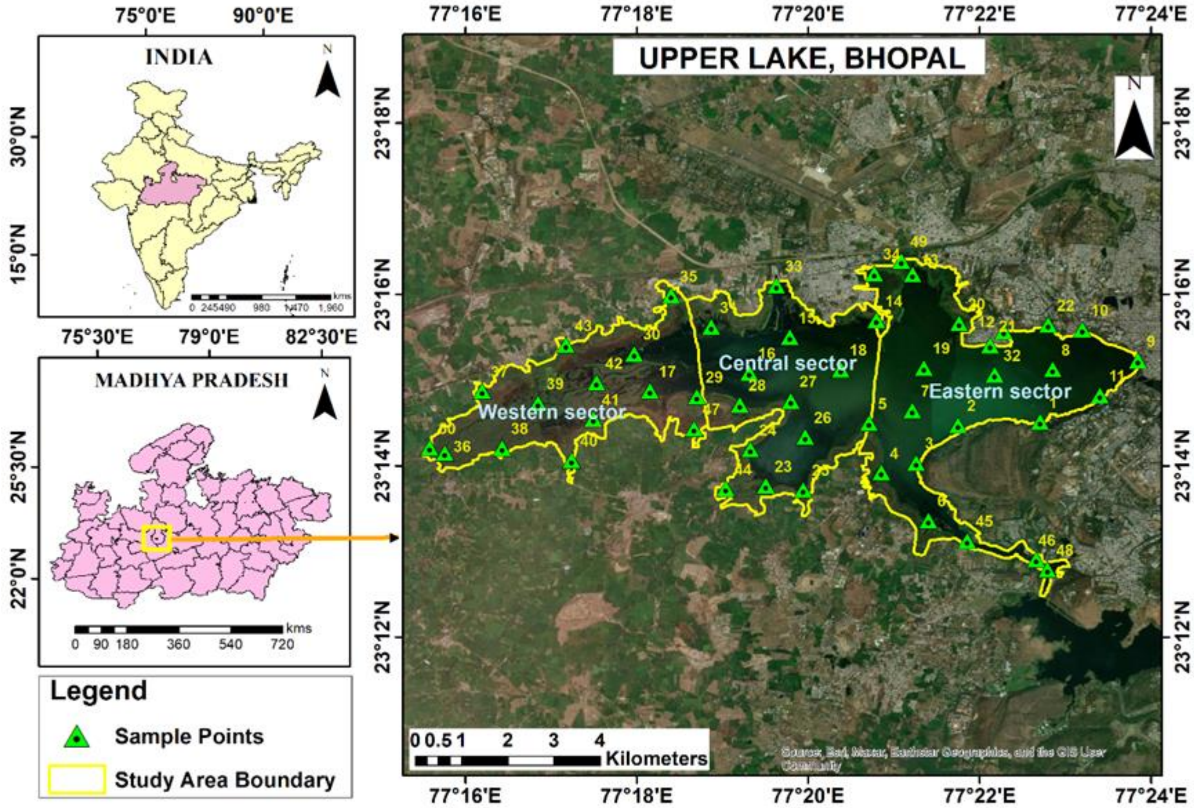

Fig. 1. The study area - Upper Lake, Bhopal showing different sectors and sample locations

2.2 Experimental design and sample collections

This study adopted a spatiotemporal approach to assess the physiochemical characteristics along with Trophic State Index (TSI) of Upper Lake, Bhopal, through in-situ observations, and laboratory-based analyses. In-situ measurements of Secchi disk transparency (SDT), dissolved oxygen (DO), pH, water surface temperature (WST), total dissolved solids (TDS), conductivity, turbidity, total alkalinity, and total hardness were collected from 50 sampling stations corresponding to GPS locations during the pre- and post-monsoon season of 2022. The appropriate procedures were followed for sample collection during fieldwork. The lake can be divided into three distinct sectors based on its depth, Secchi disk transparency and nutrients: eastern sector, central sector, and western sector (Fig. 1).

2.3 Methodology

The methodology involved systematic site selection, pre- and post-monsoon water sampling, physiochemical parameter assessment, TSI computation, statistical analysis, and GIS-based spatial visualization. The methodology for measuring several physiochemical characteristics of water was based on as per below given methods from APHA (1998), and Adoni et al. (1985).

Secchi Disk Transparency (SDT)

SDT is an important parameter that indicates the presence or absence of suspended matter and reflects the overall water quality of aquatic systems. The secchi disk, which provides transparency to the lake, can be utilized to estimate its trophic state. A Secchi disk is a 20 cm (8 inch) diameter of black and white metal. A measuring rope was used to lower the Secchi disk to assess transparency. It was submerged in the lake until it was no longer visible during the measurement (Fig. 2). The point at which it becomes invisible is known as SDT.

Fig. 2. SDT measurement in Upper Lake, Bhopal

The TSI variation is a crucial indicator for evaluating lake transparency (Jally et al., 2020). Numerous researchers have utilized the connection between SDT and TSI extensively for lake water quality studies (Carlson, 1977; Paukert & Willis, 2003; Jally et al., 2024). The relationship between TSI and SDT is presented in following equation.

TSI (SDT) = 10 (6 - lnSDT / ln2)

After estimation of TSI from in-situ observation, the lake water can be categorized according to the TSI range provided in Table 1 (Fuller & Minnerick, 2007; Jally et al., 2020).

Table 1. Relation between Carlson TSI, Secchi depth and Lake Trophic Status

Carlson TSI	Secchi depth (meter)	Lake Trophic Status
<38	> 8 – 4	Oligotrophic
38–48	4 – 2	Mesotrophic
49–61	2 - 0.5	Eutrophic
>61	0.5 - < 0.25	Hypereutrophic

Dissolved oxygen (DO)

DO is the most crucial factor for lake water quality assessment as it controls the metabolic functions of biodiversity in the ecosystem. It serves as an indication of eutrophication levels, tropical state, and water quality. DO level of water body is important for the physical, chemical, and biological activities, and its assessment serves as a reliable water quality indicator. Variations in the DO level can be a good sign of changing the quality of water. DO was evaluated using a modified Winkler method. Water samples were obtained in 300 ml BOD bottles with no bubbling and were suddenly fixed by mixing 2 ml manganous sulphate and 2 ml alkaline iodide-azide solutions. To dissolve the resulting brown precipitation, two milliliters of concentrated sulfuric acid (H_2SO_4) were incorporated and shaken. A 50 ml aliquot was titrated against 0.025 N solution of sodium thiosulphate titrant using starch as an indicator. Further, the DO content was determined using the following formula.

DO (mg/L) = (8 x 1000 x N x v) / V

v: Volume of titrant

V: Volume of sample

N: Normality of titrant (0.025 N)

pH

pH is the reciprocal of the hydrogen ion concentration in moles per liter, logarithmized in base 10. The pH scale ranges from "0 to 14", the intermediate value (pH=7) represents perfect neutrality at 25 °C. The pH value depicts the hydrogen ion activity, while the alkalinity and acidity readings indicate the buffering capacity of the sampled water. The hydrogen ion concentration is a major environmental factor, the variation of which, among other causes, is linked to the system functions. In the field, the pH meter was immersed in the collected water samples and the pH was recorded.

