The changing water quality of lakes—a case study of Dal Lake, Kashmir Valley

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Abstract Lakes throughout the globe have been gravely altered or degraded at a pace much more significant than their restoration. In the heart of Srinagar, the summer capital of Jammu and Kashmir, Dal Lake, has witnessed extreme loss in water quality during the last four decades because of anthropogenic pressures. The lake is unique in that over 50,000 people inhabit the lake itself in houseboats, dongas, or islands within the lake. These people derive their livelihood from the lake in terms of tourism, agriculture, fishing, and vegetable farming. The countless ways people use the lake have led to an extreme load of pollution in the lake. Encroachment in and around the lake has led to the loss of volume of water in the lake and consequently increased the concentration of pollutants. Discharge of untreated sewage, agricultural runoff, and sediments from adjoining catchments have further degraded the lake water quality. The changes in water quality are clear from the physio-chemical properties of the lake waters. While transparency and dissolved oxygen in the lake have decreased drastically during the last 40 years, the concentration of harmful substances like phosphates, nitrates, and chlorides has increased. The hardness of water has also increased due to higher levels of carbonates and bicarbonates in the lake. This paper details the changes in the water quality of Dal Lake over the recent past. The paper analyses the strategies that can be implemented to manage the lake and restore its quality if appropriately implemented.

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Introduction

Freshwater is a limited but essential constituent of Earth's hydrosphere. It is necessary for the survival of humans, maintaining ecosystem functions, the existence of plants and animals, and for development and sustainment of economy (Loucks & van Beek, 2017). The services provided by freshwater systems are multitudinous, yet humans have failed to protect and maintain these over the years. Anthropogenic factors, such as climate change, urbanisation, pollution from industries and agriculture, nutrient loadings, sewage

discharge, and incursion of invasive plants and animals have led to rapid degradation of water quality (Ho & Goethals, 2019). The effects are more pronounced in developing countries where rapid population growth, rural–urban migrations, and economic and political developments result in extraordinary stress over land and water resources (Starkl et al., 2018; Xu et al., 2019). The water resources of Kashmir valley, especially the lakes, are no exception to this change. Dal Lake, located in the summer capital of Jammu and Kashmir, has borne the brunt of human apathy. Pollution has not only ensnared the lake waters but is jeopardizing its very existence. The lake has been destroyed over the past four decades due to excessive sewage discharge, encroachment, and weed infestation.

Dal Lake is the second-largest and the most famous lake of Jammu and Kashmir. The lake was once one of the most beautiful lakes in the world (Lawrence, 1895). However, today the statement is hardly believable, as the lake has been affected to a calamitous extent in terms of both ecology and hydrology (Ganaie & Hashia, 2020). Dal Lake has already shown the impacts of warming temperatures, variation in hydrological regime, excessive nutrient load, and invasion of non-native species. Discharge of untreated sewage from several point and non-point sources has completely deteriorated the water quality of the lake (Mushtaq et al., 2020a). The impact has been exacerbated by deforestation, grazing, agriculture, and change in land use and land cover patterns in the lake catchment (Rashid et al., 2017). These activities have increased the sediment and nutrient load in the lake waters, causing loss of water quality. In addition, large-scale encroachment and discharge of human wastes from houseboats have led to severe weed infestation of the lake (Khan & Ansari, 2005; Zargar et al., 2012). The rapid and unchecked growth of weeds, particularly Azolla pinnata, has severely affected the lake's water quality and aesthetic value (Ali, 2019; Kundangar & Abubakar, 2004). Although many locals draw their livelihood from the lake through agriculture, tourism, fisheries, etc., these activities have become a hazard to the lake (Ahmad et al., 2020).

The concentration of various pollutants in the lake water further increases due to lower hydrological inflows to the lake (Mushtaq et al., 2020b). Water that used to flow to the lake is diverted for irrigation and drinking at many places. Conversion of land under water into dry land by expanding floating gardens is another important cause of degradation. At many places, the lake has been encroached and replaced by residential areas by the local community. Furthermore, climate change in the Kashmir Himalayas has led to a significant reduction in the cryosphere, causing reduced streamflows which are an important constituent of the lake water inflows (Parvaze et al., 2016; Romshoo et al., 2015).

Several studies have been conducted to assess the water quality of Dal Lake from time to time. However, due to the dearth of long-time and continuous historic data, the changes in water quality of the lake have not been studied. During the past three decades, the lake's water quality of has changed to a drastic extent. From being famous for its crystal-clear waters to being deemed unsuitable for consumption and domestic purpose, the lake waters have seen a complete transformation. This paper aims to assess the change in water quality parameters of the lake since the 1970s with respect to the available literature on the catchment. Changes in water quality in the light of previous research over the last four decades have been studied. Important factors contributing to the depletion and degradation of the lake water quality have been documented. The paper also explains the strategies needed to implement in order to restore the lost glory of Dal Lake.

Location and extent

Dal Lake is an urban-type lake of the Kashmir Himalayas in the Srinagar city of Jammu and Kashmir. It lies between 34°5′ and 34°9′ N to 74°49′ and 74°53′ E at a mean altitude of 1583 m above mean sea level. Figure 1 shows the location of Dal Lake and its catchment area, which was extracted from the digital elevation model (DEM) of the basin using ArcGIS software. The lake catchment comprises mountain ranges on the North and Northeast side, while it is enclosed by flat arable land on other sides. The catchment is characterized by rugged terrain with high relief. It is a multi-drainage basin having a total area of 24 km^2, and the is catchment spread over 337 km^2 (Rashid et al., 2017). The lake has a total water holding capacity of 15.45 million meter cube (Mm^3), and the open water spread of the lake is nearly 10.5 km^2. Dal Lake has been the cradle of civilization of Kashmir valley and

