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REVIEW ARTICLE

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Impact of climate change and anthropogenic activities on lacustrine ecosystems of the Kashmir Valley, NW Himalaya, India

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Abstract

Due to the significant sedimentation and anthropogenic pressures, the Kashmir Himalaya lakes (Dal, Wular, Manasbal) located within and in the vicinity of urban settlements are experiencing massive degradation. The unique climate, geographic setting, and rock degradation owing to the tectonic uplift of the area, contribute to increased sedimentation in these lakes. The sewage and other anthropogenic pressures have also increased various minerals including nitrogen influx in these lakes. Total organic carbon levels in the Dal Lake are high and range from 2.72% to 25.12%, with nitrogen levels ranging from 0.92% to 9.81%. The total organic carbon of Wular and Manasbal Lakes ranges from 0.83% to 4.52%, and 3.11% to 13.74% with nitrogen ranging from 0.06% to 0.5% and 0.20% to 1.96%, respectively. The estimated sedimentation rates for the Wular, Manasbal, and Dal Lakes are 0.125 cm/yr, 0.44 cm/yr, and 0.93 cm/yr. Given these factors and the geographic setting of Kashmir Himalaya, it is believed that under the sustained threat of climate change and anthropogenic pressure, mitigation strategies to control sedimentation and pollution are unavoidable for the long-term survival of these valuable ecosystems. This review examines contributing factors, explores potential consequences, and proposes mitigation measures, to save these important aquatic ecosystems from further deterioration.

KEYWORDS
climate change, lake ecosystem, mitigation measure, pollution, sedimentation

1 | INTRODUCTION

Human survival on Earth to a great extent depends on aquatic ecosystems that provide essential services such as drinking water, food, transportation, recreation, and so on (Williamson et al., 2009). However, ecosystems all around the world are under severe threats as a result of global warming and recent climate change impacts (Rosenzweig et al., 2007). Sustained observation of these systems is believed to offer timely insights into how climate change impacts the health of ecosystems (Magnuson et al., 2000; Verburg et al., 2003). Changes in climate and anthropogenic pressures, cause chemical, physical, and biological changes in lakes (an inland aquatic ecosystem) and these changes are well documented in lacustrine sediments. Lacustrine sediments in high-altitude environments, in particular, have proven to be reliable representations for assessing the impacts of climate change (Zaharescu et al., 2016).

The intermontane Kashmir Valley, situated in the hinterland of Northwestern Himalaya, is home to a diverse range of lakes of varying sizes and altitudinal gradients (Dar et al., 2014). These Freshwater ecosystems, such as Dal Lake, Wular Lake, and Manasbal Lake, are crucial for sustaining biodiversity and providing valuable resources to local communities including drinking water, food, irrigation, fishing, recreation, and tourism (Shah et al., 2017). The quality of water in these lakes is under severe threat due to global warming and growing anthropogenic activities. The deteriorating water quality in these lakes raises significant concerns, necessitating a comprehensive investigation into the factors influencing their ecological health. Variations in precipitation patterns, weathering, erosion, and variation in land use/land cover (LULC) changes in catchment areas, as well as sewage discharge, and human exploitation have had an impact on chemical, physical and biological parameters of sediments and waters in these lakes (Bhat & Pandit, 2014; Dar et al., 2013).

The review synthesizes existing research and assesses the deteriorating health of these aquatic ecosystems (Lakes) due to anthropogenic activities, including urbanization, agricultural runoff, and improper waste disposal. The review also examines the factors influencing water quality like sediment characteristics, organic pollution, and metal pollution, and highlights their implications on the overall ecological balance. Finally, the review proposes targeted mitigation strategies, emphasizing the importance of community involvement, sustainable practices, and continuous monitoring for decision-making and long-term lake preservation of these aquatic ecosystems.

2 | STUDY AREA

The area of study, Kashmir Valley, is situated in the north-western Himalaya. The River Jhelum and its branches have created a well-developed drainage system in the valley. The Kashmir valley stretches from NNW to SSE and is around 135 km long and about 40 km wide. The Kashmir Valley is characterized by hard rock terrains with multiple high mountain ranges that serve as home to a number of glaciers and supply water to the Jhelum River and its tributaries (Dar et al., 2021; Murtaza et al., 2021; Paul et al., 2021; Paul, Romshoo, et al., 2022). It is now well established that Kashmir Valley was formed by desiccation of a massive lake (Karewa Lake), which formed due to the tectonic uplift of the Zanskar and Pir Panjal Ranges (Dar et al., 2014, 2017; Paul, Dar, et al., 2022). The climate in the valley is somewhat temperate (Romshoo et al., 2020) with the following four seasons: Winter, Spring, Summer, and Autumn. The lakes of the Kashmir Valley serve as primary sources of food, socio-economics, and freshwater for the local community as well as significantly contributing to ecological equilibrium. Wular, Dal, and Manasbal are the three principal lakes in the Kashmir valley (Exhibit 1). Wular Lake is one of the major freshwater Asian lakes. These lakes and their catchment areas are under constant pressure from over-exploitation and increased human activities. Below is a brief description of the lakes selected for the present study:

The area of study, Kashmir Valley, is situated in the north-western Himalaya

Dal Lake: The Dal is the second major lake by area in the Kashmir valley, located at an altitude of 1583 m, m.a.s.l. The Dal is located between latitudes 34° 5′–34° 9′N and 74° 49′–74° 53′E. It is surrounded by Zabarwan hills to the north and a densely populated area on the other three sides (Badar et al., 2013). The lake basin covers an area of 336 km^2. The lake basin supports the livelihood of the local community by supporting pisciculture, leisure industry, agronomy, and recreation activities. The Dal has a shallow water depth with an average of around 3.32 m (Khanday et al., 2018). It is classified as an open drainage eutrophic lake with multiple basins like Hazratbal, Bod-dal, Gagribal, Brarinambal, and Nigeen, which vary prominently in their volume, depth, area, water's edge expansion indices, and so on. The Dal comprises an area of about 24 km^2 of which around 12 km^2 area is an active open water spread (Khanday et al., 2018; Qadir & Singh, 2019).