Water Surface Temperature (WST)

WST significantly affects a number of chemical, biological, and physical processes in aquatic ecosystems, including the solubility of DO, nutrient cycling, and biological productivity. The WST was measured in-situ at each sampling station to assess the thermal characteristics of the Upper Lake. It was recorded by dipping the thermometer in lake water and noted in degree Celsius.

Total Alkalinity

The total alkalinity was estimated following the standard titrimetric procedure described by Adoni et al. (1985) in the Workbook on Limnology. Alkalinity denotes the water's capacity to neutralize acids, because of the presence of bicarbonates (HCO_3^-), carbonates (CO_3^{2-}), and hydroxides (OH^-). For the analysis, 100 mL of a well-mixed collected water samples were placed in a conical flask. A few drops of the phenolphthalein indicator were added. The development of a pink color indicated the presence of carbonate alkalinity. The samples were then titrated with standard 0.02 N sulfuric acid until the pink color disappeared, marking the endpoint for phenolphthalein alkalinity (P). Subsequently, two to three drops of methyl orange indicator were incorporated into the same solution. The titration was continued until the color changed from yellow to orange, indicating the endpoint of total alkalinity (T). The volume of acid consumed in the second step represented the total alkalinity due to bicarbonates and carbonates. The alkalinity was calculated and expressed in mg/L as $CaCO_3$ using the following formula.

Total Alkalinity (mg/L) = $V \times N \times 50{,}000 / V_{sample}$

V: Volume (mL) of acid used

N: Normality of sulfuric acid

V_{sample}: Volume (mL) of the water sample taken

Turbidity

Turbidity is a significant factor which indicate the purity of water and the presence of suspended particulate matter. It was measured in the field by digital turbidity meter. Turbidity reflects the scattering of light because of the available of suspended solids in water like silt, plankton, and organic debris. It is expressed in the unit as Nephelometric Turbidity Units (NTU). At each sampling station, water was collected in a clean, transparent cuvette provided with the turbidity meter. Care was taken to avoid introducing air bubbles or disturbing bottom sediments during sampling. The sample chamber was rinsed thrice with the lake water before final filling, ensuring that no residues or fingerprints interfered with the reading.

Total Dissolved Solids (TDS)

TDS is the total amount of all inorganic and organic materials dissolved in water. It includes minerals, salts, and small amounts of organic matter. TDS of the water samples were collected in the field using digital TDS meter. If there will be increase of TDS levels, the water becomes unfit for drinking and irrigation, which further causes the decrease of photosynthetic capacity and rise in water temperature (Simeon et al., 2020; Nisar et al., 2022). It serves as a key water quality indicator, affecting aquatic life and water usability. The TDS meter used in this study was factory-calibrated and capable of directly displaying results in parts per million (PPM). Before each measurement, the probe was rinsed thoroughly with distilled water followed by the lake water sample to ensure accuracy and avoid cross-contamination.

Conductivity

The electrical conductivity of the water samples was measured in the field using digital conductivity meter to assess the ionic concentration of the dissolved salts in the Upper Lake. It is a measurement of a solution's electrical current carrying capacity and a technique for assessing water purity (Murugesan et al., 2006; Nisar et al., 2022). This also represents the occurrence of biogenic and abiogenic impurities in lake water (Upadhyay et al., 2012). Because the electrical current is transmitted by ions in the solution, the conductivity increases as the concentration of ions increases. Consequently, it is one of the main parameters used to assess whether water is suitable for firefighting and irrigation. Conductivity is a key physicochemical parameter that reflects the water's ability to conduct electric current, primarily affected by the presence of cations (e.g., Na^+, K^+, Ca^{2+}, Mg^{2+}) and anions (e.g., Cl^-, SO_4^{2-}, HCO_3^-). The conductivity was determined using a conductivity meter. The instrument used for the conductivity measurement was factory-calibrated and equipped with automatic temperature compensation to ensure accuracy across varying field conditions. The results are expressed in µS/cm.

Total Hardness

The term "hardness" describes the qualities of highly mineralized water. It is controlled by the amounts of magnesium and calcium salts, which are generally mixed with carbonate and bicarbonate (temporary hardness), sulfates, chlorides, and other anions of mineral acids (permanent hardness) (Nisar et al., 2022). It is usually stated as mg/L of $CaCO_3$. Water with a hardness of over 300 mg/L is typically regarded as hard, more than 150 mg/L is noticeable by most people, and less than 75 mg/L is regarded as soft. From a health point of view, hardness of up to 500 mg/L is safe, but higher levels may create laxative effects. The total hardness of the water samples was calculated using the EDTA titrimetric method, as described by Adoni et al. (1985) in the Work Book on Limnology. The presence of divalent metal ions, especially calcium (Ca^{2+}) and magnesium (Mg^{2+}), is the main cause of the total hardness, which is measured in milligrams per liter (mg/L) as calcium carbonate ($CaCO_3$). For the analysis, 50 mL of a well-mixed water sample was placed in a conical flask. To this solution, 1–2 mL of buffer solution (pH 10) was added to maintain the required alkaline conditions. The buffer helps complex interfering ions and provides an optimal pH for the reaction. A pinch of Eriochrome Black T (EBT) indicator was then mixed, which imparted a wine-red color to the solution owing to the formation of a weak complex with the metal ions present. The sample was then titrated with a standard solution of 0.01 N ethylenediaminetetraacetic acid (EDTA) until the color changed sharply from wine red to clear blue, indicating the endpoint of the reaction. EDTA reacts with free Ca^{2+} and Mg^{2+} ions, forming stable chelates, and the color change signifies that all hardness-causing ions have been complexed. The volume of EDTA consumed was considered to determine the total hardness, using the following formula.

