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Assessment of Spatio-Temporal Dynamics of Dal Lake's Trophic State

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Abstract: The ecosystem of Dal Lake, an important freshwater lake in Srinagar, India, has been rapidly degraded in recent decades due to intensified eutrophication. The main causes of eutrophication were determined to be different types of human activities in the catchment area and its inappropriate development as well as excessive loads of pollutants introduced into the lake. The heightened algal blooms brought significant water quality deterioration, a reduction in indigenous fish populations, and a general disturbance of the ecological balance of the lake. Such changes adversely influenced the living conditions of the inhabitants depending on the lake for tourism, fishing, and other economic pursuits. The aim of the research was the evaluation of the specificity of the course and spatio-temporal dynamics of Dal Lake eutrophication process on the base of accurate assessment of its actual trophic state. The applied assessment methodology was based on the biotic balance approach. As an indicator of the biotic balance in water, the Index of Trophic State (ITS) was chosen and adopted for the conditions of the lake ecosystem in humid subtropical climate conditions. The assessment was based on data from a five-year lake monitoring period (2019–2023) and analyzed for four lake basins: Hazaratbal, Nishat, Nagin, and Gagribal. The results indicated a steady increase in the lake's trophic status, with the Hazaratbal basin evolving from mesotrophic to eutrophic, while the other basins progressed from meso-eutrophic to eutrophic during the research period. At the end of the research period, the whole lake was classified as eutrophic, with a modest inclination towards heightened eutrophication severity. The research underscores the pressing need for elaboration of a holistic lake management approach, where ITS, which has proven to be a valuable and reliable express-monitoring tool, can be used for obtaining information necessary for solving different applied tasks for protection and conservation strategies.

Keywords: eutrophication; Dal Lake; trophic state assessment; balance approach; water management

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1. Introduction

Dal Lake is a unique water body due to its natural features, ecological significance, and socio-economic importance, as well as its role in the development of the region and the well-being of its inhabitants. "The Jewel in the Crown of Kashmir" and "Srinagar's Treasure" are the names given to Dal Lake. It is also the second largest lake in the state, located in the east of the city of Srinagar—the biggest city in the valley and the summer capital of the Indian-administered Jammu and Kashmir in the disputed Kashmir region (Figures 1 and 2). Dal is a freshwater urban lake, and the most visited place in Srinagar by tourists and locals, but it is threatened by excessive anthropogenic activity [1]. The

aim of the research was the evaluation of the specificity of the course and spatio-temporal dynamics of Dal Lake's eutrophication process on the base of the accurate assessment of its actual trophic state, that is necessary for further development of the lake management strategy. The research results will constitute the basis for developing the concept for the lake protection against further degradation as a result of eutrophication.

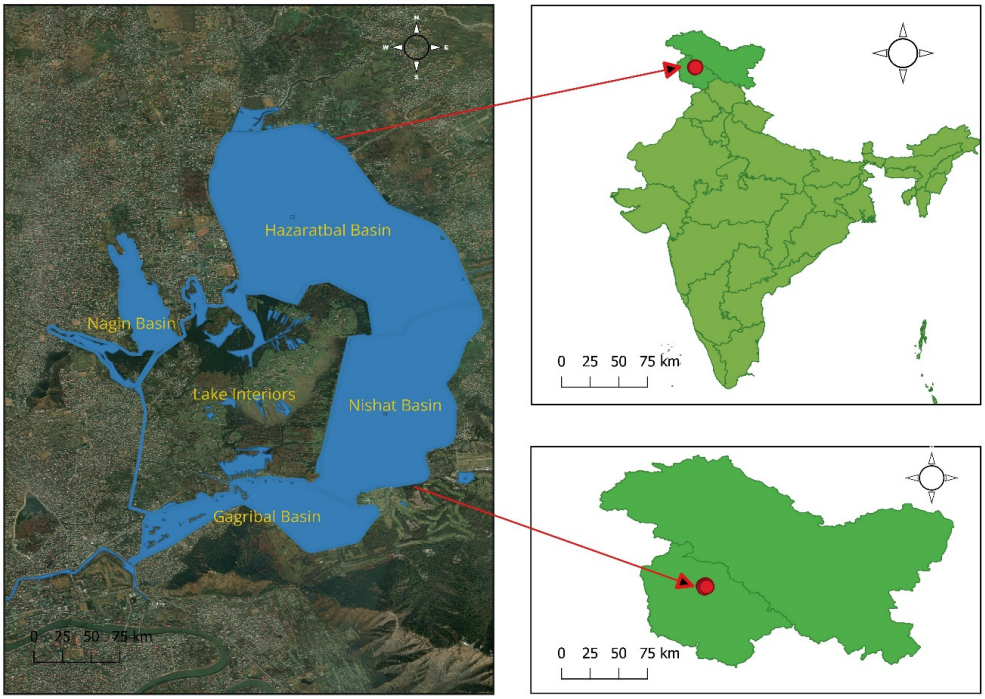

Figure 1. Dal Lake in Srinagar.

Figure 2. Winter view of Dal Lake (author: Irfan Ali).

The origin of the lake remains unresolved. The origin of the lake is thought to be either glacial or fluvial; scientists are undecided. Another theory suggests that the lake originated from volcanic activity. Some geologists believe that Dal Lake is the remnant of the Pleistocene oligotrophic lake that once covered the entire valley of Kashmir, while others claim that Dal Lake is a floodplain lake [2,3].

The Kashmir valley exhibits intense seismic activity and falls in Zone V of the 1984 Bureau of Indian Standards of Seismic Zoning map of India [4]. It can be expected that the frequent destruction is caused by earthquakes of magnitude IX and higher in this highly dangerous zone. Dal Lake is located at the foot of Mount Zabarwan, a branch of the Himalayan chain, with poorly porous rock within the catchment area and the presence of numerous springs. The lake lies east and north of Srinagar and covers 18 km^2, and it is part of a natural wetland that covers 21.1 km^2, including its floating gardens (sometimes the area is indicated within 22–24 km^2). The main inflow is the Telbal Nallah channel from the Marsar Lake. The main outflows are two regulated channels: Dal Gate and Nallah Amir Khan. The lake's major surface water supply is the glaciers from the upper belt of the Dachigam, which has an area of around 337 km^2. The lake is also supplied by groundwater sources and abundant springs [2,3]. The lake is located at an altitude of 1538 m [4]. The hydrological balance for Dal Lake is presented in Table 1.

Table 1. Hydrological balance of Dal Lake [4].

Values, m^3/day	Precipitation	Inflow	Ground Water	Outflow	Evaporation
Minimum	5427	53,885	31,279	112,110	0.00
Maximum	161,443	1,474,422	674,484	2,489,742	0.44
Average	53,591	618,622	276,484	949,436	0.24

The five linked basins that comprise the major drainage system of the lake are the Nehru Park basin, the Nishat basin, the Hazratbal basin, the Nigeen basin, and the Barari Nambal basin. All these basins are connected by causeways. Dams divide the main lake from the lakes Nishat, Hazratbal, Nagin, Barari Nambad, and Nehru Park. Transportation connectivity to all five basins is provided via the navigation canals that connect the lakes (Figure 3) [5].

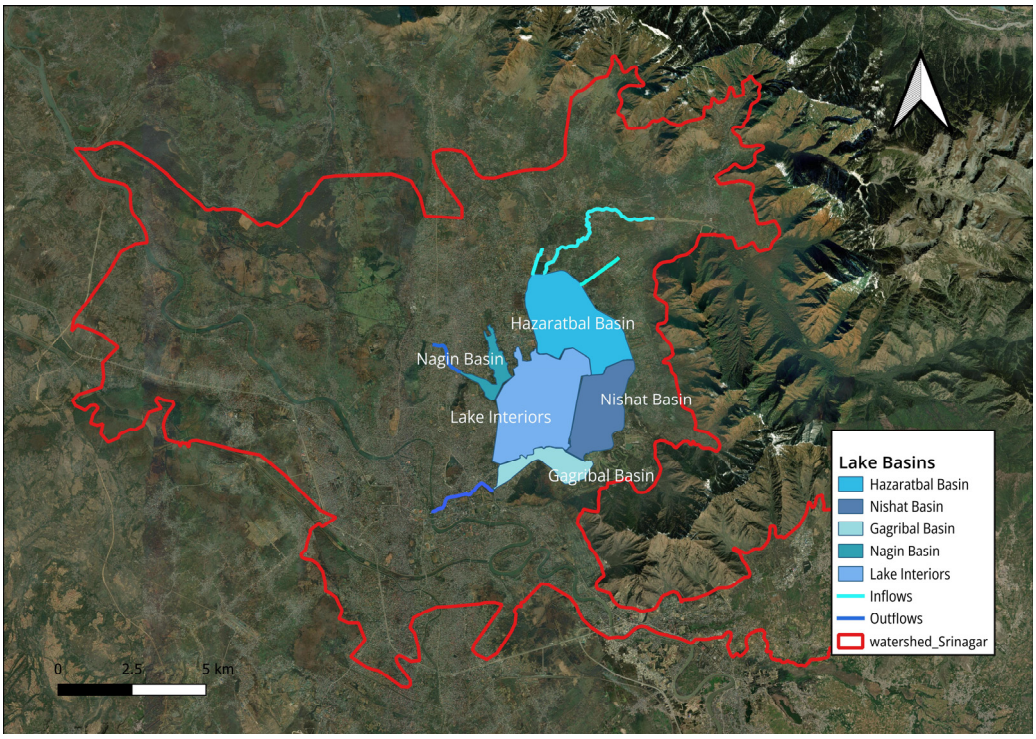

Figure 3. The inflows, outflows, and the basins of Dal Lake.