Wular Lake: Wular is the major freshwater lake of the valley, situated in north Kashmir and lies between 34° 16′–34° 25′N and 74^0 29′E–74^0 40′E at a height of 1580 m a.s.l. Streamflow from streams such as Erin, Madhumati, and Jhelum River flows directly into the Wular Lake. The Jhelum main is the largest of these streams bringing water and sediment from the Jhelum catchment and depositing it in the Wular Lake (Shah et al., 2021). There are several viewpoints about the areal extent of Wular Lake. For example, the area occupied by the lake, as per the Survey of India (SOI) map of 1962 is 5870 ha although due to the annual changes in the amount of water stored in the lake, the area approximation is subject to significant fluctuations. According to recent high-resolution satellite data mapping (Shah et al., 2017), the area of the Wular Lake is 18,900 ha. Based on its immense hydrological, biological and socio-economic significance, the Wular Lake was designated as a wetland of national importance and was later acknowledged as a Ramsar site (site No. 461) on March 23, 1990. The lake is also one of the largest sources of fresh water, and fishery and provides livelihood to thousands of local people. The lake provides habitat to a variety of animal species and migratory water birds.

The Wular Lake is bordered by various geological formations. The dominant rock formations present are upper Palaeozoic and Triassic rocks. The upper Paleozoic rocks include granites. Panjal Traps, slates, and Agglomeratic slates (Stojanovic et al., 2016). The other formations include Panjal trap, gneiss, granite, Agglomeratic slate and metamorphic schist and alluvium. The Karewa Lake which existed during the last 4 Ma was a large lake covering the valley (Dar et al., 2014). Due to the continuous uplift of the Pir Panjal range, the lake started shifting toward the North-eastern direction of the valley. The further uplifting toward the Pir Panjal range resulted in the drainage of Karewa Lake through Baramulla-Uri gorge about 85 ka ago. The current lakes of Kashmir Valley along with Wular Lake are principally the remnants of the Karewa Basin (Dar et al., 2013). Wular Lake serves as a massive flood absorption basin, which is one of its most essential functions (Dar et al., 2019; Romshoo et al., 2018). This lake collects floodwater from all across the valley and empties it down the Baramulla-Uri gorge.

Manasbal Lake: Manasbal is one of the deepest lakes situated in the Sindh watershed toward the Great Himalayan range of Kashmir alley. Its water is used for drinking, irrigation, fisheries, recreation, tourism, and other activities which have economic importance. The catchment

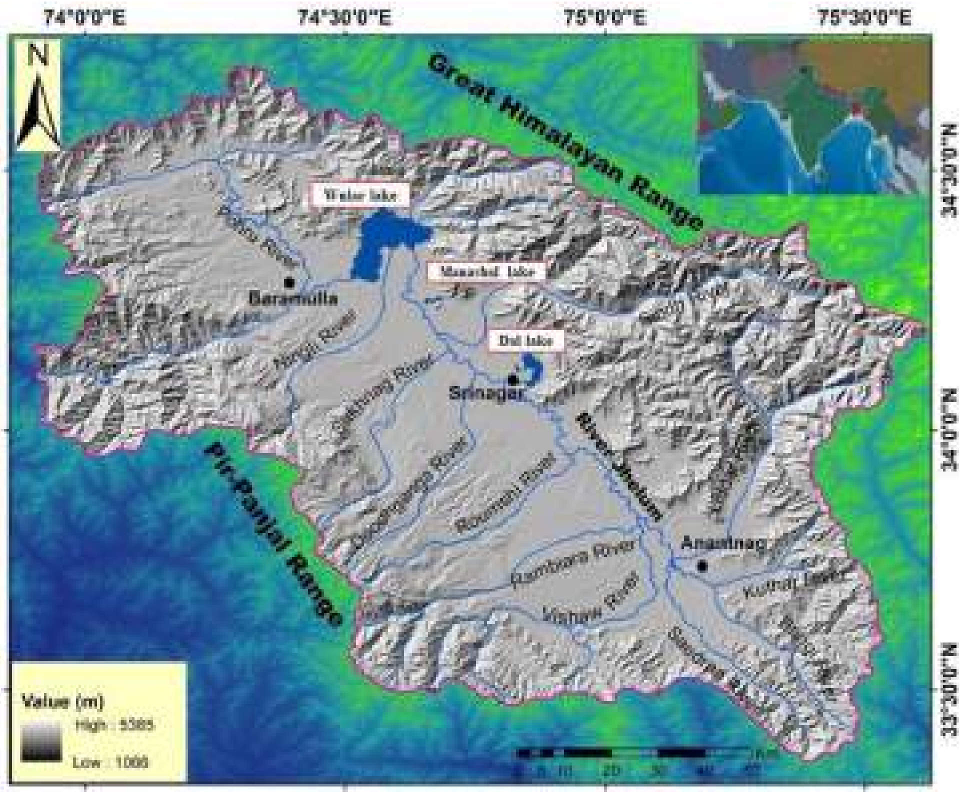

EXHIBIT 1 ALOS PALSAR derived hill shade map of the study area. The location of Kashmir Valley, important Lakes and Rivers are also shown in the map. [Color figure can be viewed at wileyonlinelibrary.com]

of Manasbal spreads over an area of 11 km^2 and is located between 34°15–34°14 N and 74°40–74°43 E at an altitude of 1583 m a.s.l. Its maximum length is 3.5 km, its breadth is 1.5 km and a maximum depth of 13 m. It receives water mostly from groundwater, natural springs, and precipitation and no major streams are flowing into the Manasbal Lake. However, one perineal stream, Laar Kul feeds the Manasbal Lake from the eastern side during summers. The area observes an annual average rainfall of about 650 mm (Romshoo & Muslim, 2011). The geological formations surrounding the Manasbal Lake include Agglomeratic slate, Triassic limestone, Karewa deposits and Recent Alluvium (Lone et al., 2017). The different land cover types of catchments consist of forests, paddy agriculture, barren lands, wastelands and horticulture (Romshoo & Muslim, 2011)

3 | METHODOLOGY

We conducted a comprehensive review of research papers investigating the influence of climate change and human activities on the lacustrine ecosystem of the Kashmir Valley. This study synthesizes findings from 23 research papers specifically addressing the impact of anthropogenic activities on the lakes in the Kashmir Valley. Our review presents results about the TOC and Total Nitrogen (TN) levels in sediment samples. Additionally, we examined the heavy metal content and geochemistry of lake sediments. The paper includes an analysis of the Geo-accumulation (Igeo) index (Muller, 1979) to assess heavy metal concentrations in lake sediments relative to the natural crustal mean concentrations. Furthermore, we applied the Enrichment factor (EF) to assess the extent of anthropogenic metal pollution in the lakes

Igeo index is a means to assess sediment contamination by establishing a relationship between the concentration of a specific heavy metal in the sample and the mean concentration of that metal in the crustal source (Muller, 1979). The Igeo for each sample was determined using the formula:

$$Igeo = \frac{Cn}{1.5Bn} \tag{1}$$

Here, "Cn" represents the calculated value for the element "n," and "Bn" denotes the average background value of the metal (Wedepohl, 1995). The Igeo index is categorized into six levels, indicating sediment quality: 0 (no pollution), 0–1 (no to moderate pollution), 1–2 (moderate pollution), 2–3 (moderate to significant pollution), 3–4 (highly polluted), 4–5 (highly to extremely polluted), and >5 (extremely polluted state).