Total Hardness = $V \times N \times 50{,}000 / V\text{sample}$

V: Volume (mL) of EDTA used

N: Normality

V_{sample}: Volume (mL) of water sample titrated

In present study, the in-situ collected data of SDT for the pre-monsoon season of 2022 are interpolated to produce two-dimensional images. Various interpolation methods have been tested (Table 2), and the most suitable one is used. To determine the proximity of the in-situ measured value to the interpolated value, the absolute difference (AD), absolute percentage difference (APD), and root mean square error (RMSE) were calculated using 22 randomly selected sample points. The values of AD, APD, and RMSE are determined using following equations (Melin et al., 2007; Jally et al., 2020; Jally et al., 2024).

$$\mathbf{AD} = \left(\frac{1}{N}\right)\sum_{i=1}^{i=N}(|yi - xi|)$$

$$\mathbf{APD} = 100 * \left(\frac{1}{N}\right)\sum_{i=1}^{i=N}\frac{(|yi - xi|)}{xi}$$

$$\mathbf{RMSE} = \sqrt{\sum_{i=1}^{n}(|yi - xi|)^2/N}$$

x: In-situ measurement value

y: Interpolated value

N: Number of sample points

3. RESULTS

The primary objective of this study is to use in-situ observation data to show the spatiotemporal distribution of the TSI and important physiochemical characteristics of Upper Lake, Bhopal. Along with SDT measurements, several water quality measures are collected and analyzed in the pre- and post-monsoon period of 2022. These parameters include DO, pH, WST, TDS, conductivity, total hardness, total alkalinity, and turbidity. These are significant water body indicators that are taken to evaluate the overall health of the lake ecosystem (Sharma et al., 2010). SURFER software is used to analyze and process the aforementioned field data. In this study, an effort is made to get the best interpolation technique that can effectively describe the distribution pattern of lake environmental characteristics. Different methods are compared, and statistical outputs are putted in Table 2. The most suitable one is selected on the basis of closeness of the in-situ measurement data with that of the interpolated image.

The in-situ measured value of SDT were used to assess the different interpolation methods (Table 2). The output results are shown in Fig. 3. Table 2 shows the output results of AD, APD, and RMSE for the in-situ observed and interpolated values at selected sampling sites. From the results of the investigation, kriging gives the best-interpolated image in terms of shape and interpolated value range. The AD, APD and RMSE results of kriging are near to the Inverse distance to power, modified Shepherd's methods, Nearest neighbour, and Triangulation with linear interpolation. However, the results show out-of-range values for inverse distance to power, modified Shepherd's methods, nearest neighbour, and triangulation with linear interpolation methods, as well as the other methods used. As a result, in the current study, the kriging interpolation technique is employed to interpolate in-situ data observations.

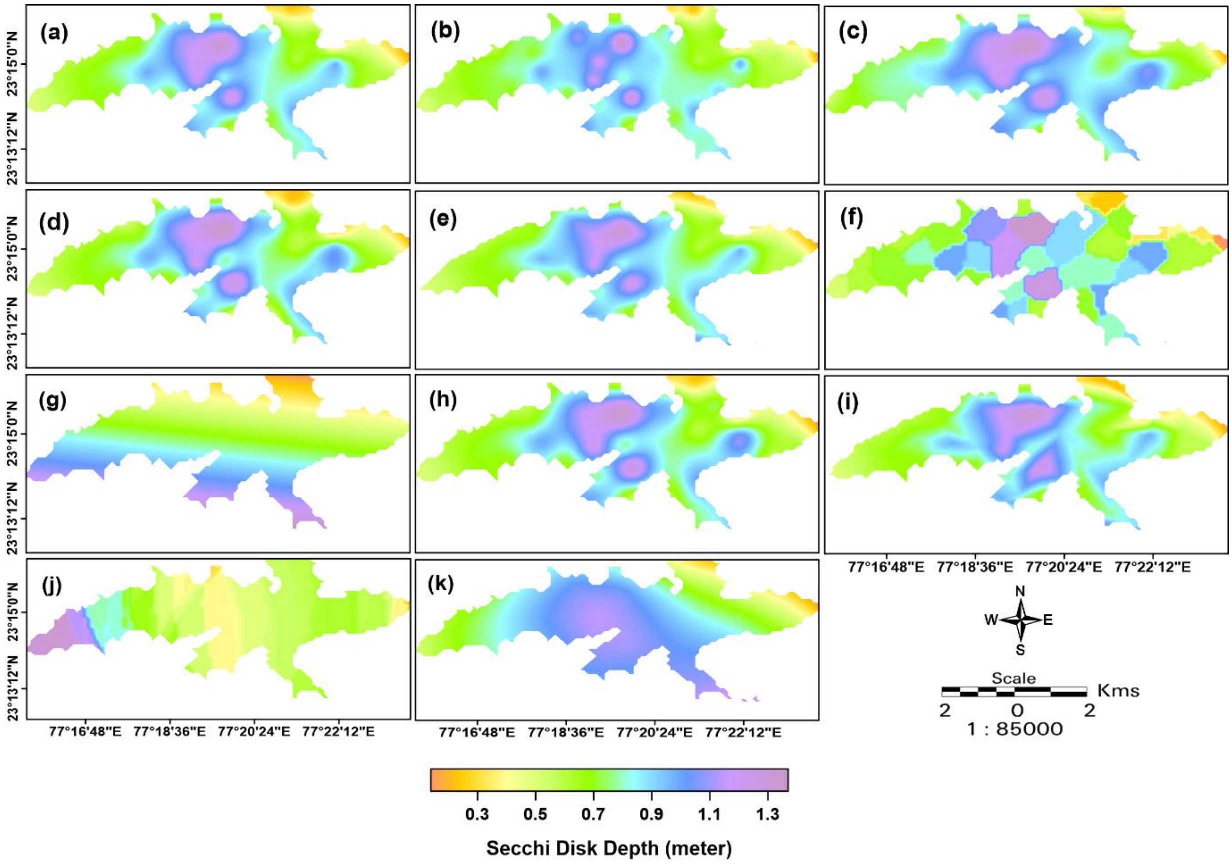

Fig. 3. Interpolated images of SDT using different interpolation methods of Upper Lake, Bhopal

Table 2. Interpolation methods and results of AD, APD and RMSE derived from the in-situ measured and interpolated values of SDT

Sl. No.	Methods	AD	APD	RMSE
1	Kriging (a)	0.005285442	0.45921663	0.008707250
2	Inverse distance to power (b)	0.012221597	1.255552362	0.018422694
3	Minimum curvature (c)	0.033879362	2.743505354	0.035001872
4	Modified Shephards Method (d)	0.006915196	0.776995411	0.010516520
5	Natural neighbour (e)	0.012399231	1.268272636	0.018037438
6	Nearest neighbour (f)	0.006722245	0.739818524	0.009888122
7	Polynomial regression (g)	0.234937829	25.00580661	0.305482306
8	Radial basis function (h)	0.035463817	2.725649745	0.046002362
9	Triangulation with linear interpolation (i)	0.009320001	0.947348666	0.012691945
10	Moving average (j)	0.228843177	24.57173399	0.285179046
11	Local polynomial (k)	0.149506911	14.83706931	0.203857667

The interpolated images of in-situ observations of SDT, DO, pH, WST, Total Alkalinity, Turbidity, TDS, Conductivity, Total Hardness, and TSI are generated during the pre- and post-monsoon season of 2022 and displayed in Fig. 4(a–t). The sector-wise distribution of maximum, minimum, and average value of different physiochemical properties and TSI during the pre- and post-monsoon seasons of 2022 are shown in Table 3. The in-depth analysis of those water quality properties and TSI is described below.