The depth of Dal Lake ranges from 6 to 2.5 m; the length is 7.44 km, and the width is 3.5 km. The bathymetric map for appropriate basins of Dal Lake is presented in Figure 4 [6].

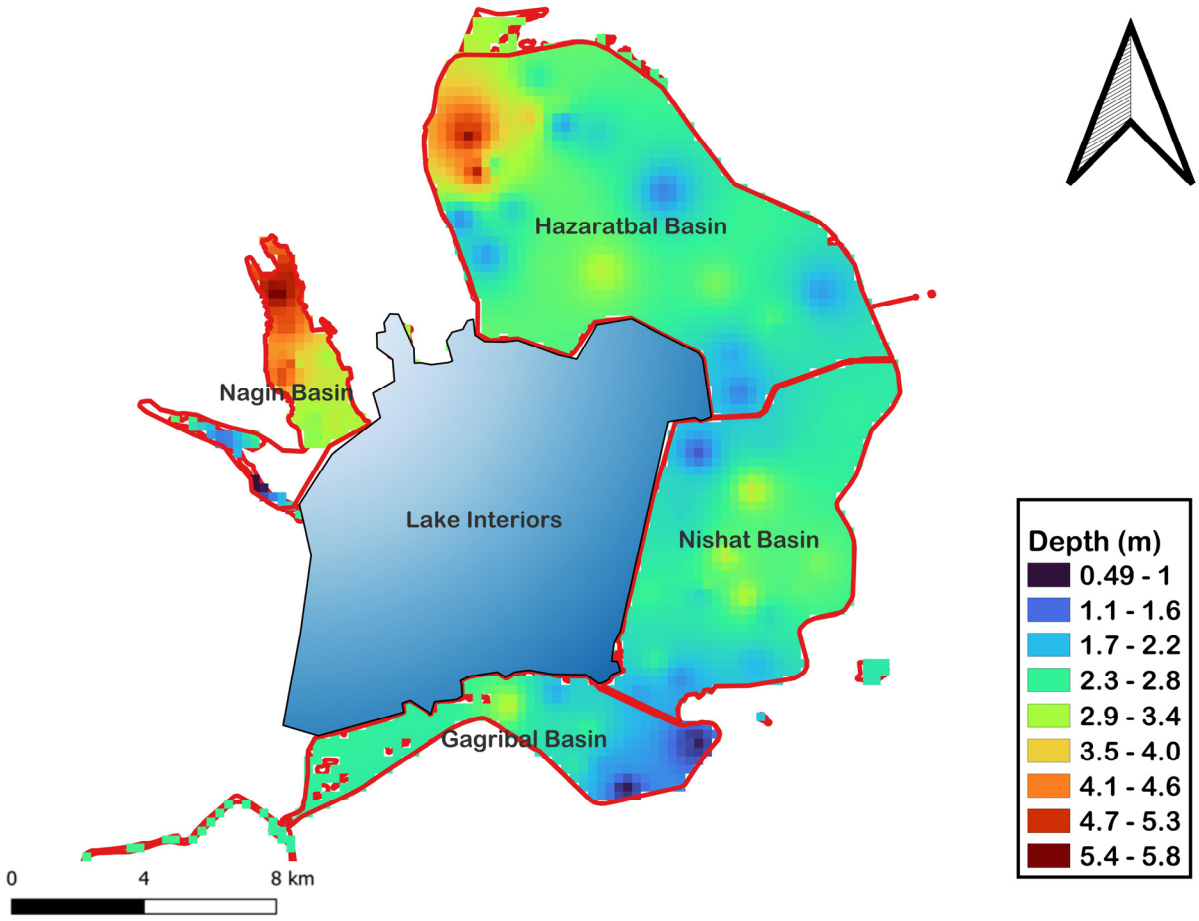

Figure 4. The bathymetric map of Dal Lake.

The main characteristics of Dal Lake are presented in Table 2.

Table 2. Basic characteristics of Dal Lake.

Characteristics	Description
Catchment area	316 km^2
Inflow	291.9 mln m^3
Outflow	275.6 mln m^3
Max length	7.44 km
Max width	3.50 km
Surface area	18–22 km^2
Max depth	6 m
Average depth	1.42 m
Water volume	983 mln m^3
Residence time	22.16 days
Shore length	15.5 km
Surface elevation	1.583 m
Islands	Char China, Son Lank

Dal Lake is a warm monomictic lake, indicating that it has thermal stratification for most of the year. The lake's water temperature fluctuates between 1° and 11 °C in the winter, and between 12° and 30 °C in the summer. In the winter, air temperatures may

drop to as low as −11 °C, sometimes resulting in the freezing of the lake. There are two islands in the lake that slow down the flow of water, so on one edge, the lake has retreated, leaving many swamps, with plans to drain them and build residential areas [4].

2. Catchment Area Development

Dal Lake has suffered in response to anthropogenic catchment area development and land cover change. The lake lies within the habitable zone, covering 316 km^2 in the Zabarwan Valley and the Kashmir Valley, surrounded by the Himalayas. Since the middle of the 19th century, the morphometric features of the lake have undergone constant changes, mainly under the influence of anthropogenic activity in the catchment area, especially during the last 40 years. The increase in population numbers, intensive urbanization processes, the development of agriculture, fishing, and tourism sectors, and the expansion of the lake's interior, among other activities, contributed to these changes [7].

The evolution of the lake and the changes in the ways of developing the lake catchment area are shown at Figure 5, together with the dynamics of changes in the lake and wetland system surfaces and shoreline length changes, The expansion of lake interior, floating gardens, and the areas of aquatic vegetation development are also presented. The authors of the studies [7–9] stated the decrease up to almost 25% during 1962–2013 period of the lake surface during the 155-year period and significant degradation of the ecological state of the lake ecosystem (water surface decrease, eutrophication, deterioration of water quality, and reduction in biodiversity).

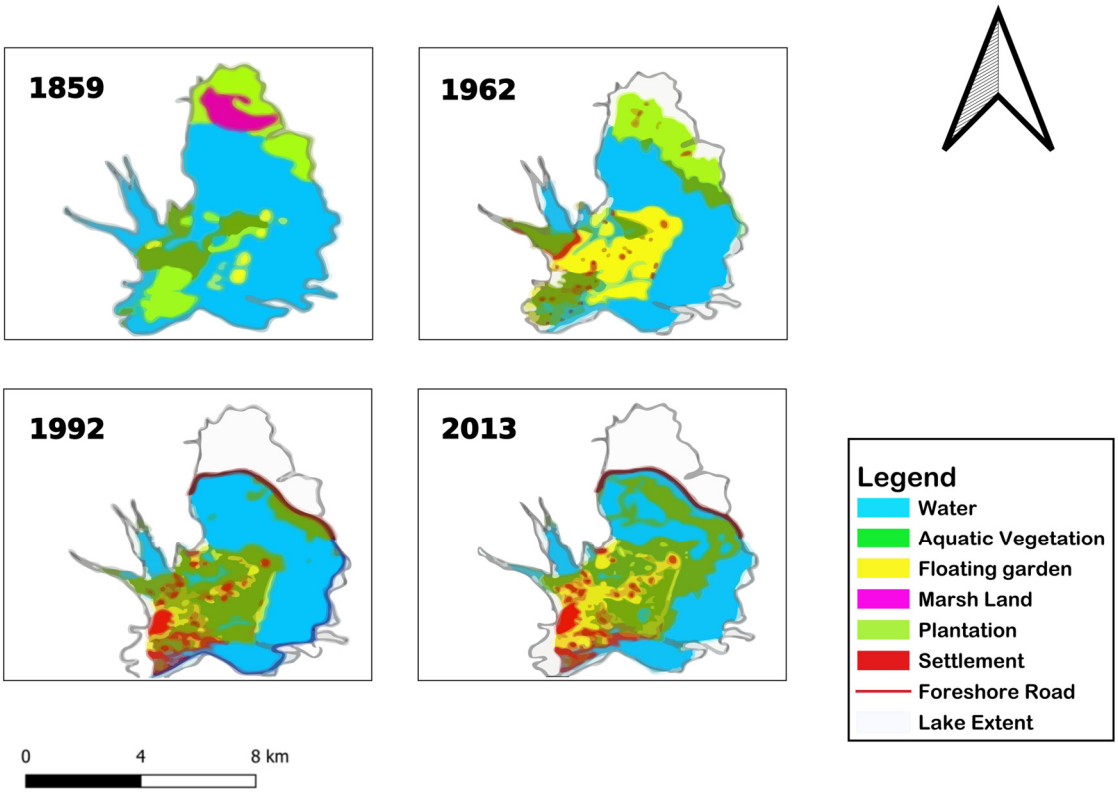

Figure 5. Dal Lake and catchment area evolution [10].