For the assessment of EF in lake sediments, the extent of anthropogenic metal pollution is evaluated. The normalization is achieved using a normalized element "r," where various trace elements such as Al, Fe, and K serve as normalizing factors. The EF is calculated with the formula:

$$EF = \frac{\left(\frac{\text{Metal}}{\text{Al}}\right)_{\text{sample}}}{\left(\frac{\text{Metal}}{\text{Al}}\right)_{\text{background}}}. \tag{2}$$

The average composition values of surficial rocks from Wedepohl (1995) were used as background values. Interpretation of EF follows the criteria outlined by Sakan et al. (2009): values <1 indicate no enrichment, 1–3 imply minor enrichment, 3–5 suggest moderate enrichment, 5–10 indicate moderate to severe enrichment, 10–25 signify strong enrichment, 25–50 represent very strong enrichment, and >50 denote extremely intense enrichment.

4 | RESULTS AND DISCUSSION

4.1 | Dal Lake

The Dal Lake being a post-glacial (Trisal, 1987) has its outlet in the southwest of Srinagar that drains water into the Jhelum River. The ecological health of the lake is deteriorating at an alarming speed and is fast changing from an oligotrophic to a eutrophic lake. Studies carried out on the Dal Lake have revealed that the aquatic pollution in and around the lake is growing at an alarming rate. The degraded water quality has in turn adversely affected aquatic life (Parveen et al., 2013). The study carried out on the physico-chemical parameters like nitrates, phosphates, alkalinity, hardness, ammonia, nitrites, residual chlorine, TDS, pH, and so on, (Jeelani & Shah, 2006) reveals that anions are in higher concentration in Hazratbal and Nigeen sub-basins of Dal Lake. Besides, the concentration of anions has increased significantly from 2008 to 2015 (Saleem et al., 2015; Saleem & Jeelani, 2016). It is believed that the inclination of nutrients in this freshwater lake is due to the disposal of solid wastes through small and narrow drains, fertilizers and manures used in surrounding cultivated land.

As with other natural lakes, the Dal Lake also experiences varying degrees of anthropogenic pressure. The lake is of special ecological and non-socio-economical interest besides being a valuable tourist attraction. The freshwater has been considerably contaminated over the last few years as a consequence of the continuous ingress of sewage, overflow and dumping of solid wastes into the lake. Current anthropogenic activities in and around the lake such as agriculture cultivation, ingress of untreated sewage, urbanization, dredging, and so on, are also accountable for its eutrophic position. The prevailing pace of pollution of the Dal Lake, if not managed properly, may result in severe environmental damage and can lead to its dystrophic status in the near future.

TOC values reported in the lake bottom sediments of the Dal Lake range from 2.72% to 25.12% with a mean value of 14.35% (Exhibit 2). Nitrogen revealed a high concentration ranging from 0.42% to 9.81% with an average value of 4.14% (Shah, et al., 2021). The higher nitrogen concentration was observed mostly toward the urbanized areas suggesting direct sewage flush into the lake from these areas. Pertinently, TOC and N are two basic elements of the Redfields ratio and result in excessive vegetation growth. The concentration of these two elements has turned the Dal Lake into a highly eutrophicated basin. A comparison of mean N and TOC of Dal Lake sediments with the earlier published data of other lakes (Wular and Manasbal) (Exhibit 3) reflects that its sediments are severely polluted reflecting, more urbanization and anthropogenic pressures (Lone et al., 2018; Shah et al., 2017). Overall, the Dal Lake is the most organically polluted lake among all the lakes in the valley. The complete remedy for the Dal Lake eutrophication is nearly impossible due to the excessive TOC and N in the lake. However, putting a stop to its major pollution sources and continuous monitoring of the lake's ecological health could help in restoring the balance on a long-term basis.

Similarly, the reported mean Igeo index of the Dal Lake sediments is 1.27 for Cr; 0.93 for Cu, 0.8 for Ni; 0.24 for Fe; 0.19 for Pb; 0.17 for Zn; 0.16 for Mn; and - 0.08 for Co (Exhibit 4a). Among all the metals evaluated by pioneer researchers only Ni, Cr, and Cu have reflected moderate contamination, while the rest of the metals reveal insignificant geo-accumulation index states. However, the mean enrichment values of the Lake sediments as reported by Shah et al. (2021) are 1.02 for Pb; 1.03 for Zn; 2.16 for Cr; 1.49 for Ni; 1.65 for Cu; 0.95 for Mn; and 0.81 for Co (Exhibit 4b). The reported values indicate moderate to strong enrichment of Cu, Cr, and moderate enrichment for Zn, Pb, and Ni; while the rest of the metal show insignificant enrichment.

The reported high concentrations of TOC and nitrogen in the sediments of the Dal Lake are of substantial concern. The excessive values indicate severe organic pollution and eutrophication. Comparing these levels with baseline data from other regional lakes, Dal Lake emerges as the most organically polluted of all. The implications are profound, suggesting a critical need for immediate action to address the sources of TOC and nitrogen, such as solid waste disposal and agricultural runoff.

The reported high concentrations of TOC and nitrogen in the sediments of the Dal Lake are of substantial concern

In terms of metal pollution, the Geo-accumulation and enrichment factor values for certain metals like Cu, Cr, and Ni indicate moderate to strong contamination. These levels surpass baseline or acceptable limits, underlining the urgent need for controlling anthropogenic activities contributing to the metal influx. Continuous monitoring is crucial to assess the effectiveness of mitigation measures and prevent further deterioration. Consideration is needed to look into the managing policies of water quality as well as the biological variety of the freshwater along with the developing procedures and maintenance approaches that are in exercise.