Table 3. In-situ data of various physiochemical parameters collected over the Upper Lake, Bhopal during the pre- and post-monsoon period of 2022

		Pre-monsoon season, 2022			**Post-monsoon season, 2022**		
In-situ data	**Sector**	**Max.**	**Min.**	**Avg.**	**Max.**	**Min.**	**Avg.**
SDT (meter)	Eastern	1	0.1	0.5	1.3	0.4	0.9
	Central	1.3	0.2	0.8	1.8	0.3	1
	Western	1.4	0.5	0.8	1	0.3	0.6
DO (mg/L)	Eastern	7.5	4.2	5.6	6.9	4.5	5.7
	Central	9.6	6	7.3	8.4	5.6	7
	Western	8.6	6.1	7.2	7.4	5.2	5.9
pH	Eastern	6.8	5.4	5.7	7.3	5.6	6.2
	Central	7.8	5.6	6.6	8.6	5.8	6.8
	Western	7.1	6.1	6.5	7.6	5.5	6.2
WST (°C)	Eastern	33.7	27.8	30.9	22.2	18.9	20.6
	Central	32.2	27.7	29.2	21.8	17.5	19.3
	Western	29.8	27.5	29.1	20.8	17.4	18.3
Total Alkalinity (mg/L)	Eastern	114	103	109	116	97	105
	Central	113	86	100	110	86	100
	Western	103	78	84	115	88	106
Turbidity (NTU)	Eastern	20.4	14.3	17.6	23.1	15.7	19.4
	Central	16.2	7.1	11.9	26.8	9.5	14.9
	Western	11.9	4.3	8.3	28.8	10.8	24.8
TDS (PPM)	Eastern	328	274	299	346	287	313
	Central	299	266	277	316	276	289
	Western	312	267	291	352	278	319
Conductivity (µS/cm)	Eastern	505	321	443	476	238	395
	Central	496	215	346	512	218	298
	Western	383	215	244	529	218	463
Total Hardness (mg/L)	Eastern	118	105	113	116	102	110
	Central	115	94	105	112	90	103
	Western	108	89	97	118	90	112
TSI (0-100)	Eastern	79	60	70	70	56	62
	Central	81	57	65	73	52	61
	Western	70	55	64	77	61	69

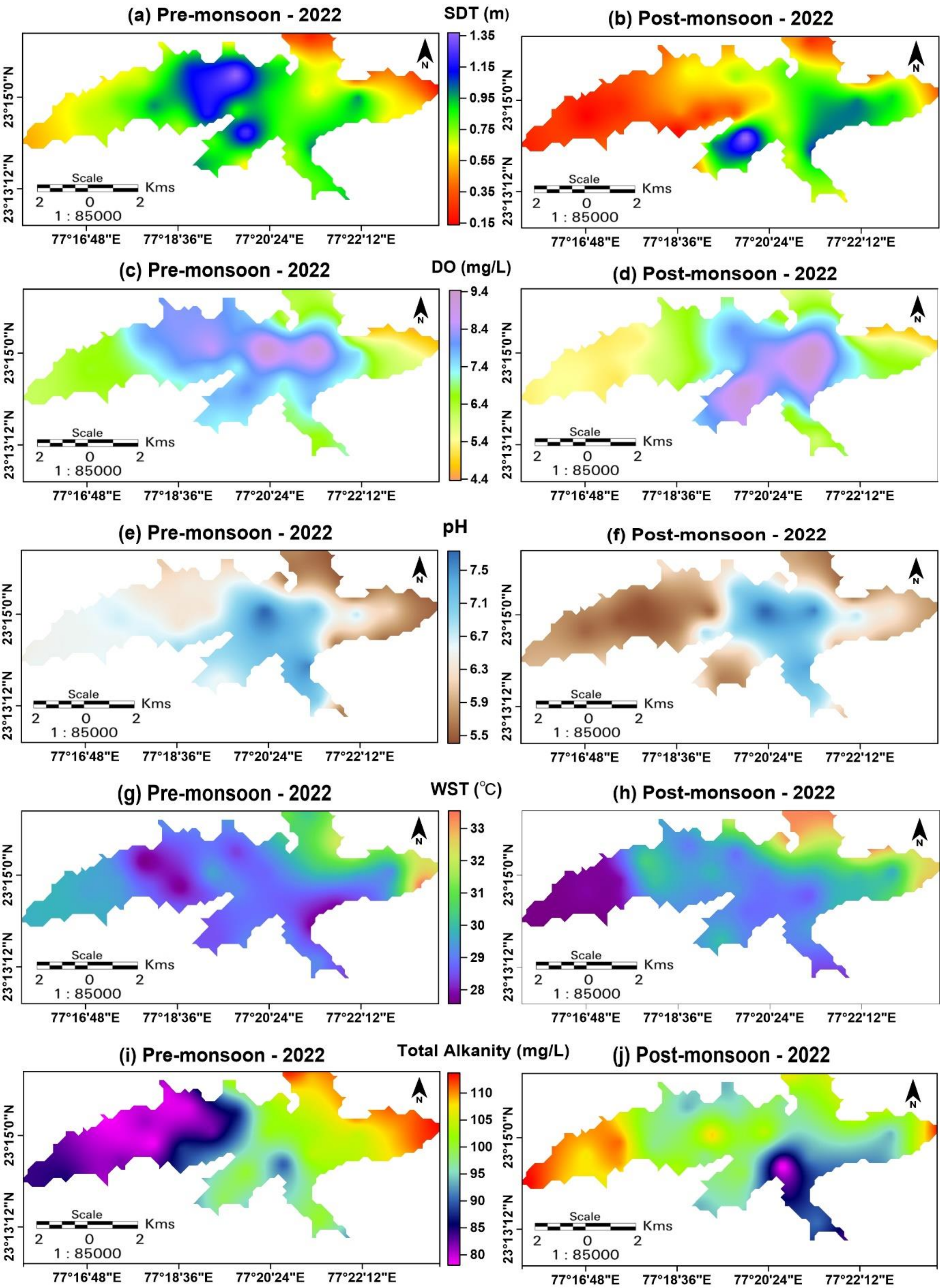

Fig.4 (a - j). Spatial distribution pattern of SDT, DO, pH, WST and Total Alkalinity of Upper Lake, Bhopal in pre- and post-monsoon season, 2022