3. Pollution of Dal Lake

There are several significant sources introducing great loads of pollution into Dal Lake, which are represented by surface runoff from agricultural lands and built-up areas, discharge of insufficiently treated sewage from the treatment plant, sanitary sewage from households directly disposed into the lake, and intra-lake sources of pollution related to

the generation of sewage, and other kinds of pollution from houseboats and hotels within the lake basins.

The ongoing causes of pollution that lead to eutrophication can be classified into three main groups. The first group is known as non-point sources (surface runoff from agricultural and residential area), accounting for 55% of total pollution load. The second group consists of point sources (mainly sewage discharge from sewage treatment plants and directly from households), which make up 25% of the pollution load. Lastly, houseboats and hotels contribute 20% to the overall pollution. These sources represent the entirety of pollution impacting the water body; nonetheless, non-point sources remain the predominant contributors [7].

Currently, Dal Lake is home to the majority of Srinagar's over 900 houseboats (Figure 6). Nearly 50,000 people reside within the lake area, and the houseboats can accommodate a further 10,000. There are different kinds of structures in these hamlets. There are 775 houseboats, 328 doonga boats (small houseboats), 4210 pucca houses (permanent houses), and 3493 huts in the lake, which are the source of around 9000 tons of municipal waste enter the lake every year. The houseboats and doonga boats occupy 139,716 m^2 of water area, while the pucca houses and huts occupy 248,120 m^2 and 6096 m^2 of lake area, respectively [7]. Dal Lake receives lots of sewage from the houseboats. According to the Lake Conservation and Management Authority (LCMA), 9–10 tons of household garbage is collected every day from houseboats, hamlets, and villages on the lake and from open water surfaces, including inflow and outflow canals [11,12].

Figure 6. View of Dal Lake and boat house (author: Irfan Ali).

In addition to the intra-lake sources of pollution, there are also significant sources of pollution from the 5 million people living in the catchment area of the lake. There are also 15 major drains from Srinagar that carry sewage into the lake. According to the 2020 report of the J&K Pollution Control Board, Srinagar City generates 201,000 m^3 of sewage daily. However, only 53.800 m^3 can be treated in activated sludge technology, in Fluidized Aerobic Bioreactors (FABs) or Sequential Batch Reactors (SBRs), considering the existing

treatment facilities' capacity [12]. Around 73% of untreated sewage is discharged into Dal Lake or the Jhelum River, flowing through Srinagar City [13]. The location of sewage treatment plants (STP) is shown in Figure 7.

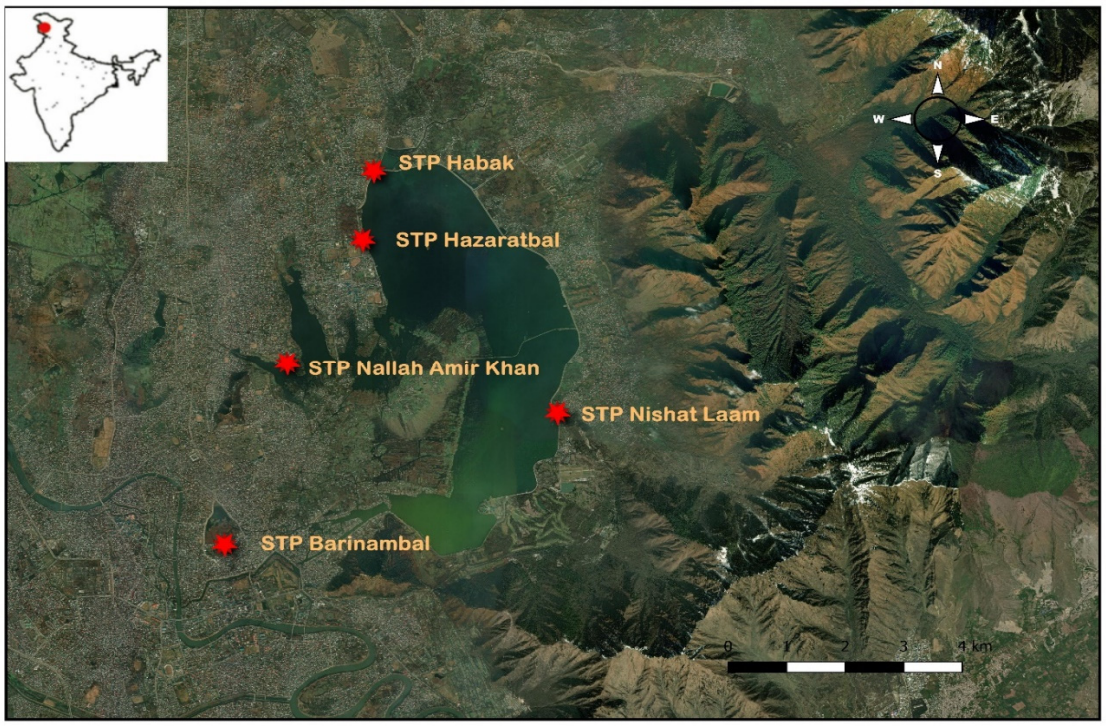

Figure 7. Location of sewage treatment plants within Dal Lake catchment area.

Another problem Dal Lake faces is siltation. About 40,000–50,000 tons of allochthone material, including the biogenic matter from the catchment area, are discharged into the lake through the Telbal and Maloori Nallahs [14]. It brings shallowing of the lake and the intensive development of water vegetation (Figure 8).

Figure 8. Garbage in the rivers and canals feeding the lake (author: Irfan Ali).

The main cause of degradation and drastic deterioration of water quality in Dal Lake is the eutrophication process. Eutrophication is a global phenomenon that is practically unavoidable and has a progressive impact on aquatic ecosystems across various countries

and continents. The cause of anthropogenic eutrophication is excessive supply of nutrients, creating conditions for the increase in water productivity and accelerated vegetation development. The concentration of nutrients in water is the initial trigger of eutrophication, but its development intensity depends on many factors: climatic, hydrological, geological, biological, morphological, and anthropogenic. Excess vegetation development at a definite stage of the eutrophication process may lead to disturbance of the ecosystem equilibrium and degradation of water quality. Due to their morphometric features, lake ecosystems, especially valley lakes in densely populated and urbanized catchment areas, are extremely sensitive to eutrophication. Dal Lake is just such a type of ecosystem, and the situation is further complicated by the intensive anthropogenic exploitation of the lake basin and its biological resources (Figure 9).

Figure 9. Water blooms in Dal Lake (author: Irfan Ali).

4. Materials and Methods

The scope of eutrophication monitoring process of Dal Lake is quite limited due to the local barriers (legislative, financial, and organizational shortcomings) and mainly covers the basic hydro-chemical parameters. To make a reliable assessment of the trophic status of Dal Lake and its spatio-temporal dynamics, two different methods were used: (1) assessment based on a set of traditional eutrophication indices and (2) assessment based on the integral trophic index ITS developed based on the so-called balance approach.

4.1. Assessment Based on Traditional Indices

Reliable and operational quantitative assessment of the trophic states of waters is very important when choosing a strategy to protect aquatic ecosystems against the negative effects, and is the basis for eutrophication process management. Traditionally, the trophic state of reservoirs and watercourses are assessed based on many hydrobiological characteristics: abundance, biomass and species composition of aquatic vegetation, photosynthesis rate, chlorophyll concentrations, as well as nutrient content, and many others. The limit values of the above-mentioned indices given by different authors differ, which results primarily from the diversity of geographical areas studied by individual authors and from the fact that the course of the eutrophication process in different aquatic ecosystems depends on their morphometric, hydrological, hydrobiological properties, climatic conditions and the type of development of the catchment area. The scale of the discrepancies in the numerical values of selected indices is demonstrated in Table 3.

Table 3. Boundary values of trophic levels indicators [15].

Indicators	Ultra-Oligotrophic	Oligotrophic	Mesotrophic	Eutrophic	Hypertrophic
Total nitrogen, mg/L	<0.2	0.2–0.4	0.3–0.65	0.5–1.5	>1.5
Total phosphorus, mg/L	<0.005	0.005–0.04	0.01–0.06	0.025–0.1	>0.1
Transparency, m	6–12	8–64	1.5–8.0	0.7–2.0	>0.7
Saturation with oxygen,%	-	>90	60–90	40–60	<40
pH in summer	-	6.9–7.2	7.2–8.0	8.0–9.5	-
Primary production, mg/m^{2}xday	0–50	50–300	100–1000	250–1500	-
Pphytoplankton an. gC/m^2	0–10	10–30	30–300	70–300	200–4000
Chlorophyll-a, mg/L	0–1	1–40	2–60	7–1000	>1000
Phytoplankton biomass, g/m^3	<0.2	0.2–0.5	0.5–30	0.8–10	>10
Number of bacteria, mln cells/L	-	<0.5	0.5–1.5	2–4	-

4.2. ITS Assessement Method

There are also widely used assessment methods based on aggregated indicators, such as the Carlson Index (TSI–Trophic State Index) [16]. Vollenweider Index (TRIX–Trophic Index) [17] and others. The assessment systems developed by different institutions and organizations, e.g., the Water Framework Directive (WFD) 2000/60/EC, Helcom, are also used [18].