Fig. 1 Location of study area
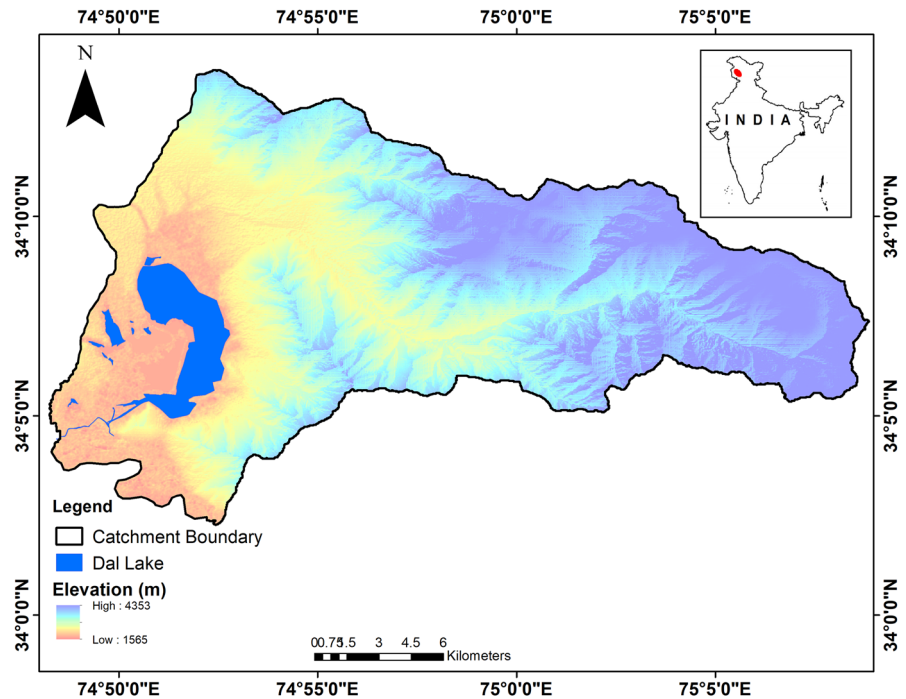
is considered the "liquid heart" of Srinagar (Masoodi & Kundangar, 2018). It has found its place amongst the most beautiful National heritage sites of India. It plays a vital role in the region's economy as it forms the livelihood of numerous people of Srinagar city. The lake is one of the most important tourist destinations as well as a significant source of fish, vegetables, and recreation to the locals. The lake waters also form an important portion of the water supply to the Srinagar city.
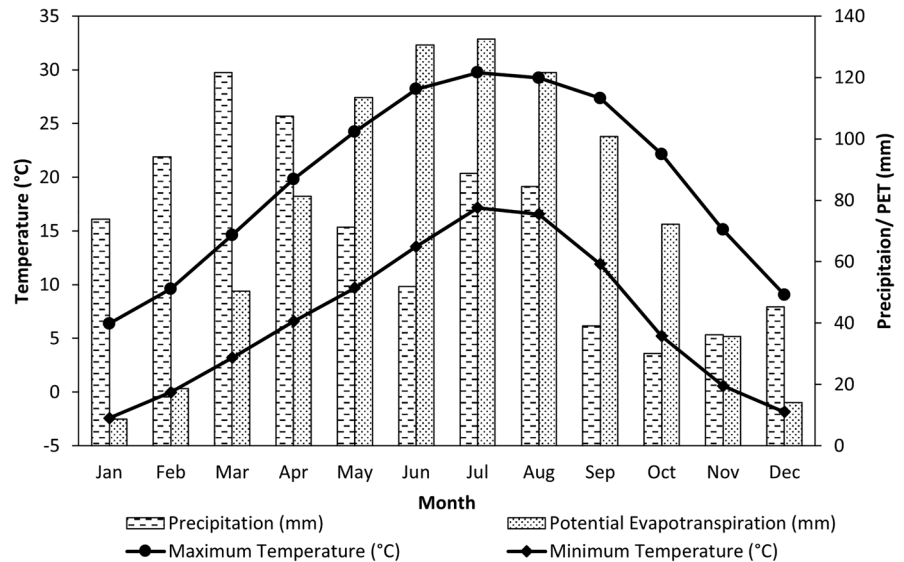
Climate

The climate of Srinagar city is sub-Mediterranean type (Mir et al., 2016). A single meteorological observatory in the catchment is maintained by Sher-e-Kashmir University of Agriculture Science and Technology (SKUAST), Srinagar since January 1985. Based on the SKUAST (1985–2019) data from, July is the warmest month with a mean maximum temperature of 29.7 °C and a mean minimum temperature of 17.2 °C. January is the coldest month with a mean maximum temperature of 6.4 °C and a mean minimum temperature of −2.4 °C. Precipitation occurs in the form of snow and rain. The normal annual precipitation (1985–2019)

of the catchment is 844 mm. Annual potential evapotranspiration (PET) is 880 mm and exceeds annual precipitation (Parvaze et al., 2021). Monthly normal of maximum temperature, minimum temperature, and precipitation are presented in Fig. 2.

Methodology and data collection

To identify the relevant existing literature in accordance with the objective of this study, a thorough evaluation of all relevant studies of the water quality of Dal Lake up to the year 2021 was conducted. The following keywords were used to search the main scientific databases: Scopus, ScienceDirect, Springer, and Google Scholar: Dal Lake, Himalayan lake, water quality, and climate change. This search focused on papers that allowed for the identification of assessment and change in water quality variables used in the various studies. In all, 62 of the 98 articles examined allowed for the extraction of the required information. Secondary data were gathered from different government and scientific reports, local NGO reports, and prior research pertaining to Dal Lake in Srinagar.

Issues concerning the lake

Like global inland water bodies, Dal Lake is beset with problems arising predominantly due to anthropogenic activities. The problems facing the lake can be summarized as below:

- Reduction in the lake areas owing to encroachments by communities and floating gardens.
- Decrease in the water holding capacity due to siltation, primarily caused by the degradation of the catchment area.
- Increased pollution because of the mushrooming number of Dal dwellers and floating gardens, discharge of raw sewage and solid wastes from the bordering areas and within the settlements, and the houseboats and agricultural return flow from the catchment into the lake.
- Reduction in the number of inflow channels and water channels within the lake causing reduced circulation.
- Nutrient enrichment of the lake water and sediment causing extreme weed growth and changes in the biodiversity of the lake.

Hydrology and water balance of the lake

Lakes in the Kashmir valley have undergone serious changes due to anthropogenic pressures. This is particularly true of Dal Lake. Besides being a world-renowned tourist destination, the lake serves important ecological and socio-economic interests of the Kashmir valley. However, changes in the water quality of the lake have been a serious concern for researchers recently. Changes in the water quality of any aquatic system are incomplete without taking into consideration the change in water balance. There have been no significant changes regarding water balance in the lake. Lake storage has been nearly the same for the last four decades. However, during the last two decades, an important component of inflow has been sewage, which has affected the water quality to a significant extent. Decrease in inflow from nallahs and increase in sewage inflow maintain the water balance but has led to a catastrophic change in the water quality of the lake.