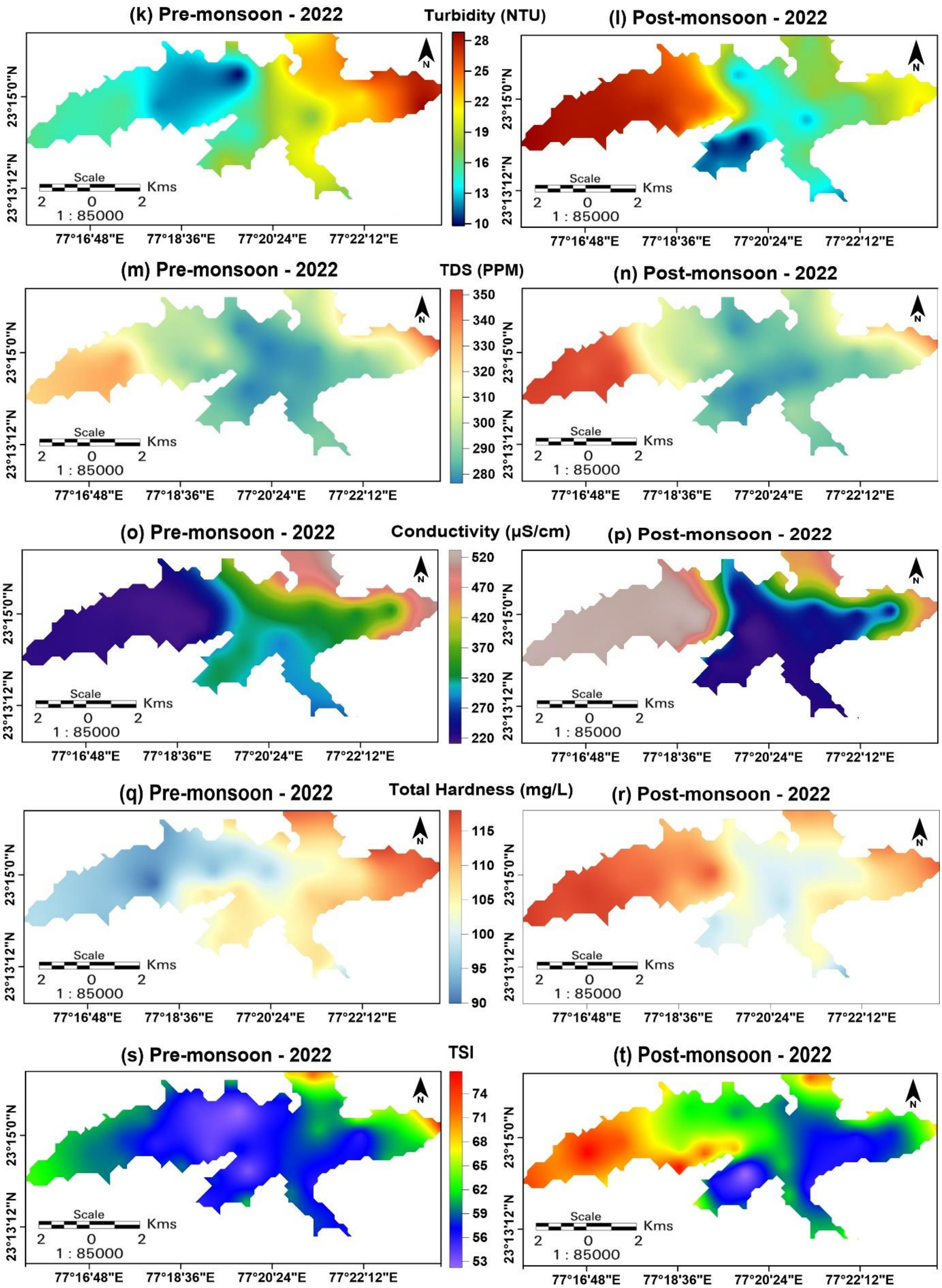

Fig.4 (k - t). Spatial distribution pattern of Turbidity, TDS, Conductivity, Total Hardness and TSI pattern of Upper Lake, Bhopal in pre- and post-monsoon season, 2022

4. DISCUSSION

The spatial variation of SDT of Upper Lake, Bhopal is examined in the pre- and post-monsoon period of 2022. The SDT data shows that all three sectors of the lake water had low transparency (less than 1 m), except some areas of the central sector that showed clear water in both seasons (Fig. 4(a,b)). During the pre-monsoon period of 2022 (Fig. 4a), SDT shows the highest to lowest values vary from 1 m to 0.1 m, 1.3 m to 0.2 m, and 1.4 m to 0.5 m in the eastern sector, central sector, and western sector, respectively. Similarly, in the post-monsoon season of 2022 (Fig. 4b), SDT values varied from 1.3 m to 0.4 m, 1.8 m to 0.3 m, and 1 m to 0.3 m in the eastern sector, central sector, and western sector, respectively. However, the average values of SDT in the western sector of the lake are observed to be 0.8 m and 0.6 m in pre- and post-monsoon seasons, respectively, that shows less SDT during post-monsoon than the pre-monsoon season. This is because of the influx from the Kolans River, which contains inorganic and organic contaminants and releases the most quantity of silt and sediment from the river drainage system during the time of monsoon and post-monsoon seasons (Sharma & Tamot, 2010). The eastern sector of the lake is observed high SDT during both the seasons. This is due to the discharge of polluted water from medical colleges and sewage inputs from urban localities (Gupta et al., 2020). The average values of SDT in the seasons of pre- and post-monsoon season of 2022 are determined 0.7. m and 0.8 m, respectively.

Fig. 4(c,d) illustrates the spatial pattern of DO concentration in Upper Lake, Bhopal, in both pre- and post-monsoon seasons of the observation period 2022, which value ranges from 4.4 mg/L to 9.4 mg/L. It is found that the high concentration of DO is noticed in the central sector of the lake (8.4 to 9.4 mg/L), whereas the lowest DO is observed in the northeastern parts of the lake (4.4 to 5.4 mg/L) during both the seasons of 2022. This is due to the mixing of pollutants into the lake water by various anthropogenic activities like sewage, hospital waste, and inorganic waste (Talwar et al., 2014). In the pre-monsoon season of 2022 (Fig. 4c), DO shows the highest to lowest values varying from 7.5 mg/L to 4.2 mg/L, 9.6 mg/L to 6 mg/L, and 8.6 mg/L to 6.1 mg/L in the eastern sector, central sector, and western sector, respectively. Similarly, in the post-monsoon season of 2022 (Fig. 4d), DO values varied from 6.9 mg/L to 4.5 mg/L, 8.4 mg/L to 5.6 mg/L, and 7.4 mg/L to 5.2 mg/L in the eastern sector, central sector, and western sector, respectively. However, the average value of DO in the western sector of the lake was observed to be 7.2 mg/L and 5.9 mg/L during the pre- and post-monsoon seasons, respectively, which shows less DO during the post-monsoon than the pre-monsoon season. This is because of the influx of the Kolans River water, which discharges a maximum amount of nutrients coming from various agricultural waste during the monsoon and post-monsoon seasons (Farooq et al., 2021). The average amount of DO in the pre- and post-monsoon seasons of 2022 are observed to be 6.9 mg/L and 6.3 mg/L, respectively.