An essential aspect when assessing eutrophication is determining the trophic state of water, which reflects the metabolism of the ecosystem (energy supply, accumulation, and consumption). The trophic state of water ecosystems reflects their biotic balance, i.e., the balance of production and decomposition of organic substances produced by aquatic vegetation. Hence, it follows that such an assessment approach to the trophic state allows for the diagnosis of the ecological status of the water body. Although there is no shortage of classifications and quantitative indicators for various types of water developed by various authors, the reliable assessment of the trophic levels of specific water bodies is still a serious problem, connected with its implementation and results interpretation.

Eutrophication of surface waters is a key problem in water resources management. Therefore, a very current task is to develop and apply indicators that would correspond to the goals of water resource protection and management and meet the following requirements:

- To reflect changes in aquatic ecosystems caused by anthropogenic factors and their basic functions.
- To be adaptable for different conditions, based on a limited number of data, and easily interpretable.
- To be suitable for process forecasting and solving application tasks.
- The cost of their assessment should be moderate [15].

Considering the above features, an appropriate methodology was selected to achieve the intended research objective. The authors used an original methodology to assess the trophic state of the water in Dal Lake based on the ITS, which reflects the state of the biotic balance in waters; this is calculated based on Equation (1) [19]. Boundary values of the ITS index are presented in Table 4.

$$\mathrm{ITS} = \frac{\sum \mathrm{pH}}{\mathrm{n}} + \mathrm{a}\ (100 - \frac{\Sigma[\mathrm{DO\%}]}{\mathrm{n}}) \quad (1)$$

where

pH—pH value;
[DO%]—water saturation with oxygen percentage;
a—slope coefficient of pH-DO% linear regression;
n—number of measurements.

Table 4. ITS boundary values for different water trophic state [19].

Type of Water	ITS Value
Dystrophic	<5.7–6.0
Ultra-oligotrophic	6.0–6.6
Oligotrophic	6.7–7.3
Mesotrophic	7.4–8.0
Eutrophic	>8.0

The justification for choosing the method of the trophic state assessment based on ITS is the following:

- ITS allows for an accurate assessment of the trophic status depending on the biotic balance in the water, which is a fundamental characteristic of any aquatic ecosystem;
- it is based only on two common hydro-chemical parameters of water quality, which are extremely important in the absence of regular monitoring and its limited scope;
- it is simple, cheap, and easy to interpret and allows for efficient and quick operational monitoring;
- it allows for a retrospective assessment of the trophic state of water in the absence of data on traditional eutrophication indicators in the past (chlorophyll, nutrients, transparency, etc.);
- being a numerical indicator, ITS constitutes the basis for formulating mathematical prognostic models and to solve engineering application tasks, ensuring an effective lake management system [15].

The reliability of the ITS index application has been verified by different authors in the assessment of many rivers, lakes, dams, reservoirs, and coastal sea waters [20–26]. Sources of information also confirmed the validity of using ITS in the studies of aquatic ecosystems in California, Bolivia, and China, and the reliability of the results.

4.3. Data Bank

The assessment of Dal Lake's trophic state was carried out based on the data bank of lake monitoring carried out by the J&K Lake Conservation and Management Authority (J&K LCMA) during the 5-year period 2019–2023 in 10 monitoring points located as shown at Figure 10.

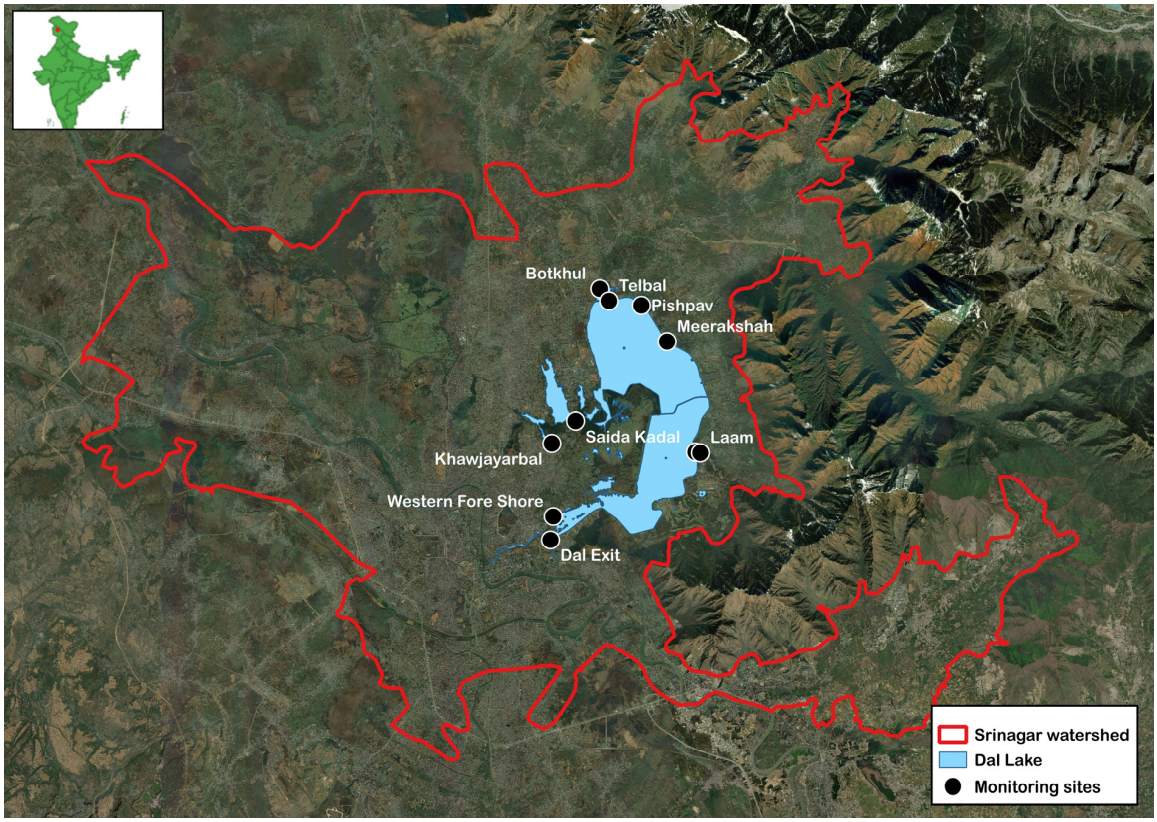

Figure 10. The map with monitoring points location.

The necessary data bank consisted of the values of the following hydro-chemical parameters: pH values, water saturation with oxygen (DO%), total phosphorus (TP), and total nitrogen (TN), measured synchronously at specified measurement points, on average, three times monthly. The total number of the parameters' values accepted for analysis was 1664. Average annual values of pH, water saturation with oxygen, TP, and TN for separate basins are presented in Tables 5 and 6. The data are normally distributed and without outliers.

Table 5. Average annual values of pH and water saturation with oxygen in separate basins of Dal Lake.

Basins	2019		2020		2021		2022		2023	
	pH	DO%	pH	DO%	pH	DO%	pH	DO%	pH	DO%
Hazratbal	7.59	62.90	7.70	62.35	7.73	60.33	7.00	73.48	7.90	62.03
Nishat	7.82	52.72	7.77	55.49	7.84	62.50	7.95	70.75	7.93	63.89
Nigeen	7.63	52.59	7.77	61.59	7.96	65.23	8.05	79.48	7.90	58.68
Gagribal	7.69	54.89	7.77	55.03	7.85	60.72	7.94	74.97	7.90	59.34

Table 6. Average annual values of TP and TN in separate basins of Dal Lake.

Basins	2019		2020		2021		2022		2023	
mg/L	TP	TN	TP	TN	TP	TN	TP	TN	TP	TN
Hazaratbal	1.65	0.88	2.50	1.00	0.83	0.93	0.75	0.76	0.64	0.81
Nishat	1.67	0.97	0.79	0.86	0.81	0.89	0.75	0.76	0.58	0.84
Nagin	3.94	2.35	5.69	1.84	0.75	1.07	0.78	0.75	1.93	1.10
Gagribal	2.55	1.57	2.03	1.42	0.64	0.78	0.71	0.70	0.42	0.60

5. Results of the Assessment

5.1. Assessment Based on Traditional Indices-Results

The assessment was based on monitoring data concerning the content of nutrients, the values of pH, and water saturation with DO% in individual lake basins. The scope of monitoring in the period 2019–2023 did not cover the traditional hydrobiological indicators; therefore, the assessment of the trophic state was limited only by the available parameters: DO%, pH value, TN, and TP (Tables 5 and 6). The results of the assessment are presented in Figure 11.