4.2 | Wular Lake

Water quality of the Wular Lake has worsened over time and there has been a progressive increase in specific conductivity, orthophosphate

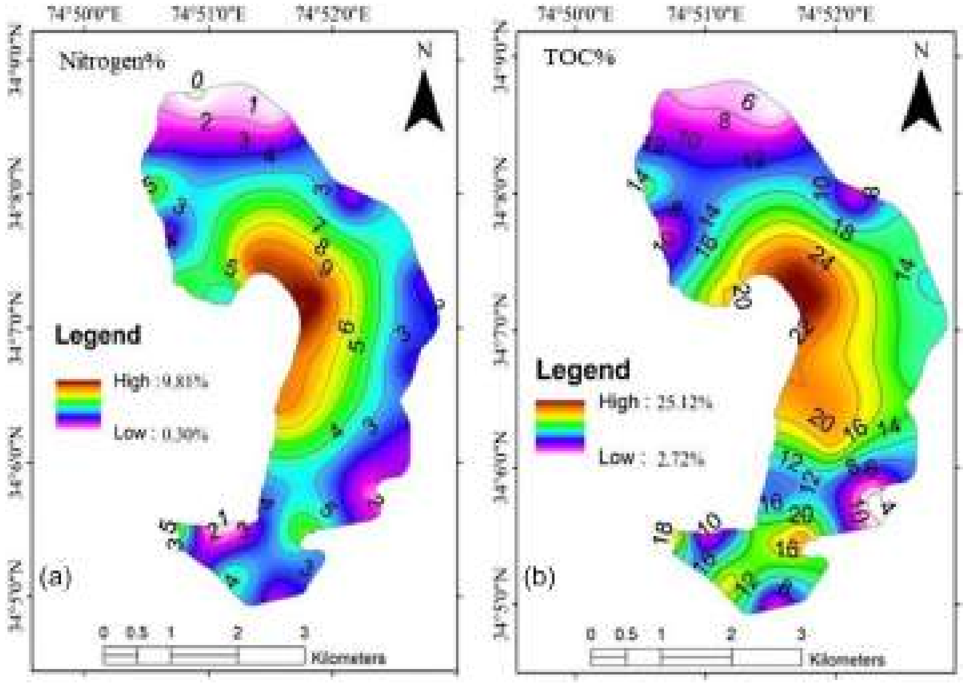

EXHIBIT 2 TOC and TN plots of the Dal Lake are modified after Shah et al. (2021). [Color figure can be viewed at wileyonlinelibrary.com]

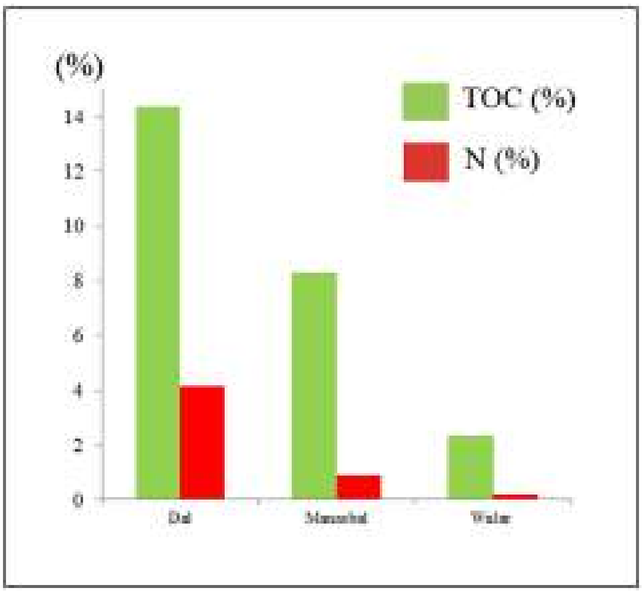

EXHIBIT 3 A comparison Plot TOC and N in the three lakes of Kashmir valley. [Color figure can be viewed at wileyonlinelibrary.com]

and total phosphate with a decline in transparency and dissolved oxygen. Following the criteria established by the Central Pollution Control Board (CPCB), the water quality of Wular Lake is categorized as "C" (Dar, 2017)

The Lake is directly affected by anthropogenic activities and is under threat of extinction due to the excessive sediment load from the catchment areas. Anthropogenic contributions, such as sewage and agrochemical waste originating from the neighboring residential, agricultural, and horticultural regions, are exerting an impact on the water quality of the Lake. Additionally, the influx of siltation from the primary river, Jhelum, and its tributaries, has caused an elevation in the concentration of diverse chemicals, resulting in alterations to the hydro-geochemical composition of the lake (Sheikh et al., 2014). This is evident from the high concentration of Nitrogen in the lake sediments. The increase in the concentration of NO_3, K, P, and Cl in the Lake reflects increased use of agricultural fertilizers as well as the draining of municipal sewage, and animal waste in the Lake (Sheikh et al., 2014). The diatom analysis further indicated the existence of organic contaminants in the lake's water (Shah et al., 2017; Shah et al., 2021). A study by Hassan et al. (2015) reveals that almost 30% of the land belonging to the Wular catchment is under agriculture activities. This 30% of agricultural land is directly responsible for the increase in Nitrogen loading in the lake waters and makes it harmful not only to aquatic animals but to the whole ecosystem. In addition, constructin channels, gullies and streams for agricultural purposes contributes to the high sediment load into the lake. Due to an increase in the demand for resources, communities are forced to adopt more exploitative forms of harvesting, particularly, in the case of fisheries.

The water of Wular Lake contains higher concentrations of heavy metals like Zinc, Lead, and Copper (Sheikh et al., 2014). Since agricultural and horticultural activities dominate the catchment area of the Wular Lake and does not contain any major industry, and also there is no metal mining plant nearby. Therefore, the only possible source of metal pollution is municipal and agricultural waste. The major portion of the municipal waste from Bandipora is dumped near the Zalwan village which is very close to Wular Lake. During heavy rainfall, and floods the municipal waste is washed into Wular Lake. This process has not only affected the lake waters but has also given rise to many epidemic diseases in the area.