The hydrology of Dal Lake is complicated due to the huge diversity of the catchments contributing to its inflow. These include the urban catchment of Srinagar city, adjoining agricultural and mountainous catchments. Presently, the lake comprises an open water area and lake interiors comprising marshy land and floating gardens (Fig. 3). The open water area is divided into three sub-basins: the Hazratbal basin in the north, the central Bod Dal basin, and the Gagribal basin in the south. Nigeen Lake on the west of Dal Lake appears to be a detached arm of the main lake. The sources of the lake include several streams and springs. Telbal Nallah is a large perennial stream that

Fig. 3 Drainage network of Dal Lake (Amin et al., 2013)
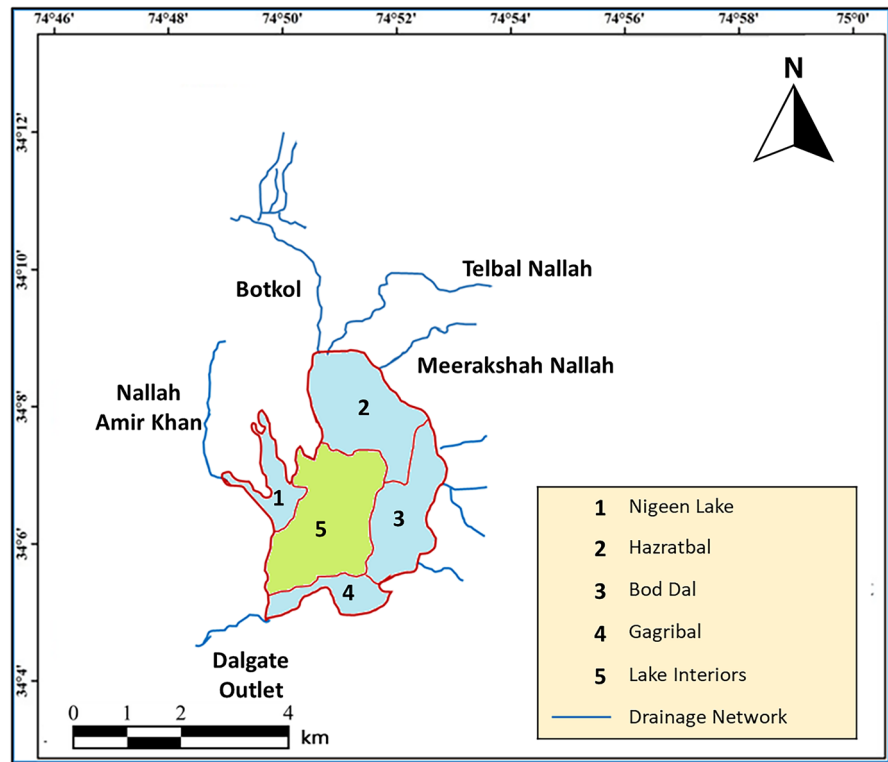
drains the Dachigam National Park on the eastern side of the lake and enters it from the northern end (Fig. 3). Another major source of inflow is the Botkol, draining the northern and north-western catchment. It also collects water from the Sindh Extension Canal, and irrigation overflows and enters the lake from the north-western end. Several smaller streams like the Meerakshah Nallah also add water to the lake. Inflow to the lake is also contributed by many springs arising from its bed as well as outwash from the surrounding mountains. Water flows out of the lake through two principal outlets — a weir and lock system at Dalgate and the Nallah Amir Khan connecting Nigeen lake with Anchar lake via Khushalsar lake. A significant amount of flow from the incoming streams is diverted for agricultural purposes through a composite canal network.

Although complete water balance studies for the Dal Lake have not been reported, the first rainfall-runoff balance was mentioned in the Enex Consortium Report (Enex, 1978). The study period was 1964 to 1976, during which maximum flow occurred in 1976 and minimum flow in 1974. Water