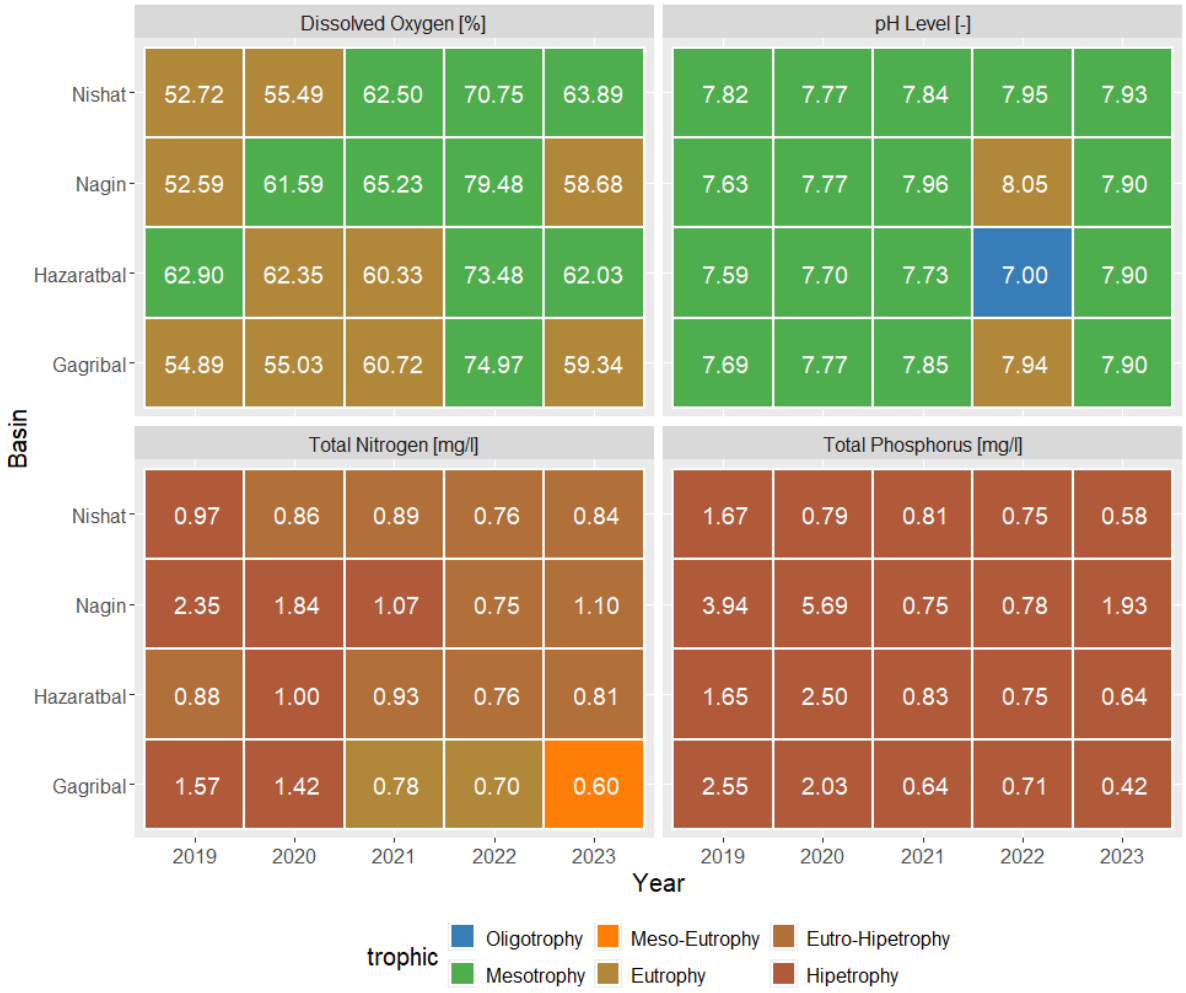

Figure 11. Dal Lake trophic status assessment based on the values of traditional indicator set.

The results of the assessment based on the values of traditional trophic indicators give very divergent results. Indicators based on boundary values developed for different types of water by different authors do not allow for a reliable assessment of the trophic state and its dynamics, and the assessment is characterized only by a certain probability.

From the assessment based on a set of traditional indicators, it can be concluded that nitrogen and phosphorous compounds (as pressure factors), especially phosphorus, qualify the studied lake basins as hypertrophic or in a borderline state between eutrophy and hypertrophy. While the pH value and DO% (indicating the aquatic ecosystem response) points out a mesotrophic or borderline meso-eutrophic state. This approach does not allow for a reliable assessment of the actual trophic state because it is not developed or adapted to the specific conditions of the studied water body, and does not consider its specificity. It also does not allow for precise tracking of the dynamics of changes.

5.2. ITS Assessment Method Results

The prerequisite for using the selected ITS index is the existence of a linear relationship between pH and DO%, which occurs in waters where the eutrophication process takes place. The correlation analysis was carried out to determine the nature of the relationship between the examined parameters and to verify the validity of using the selected ITS indicator to assess the trophic status of Dal Lake. The weighted average values of pH and DO% from the 5-year measurement period constituted the basis for correlation analysis.

Data analysis included cleaning and removing outliers; statistical analyses were conducted at the significance level of alpha = 0.05. Pearson's linear correlation coefficient (r) was used to test the strength of the relationship between pH and DO%. The value of r = 0.97 was obtained. The parameter *a* was determined from the regression line between pH and the DO%. The regression analysis result is presented in Figure 12.

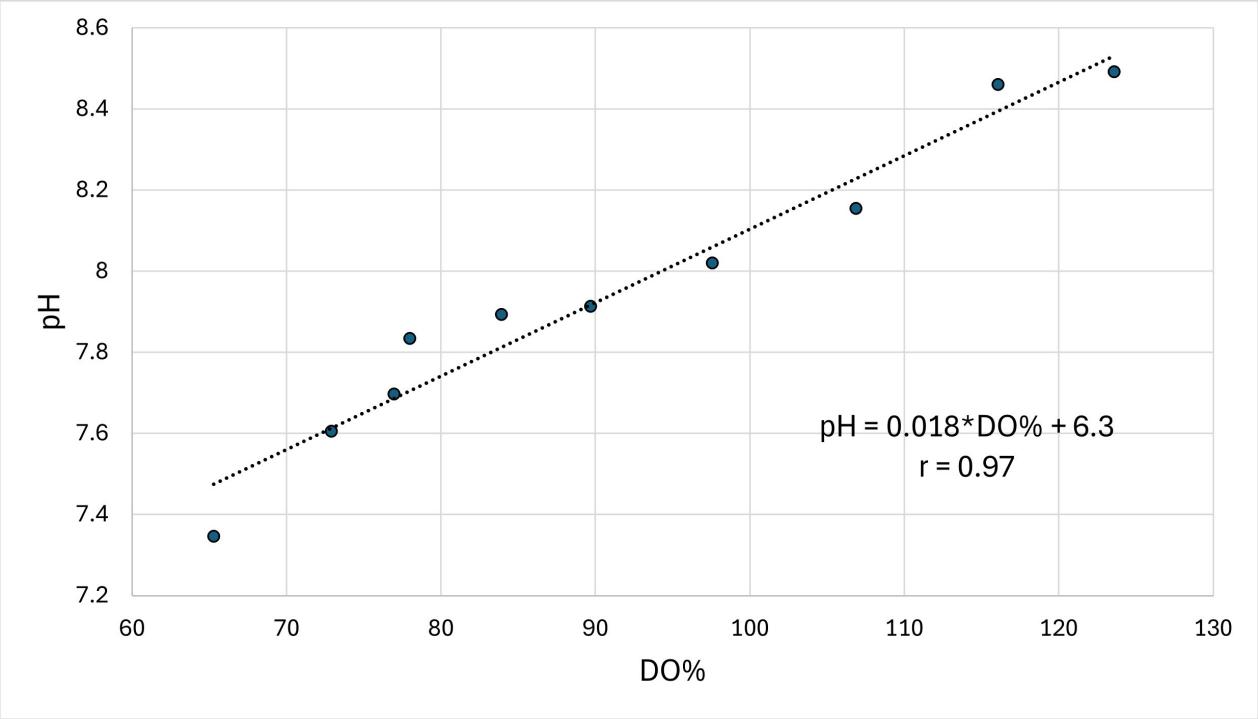

Figure 12. Relationship between pH and DO%.

A very strong correlation, characterized by the correlation coefficient value, r = 0.97, confirmed the validity of the selected method for assessing the trophic state with the help of the ITS index, and allowed for the generation of a regression equation, adapted to the conditions of the investigated water body, as the basis for calculating ITS index values and, therefore, the trophic state.

The obtained results of the assessment of trophic conditions in individual basins are presented in Figures 13–17, and illustrate the temporal and spatial changes in the trophic state of Dal Lake in the studied period.

The calculated values of the ITS index indicated a consistent increasing trend of its values and corresponded to a systematic increase in the trophic level in each of the studied basins and the whole ecosystem of the lake. If, in 2019, the lake as a whole, and its separate basins, were characterized by a borderline meso-eutrophic state, then in each subsequent year, the trophic level increased consistently, and in 2023, the lake reached the borderline of eutrophic–hypertrophic state.