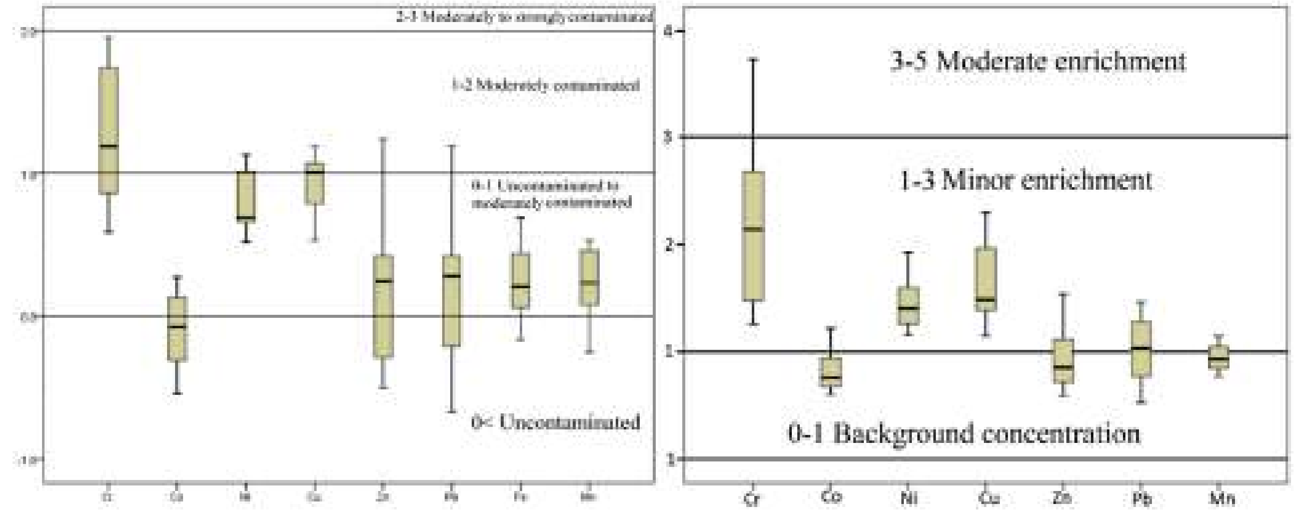

EXHIBIT 4 Stock plot for (a) geo-accumulation index and (b) enrichment factor of the Dal Lake sediments after Shah et al. (2021). [Color figure can be viewed at wileyonlinelibrary.com]

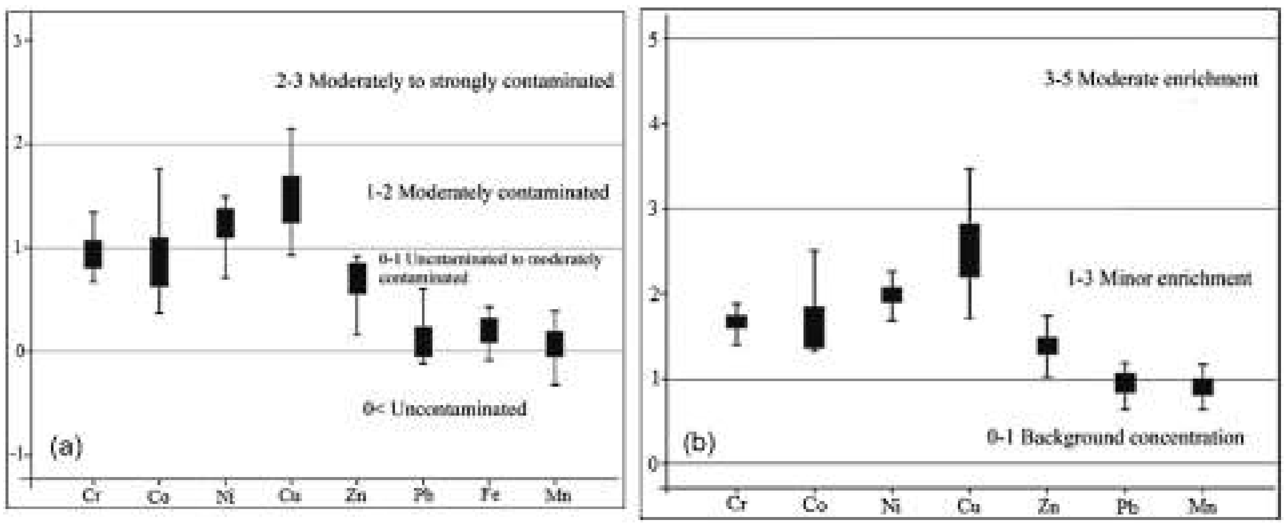

EXHIBIT 5 Stock plots for (a) geo-accumulation index and (b) enrichment factor (EF) of the Wular Lake sediments (Shah et al., 2020).

The average geo-accumulation index of surface sediments collected from Wular Lake in 2015, as reported by Shah et al. (2020), showed the following values for different metals: Cr (0.9), Co (0.88), Ni (1.17), Cu (1.51), Zn (0.66), Pb (0.09), Fe (0.20), and Mn (0.07) (Exhibit 5a). Notably, Ni and Cu displayed relatively higher Igeo indices across various study sites in the lake, averaging 1.17 for Ni and 1.51 for Cu. This suggests a moderate to strong contamination of these elements in the Lake. The same study also reported average enrichment factors, with Cu at 2.55, Ni at 1.98, Cr at 1.65, Co at 1.64, Zn at 1.39, Pb at 0.94, and Mn at 0.94 (Exhibit 5b). The enrichment factor indicated minor enrichment of Cr, Cu, Co, Ni, and Zn in the surface sediments of Wular Lake. The spatial distribution of these metals in Wular Lake revealed higher pollution levels in the vicinity of agricultural areas compared to more distant sites, highlighting horticulture and agriculture areas as the primary sources of these metals. Notably, certain heavy metals, including Co, Cu, Ni, and Zn, exhibited higher values in the sediments compared to others.

The organic matter reported from the Wular Lake sediments ranges from 1.42% to 14.89% (Shah et al., 2017) (Exhibit 6a). Two-thirds of the samples analyzed reported more than 5% of OM revealing a relatively high accumulation of organic detritus in the lake sediments (Shah et al., 2017). Total organic Carbon (TOC) reported in the same study ranges from 0.83% to 4.52% (Exhibit 6b). However, most of the samples revealed TOC in the range of 1% to 3%. The Nitrogen reported in the study ranges from 0.06% to 0.50% (Exhibit 6c). The spatial distribution maps reveal that the TOC and Nitrogen are sourced from the agricultural fields.