balance was studied for these 2 years, and the average annual inflow to the lake was estimated at 292 Mm^3. The average annual rainfall of the basin for the study period was 872 mm. Telbal nallah contributed 80% of this flow, while 20% was contributed by precipitation and drainage from the lakeside catchments. Detailed water balance for the lake was first presented in 1988 (Ishaq & Kaul, 1988a). An extensive study on the annual water balance of Dal Lake was undertaken during 1970–1980 and monthly water balance from August 1981 to July 1982. The study segregated the bottom inflow component for the lake. The average inflow to the lake during the study period was approximately 338.7 Mm^3, out of which 232.1 Mm^3 (68.5%) was contributed by the surface inflow into the lake, 9.1 Mm^3 (2.7%) by precipitation on the lake, and 95.9 Mm^3 (28.3%) by underwater springs. The major portion of outflow from the lake was through Dalgate outlet and Nallah Amir khan, forming 329.6 Mm^3 (97.3%), while evaporation formed only 9.1 Mm^3 (2.7%). The Jammu and Kashmir Lakes and Waterways Development Authority (JKLAWDA, 2010) included a
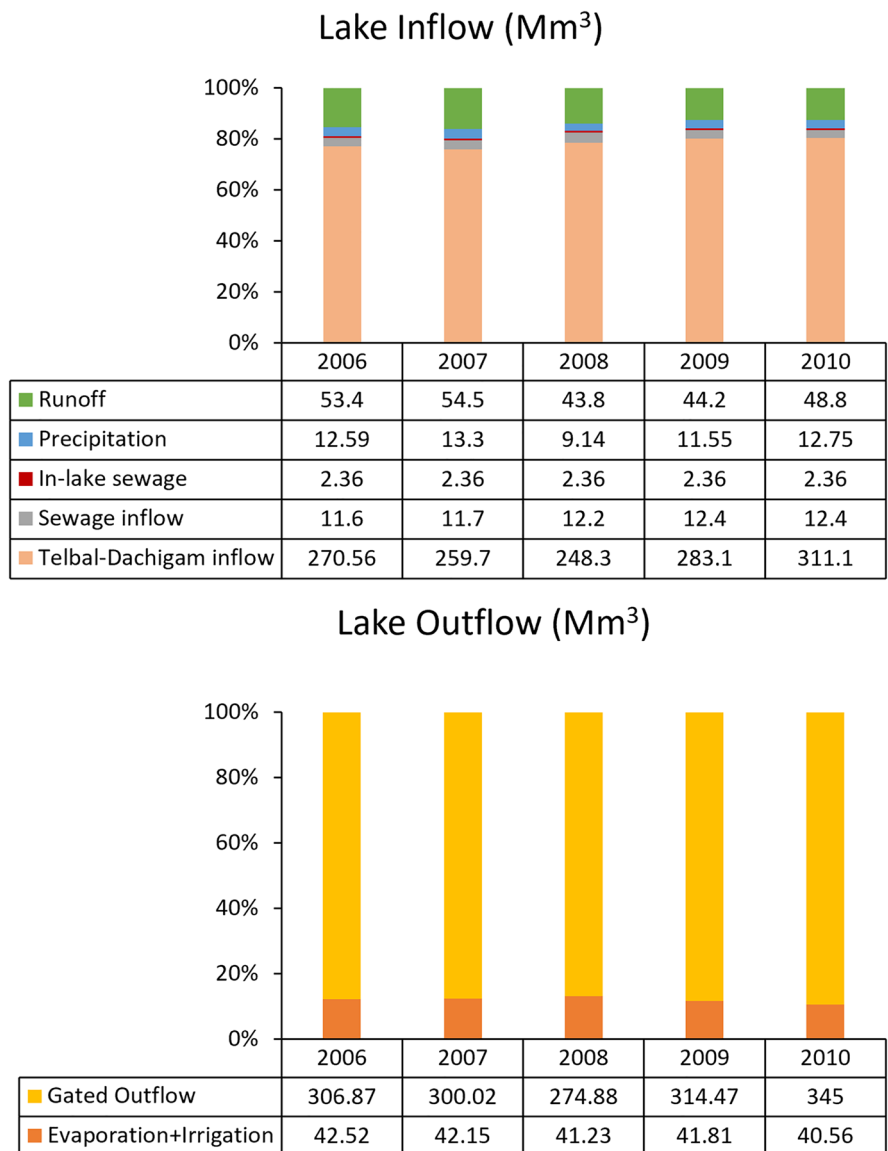
component of sewage present in the lake as well as sewage inflow into the lake. The water budget given by JKLAWDA is presented in Fig. 4. However, the report emphasised that there has been no change in the lake storage. Recently, chemical and isotope mass balance approach was used to study the water budget of Dal Lake (Saleem & Jeelani, 2017). Total monthly inflow and outflow from the lake were 0.95 Mm^3, out of which groundwater contribution to the lake was 29.9%. Surface runoff into the lake formed 65.2% of the total inflow, while precipitation contributed only 5.6% (Saleem & Jeelani, 2017).

Change in physio-chemical parameters of the lake

Transparency

In any aquatic system, the degree of light penetration has a significant impact on the biological processes and consequently, its productivity. One of the earliest documented studies reports that Dal Lake exhibits varying transparency values in different seasons (Mir, 1977). Transparency is minimum during spring and summer, while it increases to a significant extent in winter. The changes in the transparency of the lake

Fig. 4 Water budget for Dal Lake during 2006–2010 (JKLAWDA, 2010)

Lake Inflow (Mm³)

	2006	2007	2008	2009	2010
■ Runoff	53.4	54.5	43.8	44.2	48.8
■ Precipitation	12.59	13.3	9.14	11.55	12.75
■ In-lake sewage	2.36	2.36	2.36	2.36	2.36
■ Sewage inflow	11.6	11.7	12.2	12.4	12.4
■ Telbal-Dachigam inflow	270.56	259.7	248.3	283.1	311.1

Lake Outflow (Mm³)

	2006	2007	2008	2009	2010
■ Gated Outflow	306.87	300.02	274.88	314.47	345
■ Evaporation+Irrigation	42.52	42.15	41.23	41.81	40.56

were attributed to several factors, like plankton populations and extraneous materials, by other researchers (Kaul, 1977; Vass & Zutshi, 1979). These researchers also reported similar seasonal fluctuations in transparency. Mean depth of visibility in the lake had reduced from 1.96 m in 1987 (Sarwar & Zutshi, 1987) to 1.49 m in 2005 (JKLAWDA, 2005). The value has further dipped to 1.46 m in 2013 (Mushatq et al., 2013) and 1.32 m in 2020 (Gulzar et al., 2020).Lake transparency has decreased to a significant extent. Inflow of raw sewage and sediments into the lake has reduced the visibility depth. The effect has been worsened by eutrophication and profuse weed growth in the lake (Lucas et al., 2009). Moreover, land use land cover changes in the lake catchment have further added to the sediment load in the lake.

pH

Dal Lake has been an alkaline lake. pH values of the lake vary between 7.4 to 8.9 throughout the year (Khanday et al., 2018; Sharma et al., 2015). pH values have shown a fluctuating tendency since 1987. Trisal (1987) estimated the pH of the lake to be between 7.4 and 9.5 at various locations, with an average of 8.4. The average value in 1990 was estimated at 8.7 (Zutshi & Ticku, 1990). pH values decreased to 8.2 in 1997 (JKLAWDA, 1997) and 2010 (JKLAWDA, 2010) but were reported to be higher, i.e., 8.4 in 2017 (Rather & Dar, 2020a). pH is a crucial parameter for determining whether the lake waters are suitable for different purposes. The pH of the lake has been alkaline in the past and remains so. However, serious fluctuations in its value are a sign of the possibility of a gradual change in the well-buffered aquatic system (Kremleva & Moiseenko, 2017). This can be attributed to high levels of pollution loads in the lake, which increase with time.

Conductivity

Conductivity is closely related to the trophic status of a water body, being low in oligotrophic (being deficient in nutrition) and high in eutrophic ones. Conductivity values during 1998–1999 fluctuated between 122 and 759 µS in different basins of Dal Lake (JKLAWDA, 1997). Earlier, Kaul (1977) reported conductivity values between 95 and 240 µS in the various basins, while Trisal (1987) recorded a range of 270 to 490 µS.