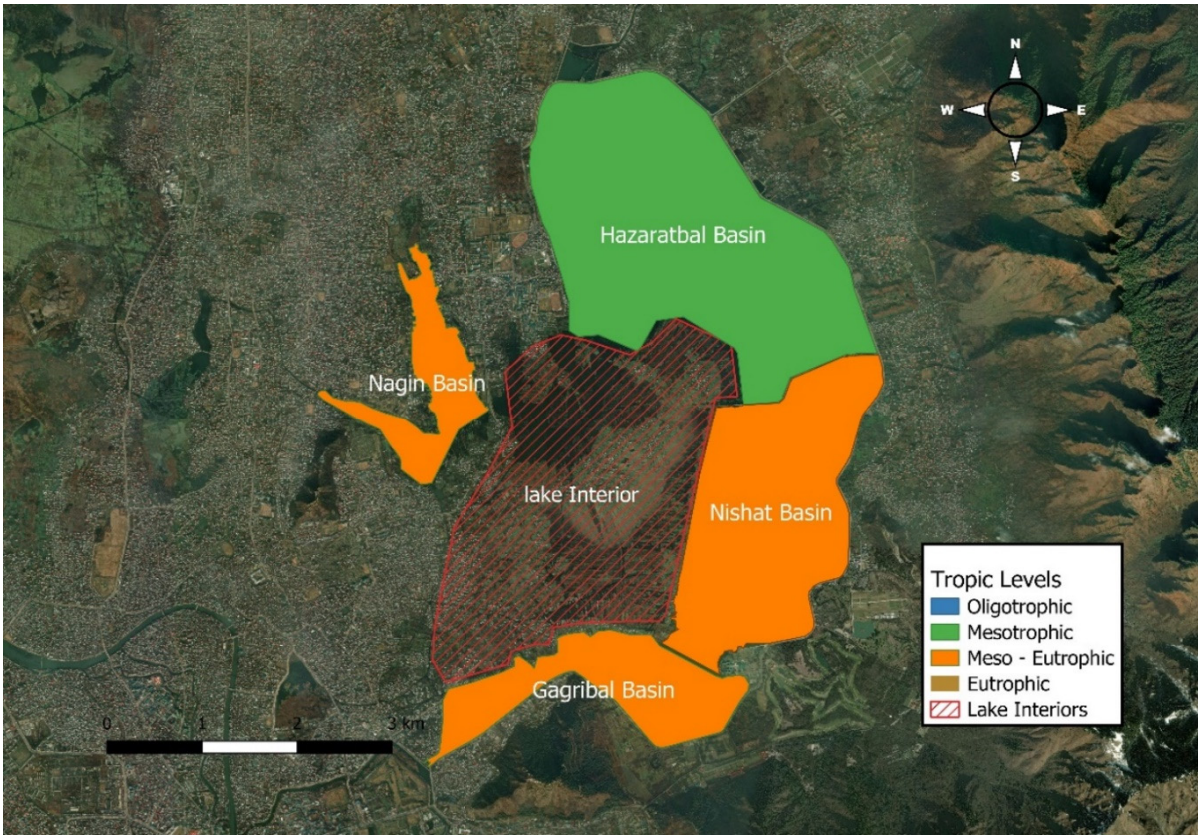

Figure 13. The results of trophic state assessment in different lake basins in 2019.

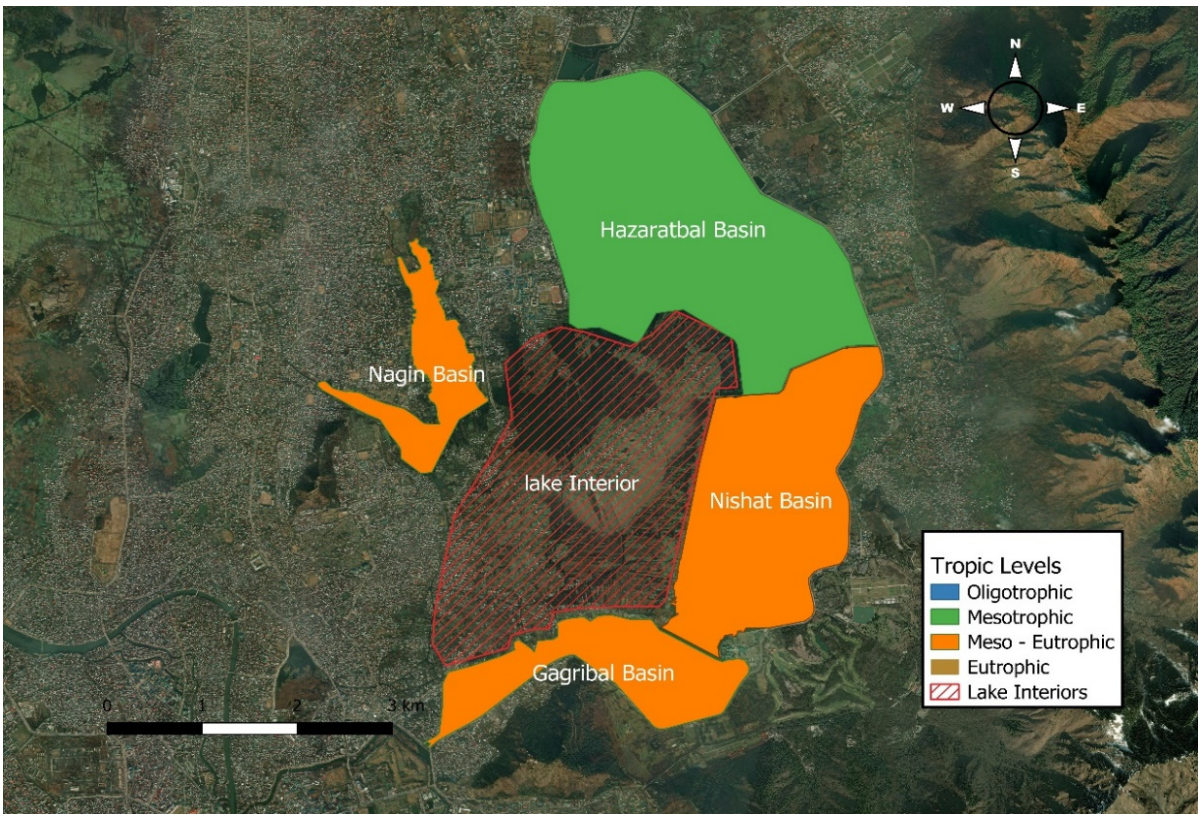

Figure 14. The results of trophic state assessment in different lake basins in 2020.

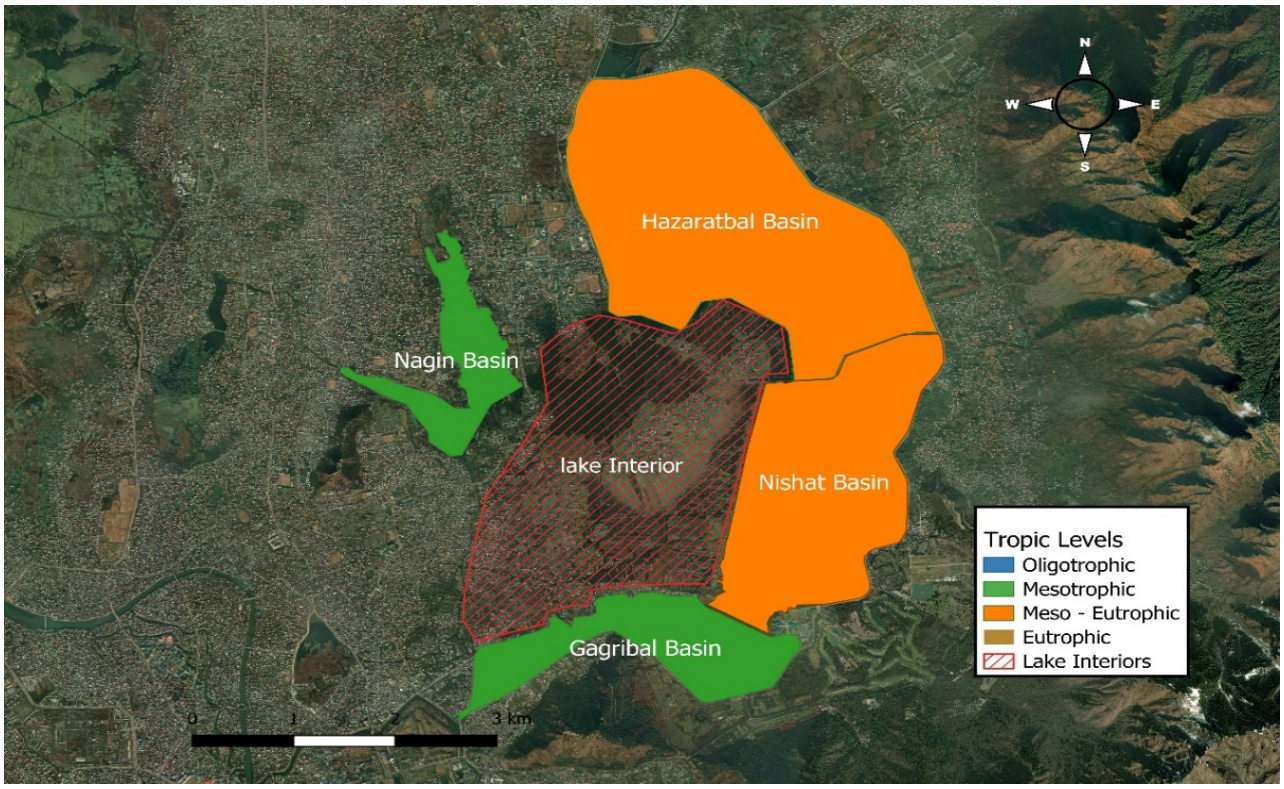

Figure 15. The results of trophic state assessment in different lake basins in 2021.