Fig. 4(e,f) depicts the spatial pattern of pH level of the Upper Lake, Bhopal, in the pre- and post-monsoon period of 2022, which ranges from 5.4 to 8.6. This depicts the pH levels of the whole lake are alkaline except for some parts in the central sector. Similarly, Fig. 4 (e,f) reveals the lake water is highly alkaline (5.5 pH) in the eastern sector of the lake during both the pre- and post-monsoon period and the western sector of the lake in the post-monsoon period only. This is because of inputs from various anthropogenic activities and agricultural waste, respectively (Bano & Chuahan, 2017). In the pre-monsoon season of 2022 (Fig. 4e), photosynthetic activity gets reduced due to higher temperatures, resulting in a slight buildup of CO_2 concentration in the lake water with a subsequent decrease in pH (Nisar et al., 2022). In the post-monsoon season of 2022 (Fig. 4f), the western sector of the lake has a higher pollution level than the pre-monsoon season. This is because of large input of land and river runoff into the lake during the post-monsoon season (Talwar et al., 2014). The pH concentration in the Upper Lake catchment area is primarily influenced by freshwater influx and monsoonal rainfall variability. The high pH concentration is also linked with the presence of numerous aquatic weeds in the lake water. Because of the absorption of CO_2 from the water column, weeds' photosynthetic activities may cause the lake water to become somewhat more alkaline. In the pre-monsoon season of 2022 (Fig. 4e), pH shows the highest to lowest values vary from 6.8 to 5.4, 7.8 to 5.6, and 7.1 to 6.1 in the eastern, central, and western sectors, respectively. Likewise, in the post-monsoon period of 2022 (Fig. 4f), pH values varied from 7.3 to 5.6, 8.6 to 5.8, and 7.6 to 5.5 in the eastern sector, central sector, and western sector, respectively. However, the average pH value of the lake for both seasons was 6.4, indicating that the lake is alkaline in nature.

Temperature has a major role in the photosynthesis process and it is crucial for lake biological communities. Fig. 4(g,h) shows the spatial pattern of WST of the Upper Lake, Bhopal in the pre- and post-monsoon period of 2022, which ranges from 18.1°C to 33.7°C. This shows a high value of WST is found in the eastern sector of the lake (32°C to 33.7°C), whereas the lowest value of WST (18.1°C to 28°C) is found in the central sector and western sector of the lake in the pre- and post-monsoon period of 2022, respectively. As it is high exposure to various anthropogenic activities, the eastern sector suffers high WST during both seasons. In the monsoon and post-monsoon seasons, due to the discharge of the Kolans River water along with other runoff activities, the western sector of the lake remains low WST than other areas. In the pre-monsoon period of 2022 (Fig. 4g), WST shows the highest to lowest values varying from 33.7°C to 27.8°C, 32.2°C to 27.7°C, and 29.8°C to 27.5°C in the eastern sector, central sector, and western sector, respectively. Similarly, in the post-monsoon season of 2022 (Fig. 4h), WST values varied from 22.2°C to 18.9°C, 21.8°C to 17.5°C, and 20.8°C to 17.4°C in the eastern sector, central sector, and western sector, respectively. However, the average readings of WST in the pre- and post-monsoon seasons of 2022 are observed to be 29.5°C and 19.2°C, respectively which shows pre-monsoon period has a very high WST than the post-monsoon period. This is mainly because of greater solar radiation, low water levels, clear atmosphere, and higher atmospheric temperature (Nisar et al., 2022).

Fig. 4(i,j) reveals the spatial pattern of total alkalinity concentration of the Upper Lake, Bhopal, in the pre- and post-monsoon season of 2022, which ranges from 78 mg/L to 116 mg/L. The average value concentration of alkalinity in the eastern sector of the lake Water is 109 mg/L and 105 mg/L during the pre- and post-monsoon seasons of 2022, respectively. Fig. 4(i,j) shows the concentration of alkalinity is very high in the eastern sector of the lake in both pre- and post-monsoon period. This is due to the factors such as decomposition of organic matter and influx of domestic wastewater, which release carbonate and bicarbonate ions in these areas (Magarde et al., 2006). In post-monsoon period, the western sector of the lake experiences high concentrations of alkalinity due to inputs from agricultural waste. The lowest concentration of alkalinity is found in the western sector and southern part of the lake during pre- and post-monsoon period, respectively. The concentrations remain low in the central part of the lake throughout the year. During the pre-monsoon season of 2022 (Fig. 4i), the concentration of alkalinity shows the highest to lowest values varying from 114 mg/L to 103 mg/L, 113 mg/L to 86 mg/L, and 103 mg/L to 78 mg/L in the eastern sector, central sector, and western sector, respectively. Similarly, during the post-monsoon season of 2022 (Fig. 4j), the concentration varied from 116 mg/L to 97 mg/L, 110 mg/L to 86 mg/L, and 115 mg/L to 88 mg/L in the eastern sector, central sector, and western sector, respectively. However, the average values of concentration of alkalinity in the pre- and post-monsoon period of 2022 are observed 95 mg/L and 104 mg/L, respectively.

Fig. 4(k,l) depicts the seasonal fluctuations of turbidity of the Upper Lake, Bhopal, in the pre- and post-monsoon period of 2022, which ranges from 4.3 NTU to 28.8 NTU. The highest concentration of turbidity is noticed on the eastern side and the western side of the lake (more than 25 NTU) in the pre-monsoon and post-monsoon seasons, respectively. This is due to the mixing of inputs from various anthropogenic activities and the inflow of river water, respectively (Singh & Samartha, 2021). Fig. 4(k,l) depicts the maximum amount of turbidity in the northeastern side as compared to other parts of the lake during both seasons. This may be due to various urban setups and anthropogenic activities in these areas. The low amount of turbidity was found in relatively central parts of the lake; this could be due to less impact of river water and other anthropogenic activities (Kumar & Chaudhary, 2013). During the pre-monsoon season of 2022 (Fig. 4k), the concentration of turbidity shows the highest to lowest values varying from 20.4 NTU to 14.3 NTU, 16.2 NTU to 7.1 NTU, and 11.9 NTU to 4.3 NTU in the eastern sector, central sector, and western sector, respectively. Similarly, during the post-monsoon season of 2022 (Fig. 4l), the concentration of turbidity varied from 23.1 NTU to 15.7 NTU, 26.8 NTU to 9.5 NTU, and 28.8 NTU to 10.8 NTU in eastern sector, central sector, and western sector, respectively. However, the average amount of turbidity of the lake in the pre- and post-monsoon seasons is observed 11.6 NTU and 19.8 NTU, respectively, which shows the post-monsoon season has a very high amount of turbidity than the pre-monsoon season. This is because of the influx of sediments and organic matter from surrounding areas. This is attributed to the runoff water from rain bringing clay, sand, and organic matter from adjoining areas into the lake, which causes the rise of turbidity levels (Shrivastava & Bhat, 2021).