Recent studies state that the conductivity values of the lake vary between 300 and 642 µS (Chashoo et al., 2020; Ruhela et al., 2020). For shallow lakes, like Dal Lake, conductivity is an important pollution indicator (Das et al., 2006) and assess the trophic status of aquatic systems (Ozguven & Demir Yetis, 2020). Increasing conductivity values of the lake waters can be attributed to a heavy load of silt, sewage, and fertilizers in the inflow streams of the lake. In addition, crop areas and human inhabitations around the lake, coupled with changes in land use and land cover of the lake catchment have led to the gradual increase of conductivity values of lake waters (Stenfert Kroese et al., 2020).

Carbonates and bicarbonates

Carbonates and bicarbonates jointly determine the overall alkalinity of an aquatic system and are employed to distinguish between soft and hard water bodies. Water with alkalinity values exceeding 90 mg/l is hard water (Moyle, 1945). Dal Lake water was classified as hard water by Trisal (1987). Alkalinity values of the lake at the time were in the range of 70–134 mg/l. During the years 1998–1999, alkalinity varied between 37 and 249 mg/l, thus suggesting a rise in the hardness of water over the previous decade (JKLAWDA, 2005). Recent data on the Dal Lake reveals that alkalinity remains over 90 mg/l for most of the year. Thus, the lake fits into a typical hard water type (Ahmad et al., 2020). Bicarbonates were reported throughout the year, while carbonates contributed mainly during the warm period when pH was high. Bottom water had only bicarbonates (Shah et al., 2019).

Dissolved oxygen

Oxygen is a crucial element for regulating the metabolic activities of aquatic organisms and also acts as an indicator of the lake condition (McCormick & Reid, 1961). The distribution of oxygen in deep waters is dependent upon the presence or absence of stratification (Lohri et al., 2013). Dal Lake is a shallow water body that displays negligible fluctuations in the oxygen levels from the surface to bottom (Mushtaq et al., 2018). The dissolved oxygen (DO) and the thermal cycle of the lake have been found to be closely related (Trisal, 1987). DO values are high during winter while low during summer. In 1987, mean annual DO values at different lake sites

were 0.8–12.05 mg/l. Deweeding only increases the DO values temporarily (Kundangar, 2003; Zutshi & Ticku, 1990). Annual DO values of the lake have decreased from 7.4 mg/l in 1997 to 6.9 mg/l in 2017 (Rather & Dar, 2020a). Dissolved oxygen levels in Dal Lake have declined significantly since the 1990s. Thriving weeds and profuse growth of macrophytes in the lake because of increased nutrient load are the primary cause of this decline. Respiration by bacteria and aquatic animals, as well as the oxygen demand for macrophytes and their decomposition causes the free oxygen to be used up rapidly. A decrease in dissolved oxygen has been one of the most significant impacts of lake pollution (Mushtaq et al., 2018).

Cationic elements

Calcium and Magnesium are the most abundant divalent cationic elements in the Dal waters (Trisal, 1987; Trisal & Kaul, 1983). The usual cation progression for the lake water is $Ca > Mg > Na > K$. According to the Ohle's classification, Dal Lake is a calcium-rich lake (Ohle, 1934). Seasonal fluctuations of cationic elements in the lake have been reported. The concentration of calcium and magnesium is high during summer (Ishaq & Kaul, 1988b). The concentration of sodium and potassium in the lake shows marked fluctuations. While sodium fluctuates without any trend, potassium concentration is highest during early spring and lowest during summer. Maximum calcium ion concentration in the lake water in recent times has not exceeded 100 mg/l and magnesium ion concentration remains below 30 mg/l. However, the values are very low as compared with previous observations. Ishaq and Kaul (1988a, b) reported calcium ion concentrations of up to 432 mg/l and magnesium ion concentrations of upto 92 mg/l. The lake shows a significant increase in the concentration of all cationic elements over the last three decades (Mushtaq et al., 2018; Rather & Dar, 2020a). High concentration of calcium and magnesium in Dal Lake is because of their leaching from agricultural soils (Ishaq & Kaul, 1988b). Increase in the cation concentration of the lake may be attributed to the increase in use of chemical fertilizers in the nearby cropped areas. Farming practices followed in the lake catchment are responsible for increased leaching of these ions into the lake water. Elevated levels of Mg^{2+} can also be a consequence of the decomposition of macrophytes (Kumar, 1990; Ohle, 1934).

Nitrates

Researchers in the 1970s and 1980s (Kaul, 1977; Kaul et al., 1978; Trisal, 1987) reported only small quantities of inorganic nitrogen in most basins of Dal Lake. Only the Brarinambal area was reported to have very high concentrations of nitrate-nitrogen ($NO_3^- N$) and Ammoniacal nitrogen (NH_3-N). Nitrate-nitrogen was reported as the most profuse source of nitrogen in the lake ecosystem, with concentration levels shifting between 80 and 650 µg/1. Other forms of nitrogen were present in traces. However, data for 1998–1999 reveal a significant increase in inorganic nitrogen in the lake, indicating the lake to be under considerable pollution stress (Mushtaq et al., 2018; Rather & Dar, 2020a). The increase in the concentration of nitrates in Dal Lake is due to an increase in the amount of organic wastes in the lake and their subsequent decomposition. Greater decomposition of organic matter in lakes speeds up the release of ammoniacal nitrogen in the water (Richards et al., 1965). Another reason for this increase may be the surge of bottom ammoniacal nitrogen to the surface by human activities, namely, dredging and de-weeding operations. It may also be ascribed to quick fertilizer overflow and direct dumping of raw sewage from in and around the lake. The rise in nitrate concentration in the lake may be due to leaching and surface runoff of nitro-phosphate fertilizers from an adjacent cropped area into the lake as well as from domestic sewage from homes and houseboats being dumped into the lake (Mustapha & Omotoso, 2008).