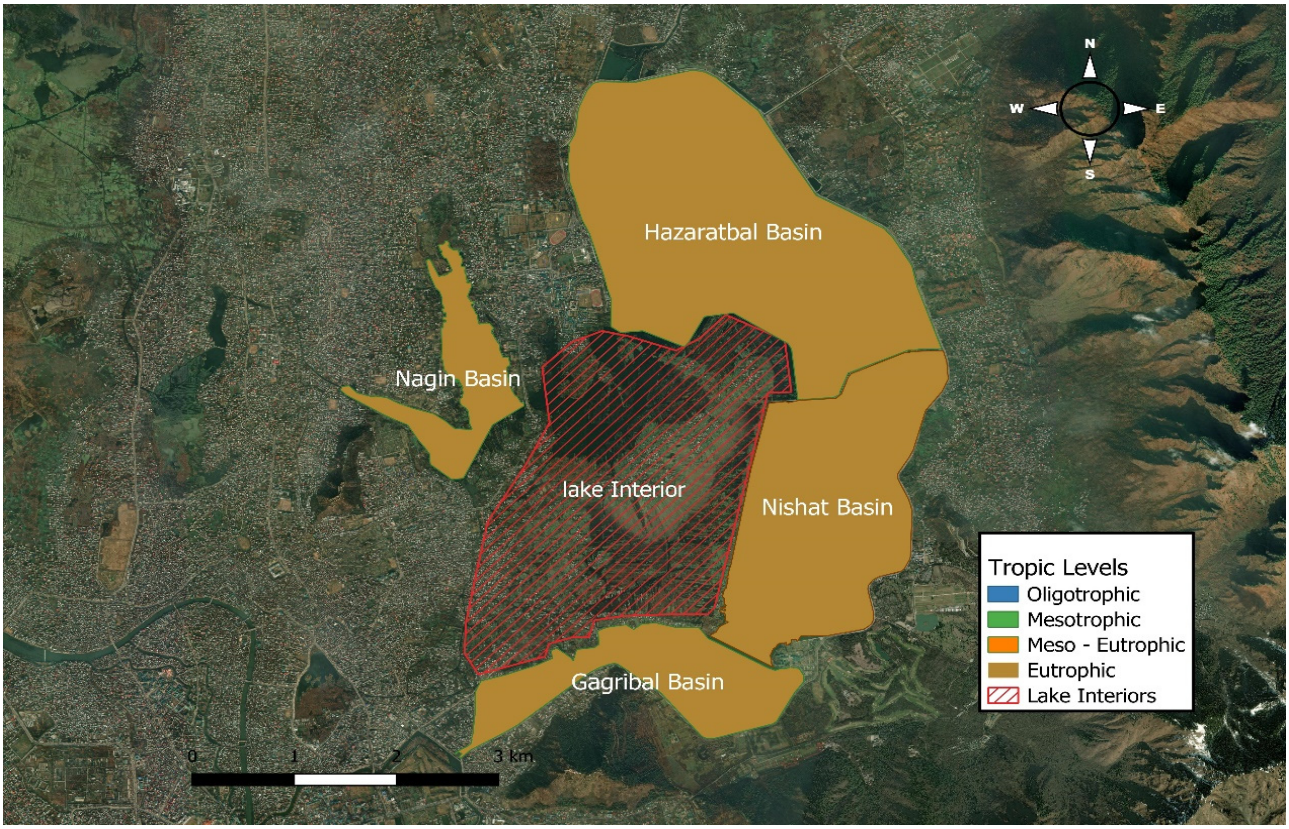

Figure 16. The results of trophic state assessment in different lake basins in 2022.

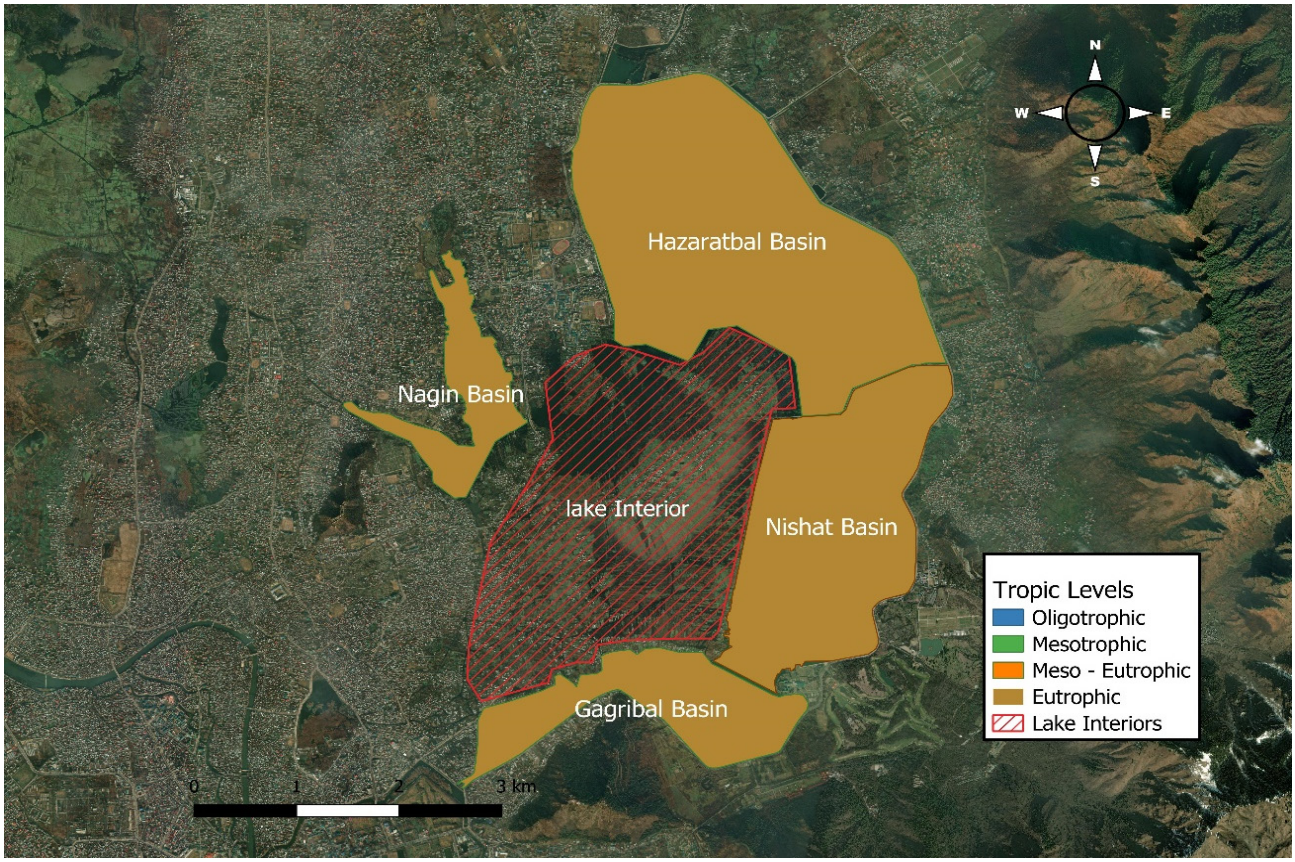

Figure 17. The results of trophic state assessment in different lake basins in 2023.

The results of analysis of the dynamics of eutrophication processes development in the five-year period studied are presented in Figure 18. The figure shows a very clear, disturbing trend of a constant increase in the trophic state, both in individual basins and in the entire ecosystem of the lake. It should be noted that in 2019, the Hazaratbal basin was characterized by the lowest mesotrophic state, which is considered optimal for the existence and breeding of fish in natural conditions. The remaining lake basins were on the border between mesotrophy and eutrophy. Over the years, the trophic state gradually increased in all lake basins, and increasingly exceeded the border of the meso-eutrophic state, reaching an advanced eutrophic state at the end of the research period, with the risk of transitioning to the hypertrophic level. One exception was the decrease in the ITS value in the Nishat basin in 2020, which, however, did not result in a change in its trophic state, but only a decrease in ITS value within boundary values for the meso-eutrophic state. Determining the exact cause of the temporary decrease in the ITS value could be due to a number of factors, such as weather conditions (e.g., temperature, precipitation, wind activity, measurement error, etc.), which would require detailed studies; this was not the aim of this research phase.

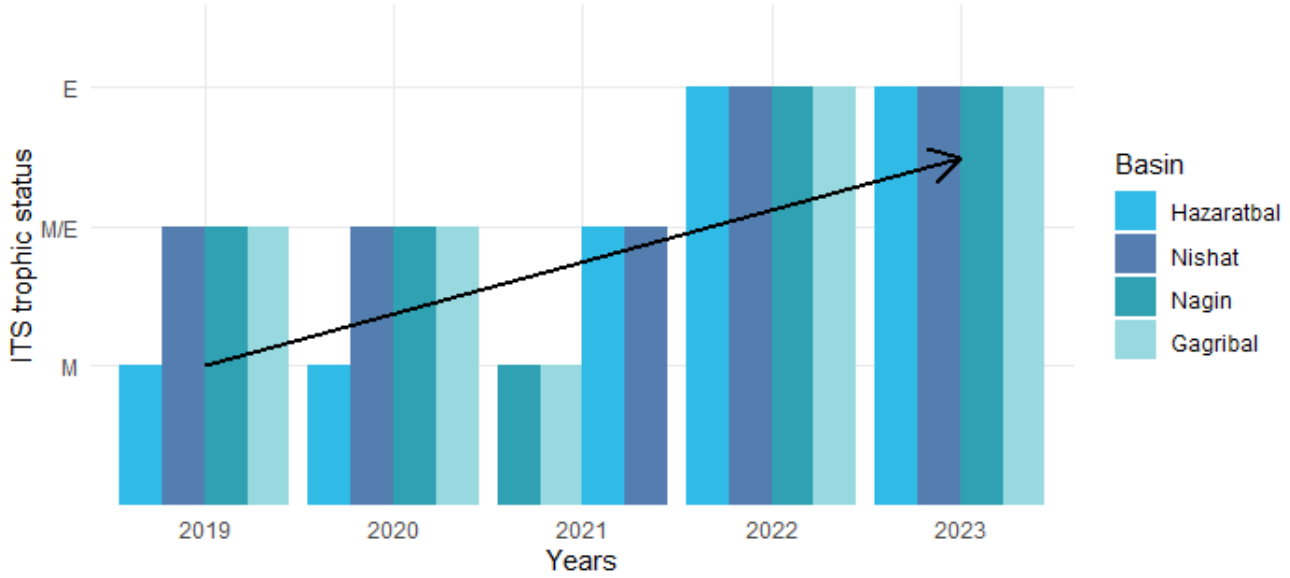

Figure 18. Increasing trend of eutrophication development in Dal Lake's basins during the period of 2019–2023.