The sediment characteristics of the Wular Lake reveal challenges associated with the increasing sedimentation, specific conductivity, orthophosphate, and total phosphate, resulting in a decline in

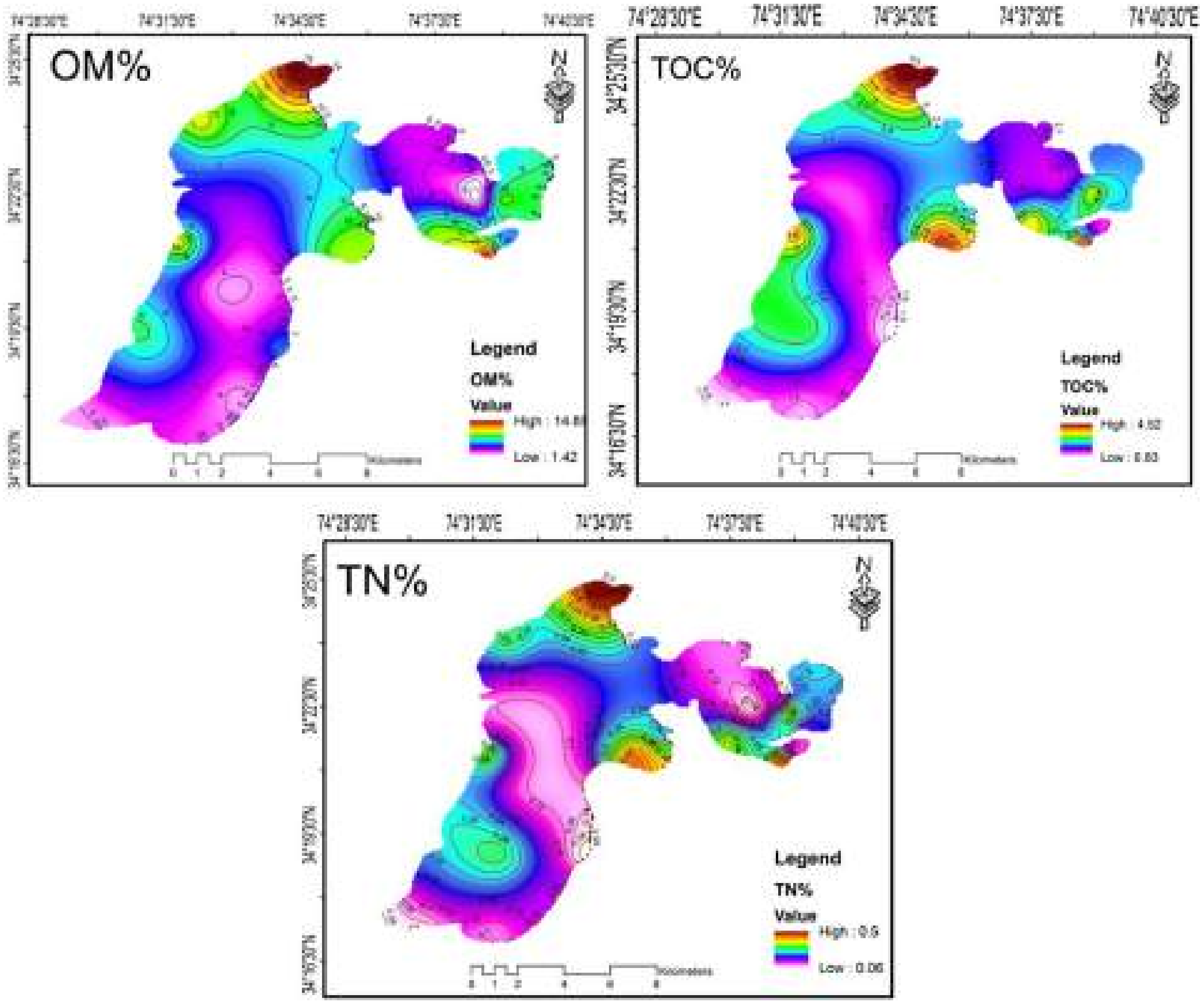

EXHIBIT 6 Spatial distribution of: (a) Organic matter, (b) TOC and (c) TN in the Wular lake (Shah et al., 2017). [Color figure can be viewed at wileyonlinelibrary.com]

transparency and dissolved Oxygen. The high concentrations of Nitrogen, particularly from agricultural activities, pose a threat to the aquatic ecosystem. These levels exceed acceptable limits, indicating a significant impact on water quality. Metal pollution in Wular Lake, specifically the enrichment of Cu, Ni, and Cr, suggests a moderate contamination status. Comparing these values with baseline or acceptable levels emphasizes the need for strict regulations on municipal waste disposal and other anthropogenic activities. Controlling these pollution sources is imperative to prevent further metal pollution and safeguard the lake's ecosystem.

4.3 | Manasbal Lake

The quality and quantity of water in this lake are deteriorating due to various pollutants originating from the catchment area, such as agricultural runoff, domestic effluents, municipal waste, sedimentation, and plastic waste. Moreover, the lake faces a critical situation characterized by a diminishing surface water area caused by encroachment and a high rate of sediment accumulation (Rashid et al., 2013; Sarkar et al., 2016). The reduction in water levels is anticipated to result in increased turbidity, habitat loss, and adverse effects on the lake's overall health. Hence, it is crucial to consistently monitor changes in the lake's surface area, providing a foundation for comprehending both natural climatic influences and human activities affecting the lake, to facilitate more effective management. The lake serves as a significant economic resource for the local population, as its unique geographic location attracts tourists from around the world. Furthermore, the lake supports the livelihoods of many locals through activities such as fisheries, fodder production, and other economically valuable species and practices. Considering the environmental and economic significance of the lake, it is imperative to regularly monitor and manage pollution to safeguard the pristine ecology and environment of this water body.