Total phosphorous

The concentration of total phosphorous in the lake has shown an increasing trend. Earlier research reported low concentrations of total phosphorous as well as phosphorous loading into the lake (Enex, 1978; Ishaq & Kaul, 1989, 1990). Total phosphorous is trapped in the sediments, especially in the top layer. This is attributed to the sedimentation of this mineral after precipitation. The concentration of total phosphorous has increased from 0.1 to 0.4 mg/l in 1997 to about 6 mg/l in 2017 (Rather & Dar, 2020a). Similar results have also been put forth by other researchers (Ahmad et al., 2020; Mushtaq et al., 2018; Rather & Dar, 2020b). Phosphorus is regarded as the pivotal limiting nutrient, leading to eutrophication of freshwater

systems (Rabalais, 2002). It is a vital nutrient that causes eutrophication and is needed by algae in meagre quantities (Schindler et al., 2016). The potential cause might be the growing degrees of eutrophication in the Dal Lake system. The notable increment in total phosphorus is because of extreme drainage from floating gardens as well as from agricultural catchments through Telbal and Botkol streams. Phosphate also passes in the lake water through domestic wastewater, explaining the expedited eutrophication.

Chlorides

Varying amounts of chlorides (Cl^-) are present in almost all-natural water bodies. The amount of chlorides in a water body is dependent on the geochemical conditions of the catchment area (Adimalla & Venkatayogi, 2018). However, the presence of chlorides in an aquatic system is an indication of pollution by sewage (Edokpayi et al., 2017). Chloride concentrations of Dal Lake have increased multi-old since the last two decades. From a mean concentration of 2–2.7 mg/l in 2007, the values have shown a steep increase up to 10.3 mg/l in 2017 (Mushtaq et al., 2018; Rather & Dar, 2020a, c). An increase in Cl^- concentration is harmful for the lake vegetation and results in increased corrosion. It further indicates a heavy load of organic wastes in the water, which leads to excessive consumption of dissolved oxygen by bacteria affecting the ecosystem of the lake. The drastic increase in Cl^- concentration in lake waters is because of the drainage of raw sewage into the lake. As the number of Dal dwellers in the lake interiors, as well as the houseboats, increased significantly in the past two decades, the inflow of sewage has also increased (Dar et al., 2020).

Effects of water quality changes on lake ecosystem

Over the years, Dal Lake's water has shown considerable changes, and at present, the lake is under immense stress. A foul smell exudes from several sections of the lake. The pressure of human dwellings along the shores, as well as its interiors, have been identified as one of the fundamental causes leading to environmental degeneration of the lake (Rohini, 2016). With the increase in population, especially the urban, the pressure on the lake and its

environs as possible settlement zones, besides agricultural activities within floating gardens and converted land, has intensified (Ganaie & Hashia, 2020; Mushatq et al., 2013). Projected population statistics report an extraordinary increase during the previous two decades. This has brought about the unlawful invasion and the reclamation of vast expanses of the water surface from the lake basin as floating islands or gardens used for vegetable farming, residences, hotels, and market sites (Ahmad et al., 2020; Rather & Dar, 2020b). Despite increased surveillance by the government and restrictive measures, illegal encroachment continues. From the above factors, it is obvious that the picturesque Dal Lake, promoted as an aquatic plaza the world over, is dying under the heightened human impact in its drainage basin. The condition of the lake in the immediate proximity of sewage outfalls has attained a serious stage. Though the pace of pollution differs from basin to basin, the impact of advancing human actions is felt throughout the lake, rising in unwanted variations, led by extensive environmental deterioration. There is an urgent need to check passage of sewage from the catchment, and effectively halt the establishment of floating gardens, which is still going on in many areas of the lake.

The variations in the biodiversity of the lake are prominent. The bacterial population has multiplied remarkably especially in the houseboat neighbourhoods and adjoining Boulevard and Gagribal due to faulty sanitary system, impaired land management practices in the adjacent vegetable gardens coupled with direct discharge of grey waters (Rashid et al., 2017; Sultan et al., 2020). Among the phytoplankters pollution indicator species viz., Cyclotella, Melosira, Microcystis, Achnanthes, Nitzchia, Euglena, Phacus, and Oscillatoria are prominent. Similarly, zooplankters viz., Keratella, Brachionus, Chydorus, and Cyclops are the leading and indicator species (Gulzar et al., 2020).

Pollution management of the lake

Solid wastes, sewage, and their management

Dal Lake in Srinagar is an example where human endeavours have degraded the lake beyond the point of natural recovery. Encroachment, silting, weed infestation,

and extensive disposition of liquid and solid wastes by the populace in the lake and on the periphery have turned this lake into a waste sink of which solid waste is one of the culprits (Chashoo et al., 2020; Ruhela et al., 2020). Moreover, the dumping of huge loads of oxygen using components of solid waste has culminated in a drop in dissolved oxygen concentration of lake waters, and at many places in the lake, it has led to anaerobic conditions (Badar & Romshoo, 2008).

A substantial number of houseboats are stationed in Dal and Nagin Lake. Most of these are anchored from Dal gate to Nehru Park, opposite Boulevard Road for tourism and other commercial purposes. The visitors, along with owners, inhabit these boats during the tourist season and discard the solid waste produced into the lake. Thus, these houseboats turn into a consistent point source for pollution of Dal Lake (Ganaie & Hashia, 2020). Apart from these houseboats, numerous settlements with inhabitation have also been established in the lake areas, which are also contributory to an enormous quantity of solid waste resulting in the pollution of the lake and subsequent deterioration (Mushatq et al., 2013).

Besides the above point sources within the lake, the inhabitation around the lake, the gardens, commercial centres, and the markets on the bordering pathways add to the littering and subsequent dumping of solid waste in lake waters either directly or through the drains flowing into the lake.

The organic elements of the garbage and food waste result in the deficiency of dissolved oxygen levels of the lake and the inorganic constituents especially nitrogen and phosphorus add to the nutrients resulting in weed growth. In addition, the floating matter, containing plastic bags, paper, tin cans, glass bottles, metal pieces etc., affects the ambience of the lake. Dal Lake had been, over decades, used as a container of substantial loads of inflows, including raw human waste (Nengroo et al., 2017). A strategy to check the flow of wastewaters as sewerage system and decentralized sewage treatment has been conceptualized and constructed. Looking at the peculiar climatic conditions, the inadequacy of vast areas of land, insufficiency of electrical power, and the uneven topography, pumping of sewage to one place where it can be treated have been avoided, and treatment by fluidized aerobic bed (FAB) has been approved (Chashoo et al., 2020; Qayoom et al., 2021). The technology employs both dispersed and attached microbial growth in bioreactors accompanied by tube settlers and centrifuge with a chemical treatment to produce effluents of standards suitable for discharge in the lake body. Design of a pumping system (minimal) has also been included.