6. Discussion

Eutrophication of surface waters is a key problem in water resources management. Therefore, a very current task is obtaining reliable information on the actual trophic status assessment of water and its time–space dynamics, which constitute the basis for further considerations and actions in order to develop appropriate strategies for aquatic ecosystem protection. The aim of this study was to assess the trophic status of Dal Lake, a site of exceptional economic and ecological importance for the Kashmir region of India, and the trends in the development process. A reliable assessment should be made based on indicators and criteria adapted to the specificity of the ecosystems studied and the individual mechanisms of their functioning in specific climatic conditions and anthropogenic pressure, considering climate change. There are many approaches to measuring the trophic state and indicators elaborated by different authors for different aquatic systems. The strategic task of this research was to select an appropriate method for assessing the trophic state, which would allow for considering very specific properties and characteristics of the studied water body. It was a difficult problem due to the limited scope of monitoring eutrophication indicators. Therefore, the assessment was carried out according to two different assessment approaches: (1) based on the values of the available set of traditional eutrophication indicators and (2) based on an aggregated indicator, ITS, which was developed to assess the state of the biotic balance of the aquatic ecosystem, as the response to different eutrophication factors. The ITS indicator was chosen because it is a simple, quick, and reliable method of measuring the trophic state of Dal Lake and its different basins without the high costs associated with taking water samples and analyzing many water parameters, especially hydrobiological ones. In particular, currently, it is in the conditions of an imperfect monitoring system and a lack of possibility of providing regular measurements of the wide spectrum of eutrophication indicators with sufficient frequency. Whereas the values of pH and DO% are the basic hydro-chemical indicators of water quality and are measured in every routine monitoring.

The results of the statistical analysis of the existing nature of the dependency between the pH value and DO% preceded the assessment in order to confirm the possibility of ITS applications for the purposes of the trophic state assessment of Dal Lake. The obtained value of the correlation coefficient ($r = 0.97$) indicates that a very strong linear relationship

exists between the two chosen variables: pH and DO%. This confirmed the validity of the selected criterion for assessing Dal Lake's trophic state, enabling the evaluation of the trophic level in individual lake basins and the analysis of its changes throughout the studied period. The assessment shows that the waters in Dal Lake have consistently increased their trophic state during the study period of 2019–2023. In 2019, the Hazaratbal basin, which makes up more than 50% of the lake's surface, exhibited a mesotrophic state, while the remaining three basins were on the verge of an initial eutrophic state. In 2020, the water in the Hazaratbal and Nishat basins changed their trophic state up to the meso-eutrophic level. In 2021, the water in the Nishat and Nagin basins reached eutrophic status. In 2022, the whole lake was characterized by eutrophic conditions. In 2023, the lake remained in a eutrophic condition, with a slight tendency toward increasing eutrophication severity within the eutrophic status.

The comparison of the assessment results based on a set of four trophic indices, and those obtained on the basis of ITS, allows for the following conclusions: (1) the assessment obtained based on the content of nutrients gives very diverse results: TP characterizes the entire lake in the studied period as hypertrophic, the assessment based on TN indicates a tendency with different dynamics to lower the trophic state in the studied period in all basins, from hypertrophic to the borderline state of eutrophy, and in the Gagribal basin-to meso-eutrophy in 2022; (2) the assessment obtained on the basis of DO% indicates a fluctuation of conditions from mesotrophic to eutrophic; (3) the pH value indicates that mesotrophic conditions prevailed in the studied period, with the exception of 2022, when eutrophic conditions occurred in the Nigen and Gagribal basins, and oligotrophic conditions occurred in the Hazaratbal basin. These very diverse assessment results, based on a set of separate indicators, cannot be considered a reliable basis for drawing conclusions about the actual trophic state due to (1) the lack of limit values dedicated to the lakes of a similar type and (2) the lack of hydrobiological indicators, which are more informative for eutrophication assessment. All this leads to an unreliable assessment result that is not suitable for practical application.

On the other hand, the results obtained based on ITS are characterized by a high level of credibility due to the following: (1) ITS reflects the integral response of the ecosystem to the factors influencing the entirety of factors that determine the trophic state of the lake; (2) ITS has been verified and adapted to the conditions of Dal Lake; (3) as a numerical indicator, ITS allows for unambiguous conclusions about the assessment of the trophic state.

The conclusions drawn based on the results of the conducted research correlate with the information provided in other scientific articles referring to the research on Dal Lake's ecological status, which clearly indicates progressive eutrophication of this ecosystem [8,13,27,28]. However, in the analyzed publications of other authors, conclusions about the trophic state of Dal Lake were drawn based on selected individual water quality parameters (mainly, nitrogen and phosphorus content, biological oxygen demand, and DO%), and allowed only a general statement about lake eutrophication. Among other things, the assessment methodology used by the authors of this article allowed for tracing the stages of the transformation of the trophic state of the lake, and even small changes in terms of time and space. The applied methodology has great potential for use in further research on the specificity of the eutrophication process in Dal Lake, for example, as a basis for formulating predictive mathematical models for various environmental application purposes as a base for water management strategy elaboration.

7. Conclusions

Dal Lake is an economically, historically, and ecologically significant freshwater lake in Kashmir. It is not only an important ecological object but also a source of income

for the inhabitants of Srinagar and a place of residence for thousands of people. It is a source of fishery and agriculture, an object of great natural value, and a center of tourism and recreation not only for the inhabitants, but also for many foreign tourists. Due to its multifunctionality and importance to regional life, Dal Lake should be under special protection. The primary issue facing the lake is the degradation of its ecosystem due to anthropogenic activities in the catchment area, resulting in primary and secondary pollution due to eutrophication and the disruption of its ecological balance. The biggest problem and cause of degradation is the phenomenon of increasing eutrophication of the lake, which has been confirmed by the conducted studies presented in the article.

The novelty of the studies consisted in (1) the application of the so-called balance approach to assess the trophic status of the studied lake for the first time; (2) the application of the ITS index for the first time to assess the eutrophication process in the lake located in humid subtropical climate conditions; (3) the adaptation of the calculation formula for the index to the specificity of the studied lake; (4) the verification of the possibility of using the chosen assessment methodology; (5) the assessment of the specificity of the course and dynamics of lake eutrophication, taking into account spatial and temporal differences within the lake and (6) for the first time, the precise assessment of the trophic status was made which allowed for capturing even small spatial and temporal differences in the advancement of the eutrophication process in the lake, about which information was not found in the literature, apart from the general statements of the fact of eutrophication.

The results of the assessment confirmed that the advanced trophic condition of Dal Lake is increasing year by year. The situation requires urgent development of a comprehensive strategy for protecting the lake from eutrophication. An appropriate assessment of the current trophic status and its dynamics is the basis of such, and an effective tool for managing water quality and determining priority actions for its protection. This strategy should be based on a systemic approach, taking into account the management of catchment area development, effective water and wastewater management, and the regulation of nonpoint runoff from agricultural and residential areas, in combination with appropriate surface water remediation methods (aeration, chemical treatment, sediment removal or capping, wetland restoration, and rehabilitation and others). In order to determine the appropriate directions for repairing the condition of the lake, it will be necessary to conduct further research in the direction of assessing the priority factors of lake eutrophication to determine the impact of the development of the catchment area on the condition of the lake's ecosystem, the research in the direction of optimizing sewage treatment technologies and increasing their efficiency and capacity, as well as selecting appropriate reclamation methods. The ecological education of residents is also very important in order to make them aware of their role in preserving this valuable natural area.

Safeguarding of Dal Lake is essential due to its ecological, economic, and cultural importance to the area and its residents. The degradation of this lake has compelled local authorities and environmental groups to undertake many restoration initiatives, including sewage treatment, weed harvesting, and coastline management. Nonetheless, these initiatives have encountered obstacles due to the intricate interaction of elements that contribute to eutrophication, including agricultural runoff, urban expansion, and climate change. Resolving these concerns requires a holistic, multi-stakeholder, and multi-sectoral strategy that integrates scientific study, policy and legislation measures, and community involvement to formulate sustainable solutions for the lake's enduring health and ecological equilibrium.

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