Fig. 4(m,n) shows the spatial pattern of TDS of the Upper Lake, Bhopal, in the pre- and post-monsoon period of 2022, which ranges from 266 PPM to 352 PPM. The results reveals that the high TDS is found except some parts in the central sector. A high amount is observed in the eastern sector and western sector of the lake during both the seasons. This is because of human actions such as washing, recreational activities, and inputs of agricultural waste, respectively (Magarde et al., 2009). In the pre-monsoon period of 2022 (Fig. 4m), TDS amount shows the highest to lowest values vary from 328 PPM to 274 PPM, 299 PPM to 266 PPM, and 312 PPM to 267 PPM in the eastern sector, central sector, and western sector, respectively. Similarly, in the post-monsoon season of 2022 (Fig. 4n), TDS amounts varied from 346 PPM to 287. PPM, 316 PPM to 276 PPM, and 352 PPM to 278 PPM in the eastern sector, central sector, and western sector, respectively. However, the average quantity of TDS in pre- and post-monsoon period of 2022 is observed as 287 PPM and 306 PPM, respectively, which shows the post-monsoon period has a very high TDS amount than the pre-monsoon period.

Fig. 4(o,p) shows the spatial pattern of electrical conductivity of Upper Lake, Bhopal in the pre- and post-monsoon season of 2022, which ranges from 215 µS/cm to 521 µS/cm. The high range of conductivity are found in the eastern sector of the lake during both the seasons and the western sector of the lake in the post-monsoon season only. This is because of inputs from domestic sewage and agricultural waste, respectively (Magarde et al., 2009; Singh & Samartha, 2021). The low conductivity is found in the western sector and central sector of the lake during pre- and post-monsoon period, respectively. The western sector has great variations of conductivity from pre-monsoon to post-monsoon season, with average values showing 244 µS/cm and 463 µS/cm, respectively. During the pre-monsoon season of 2022 (Fig. 4o), the conductivity shows the highest to lowest values varying from 505 µS/cm to 321 µS/cm, 496 µS/cm to 215 µS/cm, and 383 µS/cm to 215 µS/cm in the eastern sector, central sector, and western sector, respectively. Similarly, during the post-monsoon season of 2022 (Fig. 4p), the conductivity values varied from 476 µS/cm to 238 µS/cm, 512 µS/cm to 218 µS/cm, and 529 µS/cm to 218 µS/cm in eastern sector, central sector, and western sector, respectively. However, the average values of conductivity are observed as 325 µS/cm and 384 µS/cm in the pre- and post-monsoon period of 2022, respectively. This shows the post-monsoon period has greater electrical conductivity than the pre-monsoon season.

The term "hardness" refers to the qualities of highly mineralized water. Fig. 4(q,r) shows the spatial distribution of total hardness of the Upper Lake in the pre- and post-monsoon period of 2022, which ranges from 89 mg/L to 118 mg/L. The high value of total hardness is found in the eastern sector of the lake during both the seasons and the western sector of the lake in the post-monsoon season only. The eastern sector experiences a high value of total hardness due to stormwater runoff from concrete surfaces, roads, and domestic wastewater inflows carrying a substantial load of dissolved salts and minerals into the lake (Magarde et al., 2009). This includes calcium-rich construction debris and domestic detergents, which dissolve in the rainwater and flow into the lake. Meanwhile, in the western sector found high value is due to agricultural runoff from limestone-rich soils and the addition of chemical fertilizers in the agricultural areas contributes additional calcium and magnesium ions, especially during heavy rainfall when soil erosion is pronounced (Singh & Samartha, 2021). The low value of total hardness is found in the western sector and the central sector of the lake in the pre- and post-monsoon period, respectively. The western sector has great variations of total hardness from pre- to post-monsoon period, with average values showing 97 mg/L and 112 mg/L, respectively. During the pre-monsoon period of 2022 (Fig. 4q), the total hardness shows the highest to lowest values vary from 118 mg/L to 105 mg/L, 115 mg/L to 94 mg/L, and 108 mg/L to 89 mg/L in the eastern sector, central sector, and western sector, respectively. Similarly, in the post-monsoon season of 2022 (Fig. 4r), the total hardness values varied from 116 mg/L to 102 mg/L, 112 mg/L to 90 mg/L, and 118 mg/L to 90 mg/L in the eastern sector, central sector, and western sector, respectively. However, the average total hardness values were determined as 103 mg/L and 108 mg/L for the pre- and post-monsoon period of 2022, respectively.

The TSI variation is a key index for evaluating lake transparency (Carlonson, 1977; Kratzer & Brezonik, 1981). Fig. 4(s,t) shows the spatial pattern of in-situ measured TSI of the Upper Lake, Bhopal, in the pre- and post-monsoon period of 2022 respectively, which ranges from 52 to 81. The high concentration of TSI values is found in the northeast part of the eastern sector of the lake during both the seasons and the western sector in the post-monsoon season only. The eastern sector mainly results in high TSI concentration due to inputs from various anthropogenic activities like hospital waste, sewage, bathing, washing, etc. However, the western sector during post-monsoon results in high TSI concentrations because of the intrusion of river water and agricultural runoff (Singh et al., 2016). The low value of TSI concentration is found in the central sector of the lake in both the seasons of 2022. The western sector experiences high variations of TSI from pre-monsoon to post-monsoon season, with average values shows 64 and 69, respectively. In the pre-monsoon period of 2022 (Fig. 4s), the TSI concentration shows the highest to lowest vary from 79 to 60, 81 to 57, and 70 to 55 in the eastern sector, central sector, and western sector, respectively. Similarly, during the post-monsoon season of 2022 (Fig. 4t), the TSI concentration values varied from 70 to 56, 73 to 52, and 77 to 61 in the eastern sector, central sector, and western sector, respectively. However, the lake's average TSI value for both seasons was 65, indicating that the lake is hypereutrophic.