At present, three sewage treatment plants (STPs), proposed by the Alternate Hydro Energy Centre of Indian Institute of Technology (IIT), Roorkee (AHEC, 2000), are functioning at three locations around the lake. These are located at Habak, Hazratbal, and Lam areas around the lake. These STPs discharge treated sewage into the lake. There is a significant difference in the physio-chemical properties of the treated sewage and raw sewage as presented in Table 1.

Dal Lake, however, needs more STPs and appropriate management for the disposal of solid wastes in its vicinity. Hyper-eutrophic areas like Nehru Park and Nigeen basin need new STPs as well as the upgradation of existing ones. These STPs, because of their inability to perform many times and faulty seepage, have led to an increase in lake eutrophication (Qayoom et al., 2021). For at-site treatments, small-scale waste-water treatment plants can be established for communities or individual homes.

Harvesting and deweeding

Dal Lake holds a vivid and mixed growth of macro flora, which in some sections has developed into dense layers to make up a practically impenetrable mass (Kumar et al., 2020). The most protracted coverage is of submerged species and floating forms,

Table 1 Quality of raw sewage and treated sewage of STP, Hazratbal (Qayoom et al., 2021)

Parameters	Inflow	Outflow
COD (mg/l)	280	56
BOD (mg/l)	100	20
Total Solid (mg/l)	415	83
TDS (mg/l)	275	55
TSS (mg/l)	137	28
pH	6–6.5	7.8
DO (mg/l)	<1	<1.6
Nitrogen(mg/l)	45	9
Ammonia(mg/l)	15	3
Chloride(mg/l)	75	15

which have become a nuisance. The abundance of macrophyte vegetation in Dal Lake is not merely owing to uninterrupted supply of nutrients from the catchment but also because of many diverse beneficial conditions such as shallow depth of the basin and its gradual slope, nutrient-rich sediments, optimum light, and temperature conditions during the growth period, minimum wave effect and the existence of diverse perennial species which are adapted to efficient utilization of the prevailing environmental conditions (Rehman et al., 2016). It is well recognized that aquatic macrophyte communities are "habitat opportunists"; hence, it is difficult to dislodge a community once it is established in a particular lake or a part of it.

In order to boost the use of Dal Lake for aquatic sports, navigation, and other needed purposes, an argument has been made for removing extra biomass of macrophytes by mechanical harvesting. However, there is no refuting that in some places of the lake, weed growth is enormous, presenting a degraded view of the ecosystem. Unfortunately, while recommending the use of machines for weed cutting, the part played by macrophytes as an indispensable part of the freshwater ecosystem performing various functions has been completely disregarded. Further, it should be mentioned that the most satisfactory and reasonable management technique would be a restriction of macrophyte vegetation in Dal Lake rather than its elimination. It is rightly acknowledged that macrophytes are bio-indicators of pollution. They adequately eliminate minerals from the sediment nutrient pool and thus aid in pollution abatement by functioning as nutrient pumps and serving as biological sinks.

The resident community of Dal uses macrophytes in many forms, which include food, fodder and medicinal plants. The macrophytes also make up the primary source of food in the aquatic food chain and maintain the most convenient breeding, resting, and sheltering place for macrofauna, consisting of fish and other organisms, besides upholding considerable loads of periphyton on which a wide number of aquatic animals depend. Inhibition of sediment suspension and oxygenation of water through photosynthesis are alternative functions of macrophytes. But it is still a fact that enormous growth of macro vegetation in a lake disrupts transport, impedes irrigation, increases sedimentation by trapping silt particles and affects recreation. Accordingly, what is required is

to estimate both the advantages and disadvantages of adopting mechanical harvesting to control aquatic vegetation and then select the method that is most helpful to the system without generating unwanted changes that may be more harmful and difficult to control.

Among many in-lake rehabilitation methods, biomass removal using mechanical weed harvesting has been executed in Europe and the USA to some extent of success. In many situations, harvesting of weeds is accompanied by the application of chemicals. Use of chemicals in Dal Lake is not advocated because of multiple uses of its water.

Aquatic plant control, rather than elimination, is the most rational management procedure. Entire eradication of plant cover and full-scale harvesting should be evaded at all costs. Shallow lakes like Dal Lake are extremely susceptible to shifting from a stable vegetative state to a non-vegetative one. The vegetative state is tougher to disturbances, but excessive weed removal can neutralize their stability and cause turbid waters with algal blooms (Masoodi & Kundangar, 2018). Weed harvesting has to be selective, i.e., limited to definite zones only. Lake areas that are convenient for fish, fodder, and food plants should not be exposed to repeat harvesting. Harvesting should be carried out before blossoming, fruiting, and formation of propagules in plants. Regular monitoring should be initiated during harvesting operations involving the following aspects: Vegetation maps need to be developed for analysing variations in cover and frequency of different species. A correlation can be made with earlier vegetation maps. Aerial photographs and satellite imageries will be extraordinarily advantageous. The efficiency of machines and men need to be noted periodically. The re-establishment of vegetation and changes in the community structure must be monitored. Phenology of diverse aquatic plants must be recorded. Any variations in predominant species after de-weeding must be noted regularly.

Dredging of lake sediments

Decrease of nutrient load from catchment through collection and treatment of sewage may have a meager consequence on the improvement of Dal Lake environment, since, during the times of increased eutrophication for many decades, a considerable amount of

phosphorus and nitrogen has been adsorbed by the sediment (Mushtaq et al., 2013). Therefore, any reduction of outside loading is generally taken care of by internal loading, thereby restricting the response of the lake to the cutback of nutrients coming into the system from the neighbouring area. Nutrients coming from catchment and other extraneous sources are partially accepted by biological life but substantial loads of these are accumulated in sediments that are discharged back to water over a course of time. Although internal loading is a crucial source of nutrients in Dal Lake, no data are available on the amount of nutrients released from the sediments.

The deep sediment–water interaction, probably enormous impact of siltation, and the presence of vast patches of solid landmass along the north-eastern border negatively influence the natural functioning of the Dal Lake ecosystem (Mir et al., 2018). Dredging of lake sediments can be employed as a reclamation approach to bring about the elimination of nutrient-rich sediments, deepening of silted lake areas to enhance water flow, removal of shoals and solid land mass, and cutback of emergent vegetation.