The geological formations observed in the lake's catchment area consist of Triassic limestone, Quaternary Karewas, and Recent alluvium (Sarah et al., 2011). The Triassic limestone encompasses a broad sequence of dense blue limestone, slates, and dolomites (Krishnan, 1968; Wadia, 1975). The Karewas formation represents deposits from a prehistoric lake during the Plio-Pleistocene era and is characterized by loosely consolidated materials, including fine silt, clays with sand, boulders, gravel, conglomerates, and embedded moraines (Agarwal & Agarwal, 2005; Burbank & Johnson, 1982; Singh, 1982). The Recent alluvium deposits in the area consist of coarser sediments like sand and gravel, as well as finer sediments such as silt and clay (Dar et al., 2015). The sediments currently accumulating on the floor of Manasbal Lake primarily comprise clay (49.79%), followed by silt (35.88%), with a lower concentration of sand (14.33%) (Babeesh et al., 2017). The predominance of fine sediment fraction mainly results from the calm water column in the Manasbal Lake basin. The $CaCO_3$ has a significant concentration in the lake sediment and varies from 1.01% to 7.41%. Similarly, the higher concentration of $CaCO_3$ is a result of the weathering of the limestone lithology surrounding the Manasbal Lake basin. The TOC of Manasbal Lake varies from 3.11 to 13.74% (Exhibit 7a) and TN from 0.20 to 1.96% (Exhibit 7b). The analysed organic matter of the lake sediments ranges from 3.73% to 19.65%, with a C/N ratio ranging from 5.15 to 15.71 with an average of 9.75 (Exhibit 7c) (Babeesh et al., 2017). The C/N ratio of the lake sediments indicates a major proportion of autochthonous (within the lake) organic matter production and a minor allochthonous (outside the lake) organic matter transport into the lake.

Metal pollution in the sediments of Manasbal Lake is relatively low. Lone et al. (2017) reported the mean Geo-accumulation index for sediment samples from Manasbal Lake, which is as follows: 0.70 for Zn, 0.20 for Co, 0.74 for Cu, 0.30 for Ni, −0.66 for Pb, −0.25 for Cr, −0.81 for Fe, and −0.83 for Mn (Exhibit 8). According to the study, all the metals exhibited Igeo values below 1, indicating that the sediments are practically unpolluted to moderately polluted. The mean enrichment factor reported by the same study is as follows: 3.05 for Cu, 2.23 for Ni, 2.19 for Zn, 1.50 for Cr, 1.39 for Co, 1.13 for Pb, and 1.04 for Mn. Therefore, the reported enrichment factor values for Manasbal Lake sediments suggest a minor enrichment of metals in the sediments, except Cu, which exhibits a moderate level of enrichment.

Overall, the data from Manasbal Lake indicate relatively low metal pollution levels, with Geo-accumulation and enrichment factor values suggesting minimal to moderate contamination. This indicates that the lake sediments are currently within acceptable limits. The C/N ratio in the organic matter content implies a predominant contribution of autochthonous organic matter, highlighting the lake's self-sustaining nature. Despite the positive findings, continuous monitoring is essential to ensure that metal pollution remains at manageable levels. Understanding the baseline or acceptable limits for these metals is crucial for early detection of any adverse trends. This emphasizes the significance of continuous surveillance to preserve the pristine ecology of Manasbal Lake and take timely corrective actions if needed.

4.4 | Mitigation strategies

Emphasizing the critical need for policymaking is imperative in addressing the identified issues in the aforementioned lakes. Policymakers should prioritize enacting stringent regulations for solid waste disposal around Dal Lake to curb nutrient influx. Additionally, controlling the use of fertilizers and manures in the surrounding cultivated land is crucial to curb nutrient runoff into the lake. Mitigation efforts should also focus on reducing anthropogenic pressures, such as dredging, weeding operations, and agricultural activities around the lake. Implementation of sustainable agricultural practices and regular monitoring can help ease stress on the lake's ecosystem. However, due to the excessive levels of TOC and nitrogen, complete restoration may be challenging. Still, effective mitigation involves identifying and curtailing major pollution sources and continuous monitoring to sustain long-term improvements.

Similarly, addressing water quality issues in Wular Lake requires a multi-faceted approach. Controlling sedimentation and nutrient loading from the catchment areas is of vital importance. Efforts should be directed towards regulating agricultural runoff, especially in areas contributing to high nitrogen levels. Adopting eco-friendly agricultural practices and creating buffer zones can significantly reduce the impact of fertilizers on the lake. To tackle heavy metal pollution, strict waste disposal regulations, particularly for municipal waste near big settlements, are necessary. Initiatives to prevent runoff of municipal waste into the lake during heavy rainfall and floods are vital. Additionally, monitoring and regulating industrial activities near the lake is essential to prevent further metal contamination.

Similarly, addressing water quality issues in Wular Lake requires a multi-faceted approach

Mitigation of the Manasbal Lake pollution involves a combination of measures. Preservation of the lake's water surface area is crucial, requiring effective management to prevent encroachment and sediment accumulation. Continuous monitoring of the lake's health, including the overall water quality and quantity, is essential for informed decision-making. Given the low metal pollution levels, preserving the status quo is critical. However, sustainable land use practices in the catchment area should be promoted to prevent the transport of pollutants from the catchment into the Lake. Initiatives to reduce plastic waste, control agricultural runoff, and management of domestic effluents will contribute to maintaining the ecological balance of Manasbal Lake.