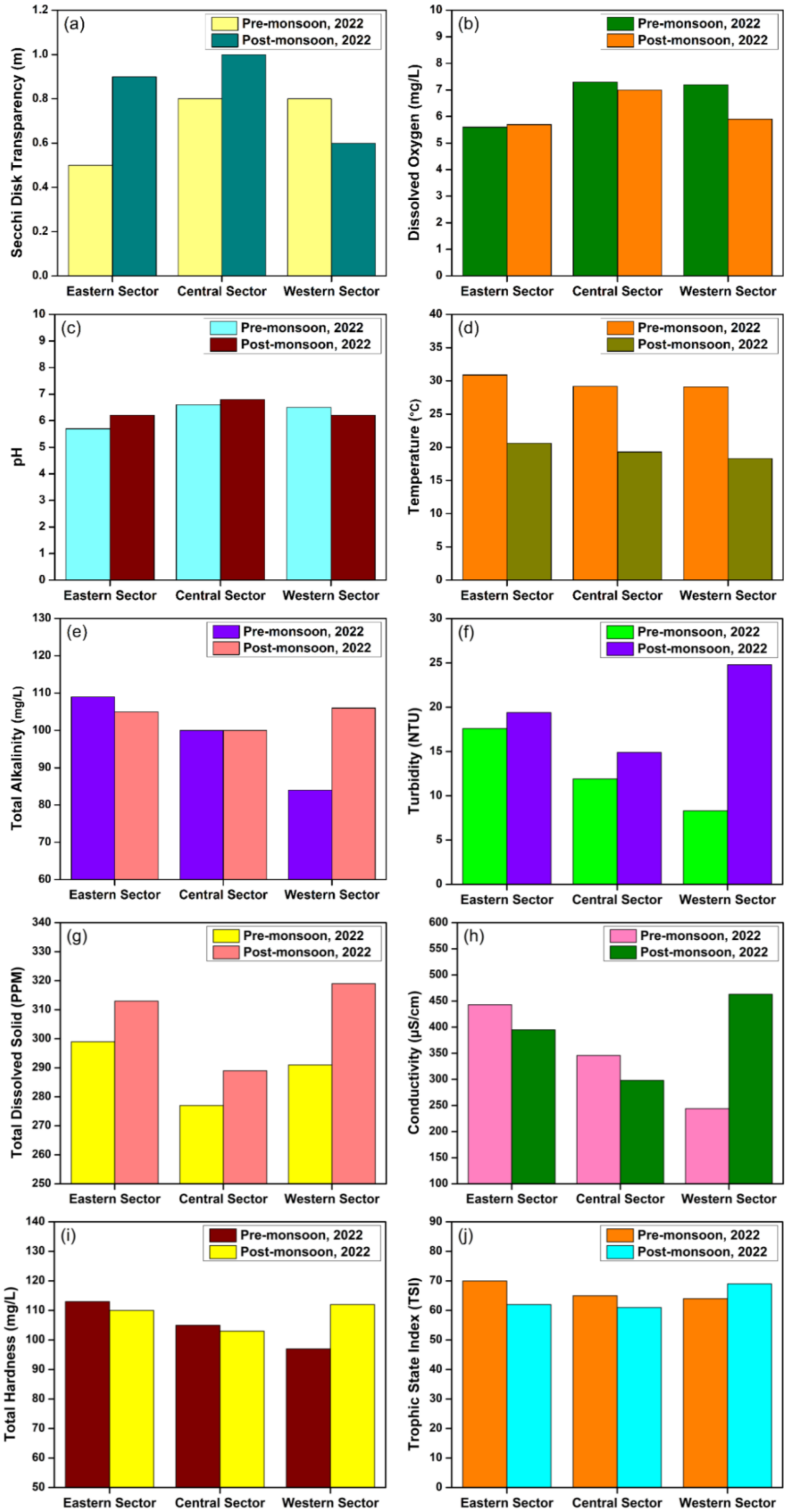

Fig. 5. Sector-wise comparison of average value of physiochemical parameters and TSI of Upper Lake, Bhopal during pre- and post-monsoon season, 2022

The Fig. 5 shows the comparative analysis of the average values of in-situ measurement physiochemical parameters and TSI of Upper Lake, Bhopal, across three sectors during the pre- and post-monsoon period of 2022. The central sector shows the highest average value of SDT (1.0 m) in the post-monsoon period of 2022, whereas the eastern sector shows the lowest average value of SDT (0.5) in the pre-monsoon season (Fig. 5a). In the post-monsoon season, the western sector has the lowest average SDT value (0.6 m). Fig. 5b depicts the eastern sector has the lowest average DO value during the pre-monsoon season (5.6 mg/L), while the central sector has the highest average DO value (7.3 mg/L) in the pre-monsoon season of 2022. The eastern sector exhibits the lowest average DO value (5.7 mg/L) during the post-monsoon observation period. Fig. 5c indicates that the lake's eastern sector has the lowest average pH (5.7) during the pre-monsoon season, whereas the central sector has the highest average pH (6.8) during the post-monsoon season. The post-monsoon season exhibits a higher average pH value than the pre-monsoon season during the observation period. Fig. 5d demonstrates that during the post-monsoon observation period, the western sector has the lowest average WST value (18.3°C), whereas the eastern sector has the highest average WST value (30.9°C) during the pre-monsoon season of 2022. Fig. 5e shows that during the pre-monsoon season, the western and eastern sectors have the lowest and highest average alkalinity values, respectively. During the post-monsoon observation period, the western sector has the highest average value of alkalinity (106 mg/L), followed by the central sector. Figure 5f indicates that the western sector has a low average turbidity value of 8.3 NTU in the pre-monsoon season and a maximum average turbidity value of 24.8 NTU in the post-monsoon period of 2022. Furthermore, the post-monsoon season has higher turbidity than the pre-monsoon season. Fig. 5g illustrates that the post-monsoon season has higher TDS than the pre-monsoon season. The lowest average TDS value (277 PPM) is found in the central sector in the pre-monsoon season, while the highest average value (319 PPM) is found in the western sector in the post-monsoon season of 2022. Fig. 5h shows that the western sector has the highest average conductivity (463 µS/cm) and lowest average conductivity (244 µS/cm) in the post- and pre-monsoon period, respectively. It is also noticed that the post-monsoon season, the lake experiences higher conductivity than the pre-monsoon season. Fig. 5i depicts that during the pre-monsoon season, the eastern sector has the highest average value of total hardness (113 mg/L), whereas the western sector has the lowest average amount of total hardness (97 mg/L). During the post-monsoon observation period, the central sector had the lowest average amount of total hardness (103 mg/L), followed by the eastern sector. Fig. 5j compares the average TSI value of Upper Lake, Bhopal across different sectors during the pre- and post-monsoon seasons of 2022. It shows that the average TSI value during the pre-monsoon season of 2022 in the western sector (64), central sector (65), and eastern sector (70) respectively. Similarly, in the post-monsoon season of 2022, the average measurement of TSI value was in the western sector (69), central sector (61), and eastern sector (62) respectively. It is found that the central sector has the lowest average TSI value in the post-monsoon period, whereas the eastern sector has the maximum average TSI value in the pre-monsoon season, followed by the western and central sectors. In the post-monsoon season of 2022, the western sector has the highest average value of TSI, followed by the eastern sector.

5. CONCLUSION

This study offers an extensive spatiotemporal assessment of the major physiochemical parameters and TSI of Upper Lake, Bhopal using systematic in-situ observational data. The findings highlight significant spatial and temporal fluctuations of those parameters, with some parameters exceeding BIS standards. The analysis reveals seasonal fluctuations corresponding to various anthropogenic pressures and hydrological inputs, which collectively influence the lake's ecological dynamics. The computed TSI results indicate that the lake is eutrophic to hypereutrophic state, raising concerns about the increasing nutrient enrichment and its impact on aquatic biodiversity and ecological health. To ensure the sustainable management of Upper Lake, immediate attention is required to control nutrient inflows, improve wastewater treatment, and implement conservation strategies. Regular monitoring, community participation, and eco-friendly bioremediation techniques, such as floating wetlands and buffer zones, can help restore water quality and maintain ecological balance of the Upper Lake, Bhopal. Future studies should integrate remote sensing with in-situ measurements to enhance the accuracy of long-term water quality assessments. This research gives significant information for policymakers and environmental managers in preserving the Upper Lake, which is a vital Ramsar site and lifeline of Bhopal.

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