Dredging can be specified as a rewarding lake restoration approach if there is a pre-implementation evaluation of the lake setting, useful equipment is selected, disposal locations are defined before the dredging begins. Therefore, the designing of the lake deepening project should take into deliberation many components such as the extent of deepening based on the area to be dredged out, the dumpsite, and the use of the lake area, which is to be dredged out.

Shoreline development

The prominence of the shoreline of a water body is an unambiguous indicator of the ecological status of the same, and Dal Lake is no anomaly. The shoreline, specifically from Dal-gate to Naseem Bagh, has evolved over the years as the much-pursued station both for tourist-associated enterprises as well as for residential expansion (Rather, 2012). For any management strategy of the Dal-Nagin Lake to be useful, the impact of the tourist and the resident community on Dal and Nagin lakes has to be investigated and visualized (Mir, 2017). An estimate of the expected uses, and the impact, has to be evaluated so that prospective development of the shoreline is identified in distinct perspective.

Research and monitoring programme

The lack of a precise plan for the comprehensive monitoring and control of the lake is now being understood extremely strongly. For illustration, despite afforestation programs, there are many areas of the catchment where erosion processes remain intense. The small silt basin formed at the lake's northern end cannot fully impede incoming silt and usually fills up. Invasion by weeds and plankton has followed dredging for silt removal (Mushtaq et al., 2015). Harvesting of invading macrophytes, either by hand or by harvesters, has not been a success story either. The weeds proceed to multiply faster and set up hurdles to navigation and recreation. Conservation programs are confined to afforestation of the catchment to control silt movements, dredging of the lake, and weed removal.

Invasion by alien species, extreme siltation and waste discharge, habitat loss, and competition with more economically significant species has taken a toll upon the local Dal flora and fauna. However, biodiversity monitoring has been trivial in the area (Chowdhury, 2018; Mukhtar & Chisti, 2013). A few individual bird counts and studies on a few species apart, little information of the lake's biodiversity exists. Species counts, production information, nutrient pools, food web characteristics, species inter-dependences, feeding and breeding patterns, habitat dynamics, and much more need to be studied over the long term to understand the impact of various management plans upon the lake's health and biological diversity.

With such a scenario, there is a revealing call to plan an ultimate research program for the lake holding regarding ongoing restoration programs, management procedures, and gaps in the interpretation of the Dal Lake ecosystem.

Public awareness program

The accomplishment of any project depends upon the engagement, assistance, and collaboration of the individuals who are "Project-Affected." It is therefore a prerequisite that the project of this nature be participatory and carries the support of the resident populace who will be directly affected by the implementation of the project. This demands that information be formed at all levels about the demand and intentions of the conservation project and how it will

be advantageous to the local population in terms of better living conditions and quality of life (Ali, 2014). It should also present information on the present position of the lake, need for its cleaning, saving the rich bio-diversity, and maintaining ecological balance in the lake system. It should also inform people regarding the steps that are being taken by the government and other agencies in the area of lake conservation and how they can participate to make it a peoples' movement (Jeelani & Kaur, 2014). In order to generate confidence in the local population, it should also provide information regarding the progress of the project implementation.

Future research needs

Although various studies have been carried out on Dal Lake, most of these focus upon distinct aspects of the lake. Overall management and monitoring studies from the management and viable development point of view are sadly lacking. Limnological studies indicate water and sediment chemistry and planktons. Various fields in the study of the lake's ecosystem need to be covered. Some of the significant future research demands include geological investigations of the catchment and the lake bed; hydrological examinations incorporating the strengthening of meteorological structure in the lake catchment; the impact of snowfall, snow-melt, and rainfall on temporal flow into the lake; role of groundwater flow from the area neighbouring the lake to it and vice versa; description of springs in the catchment and their characters; detailed applications of the catchment identifying soil types, elevation, drainage lines, land use, and their impact on flows in the drains pouring into the lake; impact of activities in the catchment on the volume of surface and groundwater flowing into the lake; hydraulic modelling of the catchment and the lake; and modelling of the lake circulation, pollution, macrophytic and plankton growth. Also, a thorough water balance of the system must be worked out before other aspects conditional upon the water body's hydrology are studied.

Conclusions

The water quality of Dal Lake has undergone monstrous anthropogenetic pressure for the last four decades. Houseboats, STPs, hotels, agricultural practices around the lake, floating gardens, lake encroachment, and other non-point sources have degraded the water quality as well as aesthetic properties of the lake. Over the years, the concentration of harmful substances, phosphates, chlorides, and nitrates has increased tremendously. Concentration of total phosphorous has increased from 0.1 to 0.4 mg/l in 1997 to about 6 mg/l in 2017. Similarly, chlorides have shown a steep increase from 2–2.7 mg/l 329 in 2007 to 10.3 mg/l in 2017. Other elements like calcium and magnesium have also witnessed an increasing trend in the lake. Lake alkalinity and pH are changing due to which lake waters have been found unfit for drinking and domestic consumption. Dissolved oxygen levels, on the other hand, have shown significant decline in the lake over the last few decades. Annual DO values of the lake have decreased from 7.4 mg/l in 1997 to 6.9 mg/l in 2017. The lake has become hyper-eutrophic at several places, which has severely affected the lake ecosystem. Changes caused due to these factors have affected the lake water quality to such an extent that these cannot be corrected naturally, and if proper and timely measures are not implemented, the chances of lake survival are bleak. Therefore, there is an urgent need to address the problems associated with lake restoration, management, and conservation by both authorities and the local population. A participatory approach-based conservation plan taking into consideration the restoration of water quality and quantity, considering all stakeholders, is the need of the hour to stop the lake from dying an untimely death. Various aspects of lake hydrology, chemistry, and geology need to be investigated for sustainable management of the lake. The impact of pollution and water quality change on the biodiversity of the lake is the most neglected component of research and needs to be investigated.

Availability of data and material The data cannot be made available because of the policy of data providing agency.

Declarations

Ethics approval Not applicable.

Consent to participate The authors express their consent to participate for research and review.

Consent for publication The authors express their consent for publication of research work.

Conflict of interest The authors declare no competing interests.

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