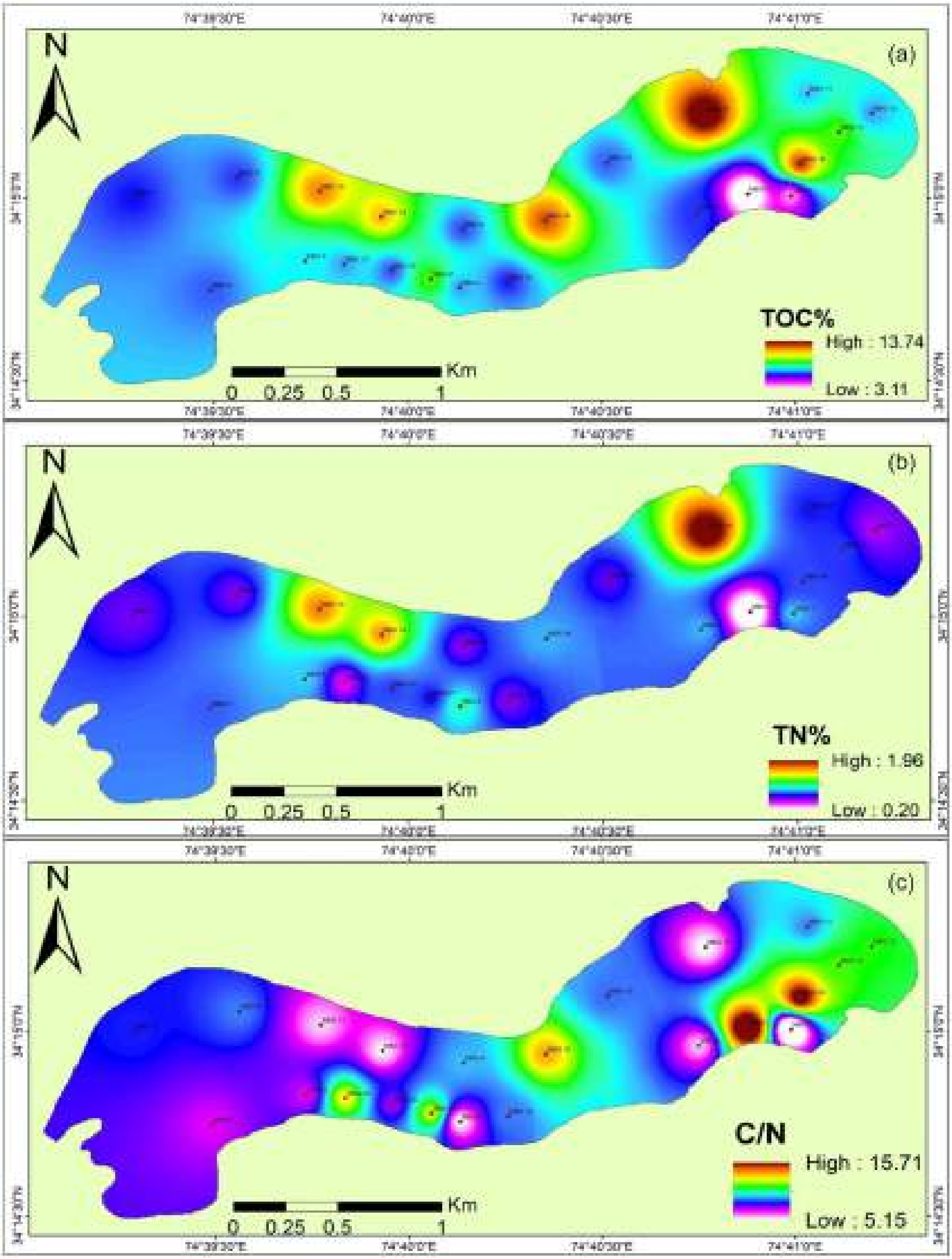

EXHIBIT 7 Spatial distribution of (a) TOC, (b) TN, and (c) C/N in the Manasbal Lake (Babeesh et al., 2017). [Color figure can be viewed at wileyonlinelibrary.com]

Policymaking plays a pivotal role in the prescription of comprehensive solutions to sustain the ecological balance of these precious water bodies. In all cases, policymakers must prioritize community involvement and awareness programs, fostering collaboration between stakeholders with local authorities for successful implementation of mitigation measures. Continuous monitoring and adaptive management strategies should be embedded in action plans to address evolving environmental challenges in these ecologically, economically and socially important aquatic ecosystems.

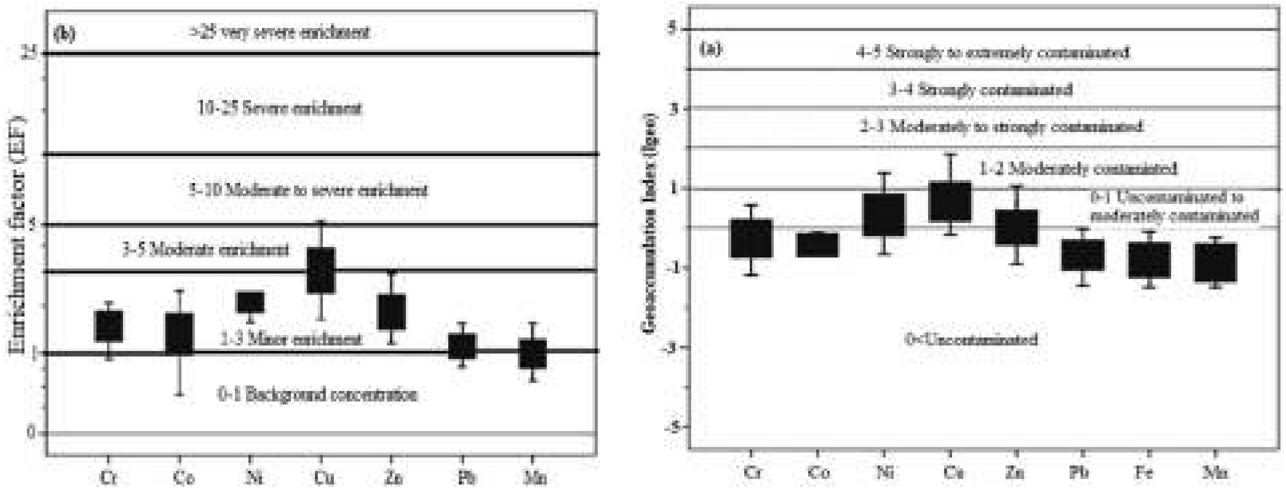

EXHIBIT 8 Description of geo-accumulation index (Igeo, a) and Enrichment factor (EF, b) of various trace metals for lake bottom sediments after Lone et al. (2017).

5 | CONCLUSIONS

The Kashmir Himalayan Lakes face severe environmental threats, marked by water quality deterioration, ecological shifts, loss of productivity and shrinkage of open waters. Dal Lake is undergoing rapid eutrophication and demands urgent measures to regulate solid waste pollution, ingress of untreated sewage and wastewater from Srinagar city into the lake, reckless fertilizer usage within and in the vicinity of the lake, pollution from houseboats and other settlements within the lake, and unregulated anthropogenic activities in the lake. Wular Lake confronts a myriad of challenges including increasing nutrient load and metal pollution, nutrient-rich agricultural runoff from the catchment, heavy sedimentation and deforestation in the catchment and uncontrolled urbanization. Manasbal Lake, though exhibiting lower metal pollution, necessitates continuous monitoring and adoption of sustainable land use practices, control and treatment of sewage from surrounding settlements, and reduction of fertilizer use in its immediate catchment. The current ecological condition of these lakes underscores the profound impact of climate change and anthropogenic activities, emphasizing the need for continuous monitoring, community engagement, and adaptive management to ensure their preservation. These lakes, valued for their aesthetics, economic, social and ecological importance, demand immediate, and collaborative efforts to mitigate their escalating environmental degradation.

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CONFLICTS OF INTEREST STATEMENT

All the authors hereby declare that they have no financial interest or any other conflict of interest.

DATA AVAILABILITY STATEMENT

The authors declare that the paper includes the data that underpins the study’s conclusions. The main dataset can be obtained by contacting the corresponding author upon a reasonable request.

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