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REVIEW PAPER

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A review of the ecological impacts of water pollution on lakes: From diatom assemblages to migratory bird population declines

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ABSTRACT

Lakes are key freshwater ecosystems that maintain the biodiversity, regulate nutrient cycles, and provide habitat for migratory birds. Their ecological well-being is greatly impacted by water quality, which affects the composition and productivity of primary producers such as diatoms. Diatoms are sensitive bio-indicators that respond spontaneously to the changing physical, chemical, and biological parameters. The dynamics of their communities extend through food webs, affecting fish, zooplankton, and, eventually, migratory bird populations. This review outlines the current scientific understanding regarding the relationships between bird communities, diatom ecology, and lake water quality, with a focus on case studies from Tamil Nadu and India. It has been demonstrated that major water quality stressors such as pollution, eutrophication, salinisation, and hydrological changes, disturb diatom assemblages, decrease the availability of prey, and deteriorate vital migratory bird stopover and breeding habitats.

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INTRODUCTION

Lakes are critical components of the global freshwater system, supporting a wide range of biodiversity and providing essential ecosystem services. They serve as reservoirs of drinking water, irrigation sources for agriculture, habitats for aquatic organisms, and key sites for nutrient cycling (Kalff, 2002; Moss, 2010). Lakes also act as sinks for atmospheric carbon and play a significant role in local climate regulation (Tranvik *et al.*, 2009). Their ecological functions extend to supporting socio-economic activities such as fisheries, tourism, and cultural practices (MEA, 2005; Carpenter *et al.*, 2011).

The ecological health of a lake is largely determined by its water quality, which reflects the physical, chemical, and biological characteristics of the aquatic environment. Water quality is influenced by both natural processes (e.g., seasonal turnover, precipitation) and anthropogenic pressures (e.g., agricultural runoff, industrial discharge, urban waste) (Wetzel, 2001; Smith and Schindler, 2009). Degradation of water quality can lead to eutrophication, algal blooms, hypoxia, and the collapse of aquatic food webs (Carpenter *et al.*, 1998; Dodds *et al.*, 2009). Assessing water quality is, therefore, essential for understanding ecosystem integrity and for guiding conservation and management actions (UNEP, 2016; Kumar *et al.*, 2020).

Role of diatoms as bioindicators

Diatoms are microscopic, photosynthetic algae found in nearly all aquatic habitats. Their silica-based cell walls (frustules) preserve well in sediments, making them valuable indicators of both present and past environmental conditions (Smoland Stoermer, 2010). Due to their rapid response to changes in water chemistry—particularly nutrients, pH, and conductivity—diatoms are widely used as bioindicators in water quality assessment (Stoermer and Smol, 1999; Battarbee *et al.*, 2001). Variations in diatom assemblages can reflect subtle ecological shifts that might not be detected through conventional chemical testing (Kelly *et al.*, 1998). Hence, they offer a powerful tool for long-term monitoring and ecological diagnosis of freshwater systems (Round *et al.*, 1990; Bennion *et al.*, 2014).

Migratory birds and their dependence on aquatic food webs

Migratory birds, especially waterfowl and waders, rely heavily on healthy wetland and lake ecosystems during breeding, stopover, and wintering phases of their life cycle (Kear, 2005; Newton, 2008). These birds feed on a range of aquatic organisms such as insects, mollusks, crustaceans, and fish—many of which are part of food webs driven by primary productivity from organisms like diatoms (Green and Elmberg, 2014; Baldassarre, 2014). Disruption in these food webs, due to declining water quality or habitat degradation, can result in altered migration patterns, reduced survival rates, and overall population decline (Davidson, 2014; Finlayson *et al.*, 2017). Thus, lake ecosystems form a vital ecological linkage between aquatic primary producers and higher trophic levels including birds (Weller, 1999; Wetlands International, 2021).This review aims to synthesize the current understanding of how lake water quality affects diatom communities and how these changes cascade through the food web to influence migratory bird populations. The review is structured into sections that progressively build on the interactions between water quality, diatoms, and migratory birds, followed by an analysis of conservation implications and future research directions.

Lake water quality parameters

Understanding lake water quality is fundamental to assessing ecosystem health and biodiversity dynamics. Various physical, chemical, and biological parameters influence the productivity, nutrient cycling, species composition, and overall ecological balance of freshwater systems (Wetzel, 2001; APHA, 2017). These parameters not only affect primary producers like diatoms but also shape the availability of food and habitat for higher trophic levels, including migratory birds (Karthick *et al.*, 2013; Saravanan *et al.*, 2022).

In India, several studies have highlighted how water quality deterioration—driven by nutrient enrichment, industrial pollution, and urban waste—has altered ecological functions of lakes and wetlands (Ramakrishnan *et al.*, 2006; Gupta and Bhatt, 2014). Specifically in Tamil Nadu, investigations of Pallikaranai Marsh, Pulicat Lake, and Vedanthangal Bird Sanctuary have revealed how changes in pH, dissolved oxygen, and nutrient levels affect plankton communities, fish populations, and ultimately waterbird abundance (Nagarajan and Thiyagesan, 1996; Saravanan *et al.*, 2022; Ramachandran *et al.*, 2020). These studies underscore the interconnectedness of water quality parameters with ecological health and conservation outcomes.

Influence of physical, chemical and biological parameters on plankton community

Temperature

Temperature plays a central role in regulating lake stratification, dissolved oxygen solubility, and biological metabolism. It influences the growth and reproduction of diatoms, with certain species preferring colder or warmer conditions (Reynolds, 2006; Wetzel, 2001). Seasonal changes in temperature can lead to thermal stratification, affecting vertical mixing of nutrients and oxygen distribution, which in turn impacts aquatic life (Kalff, 2002). Studies from Indian lakes, such as Loktak and Vembanad, demonstrate that seasonal temperature shifts significantly alter phytoplankton and zooplankton dynamics (Ramakrishnan *et al.*, 2006; Jyothibabu *et al.*, 2010).

In Tamil Nadu, seasonal fluctuations in water temperature at Pulicat Lake have been shown to influence fish populations and waterbird abundance (Ramachandran *et al.*, 2020).

Turbidity

Turbidity refers to the cloudiness of water caused by suspended solids like silt, organic matter, and plankton. High turbidity can reduce light penetration, limiting photosynthesis by diatoms and other autotrophs (Kirk, 2011). It may also clog fish gills and affect visual predators like birds that rely on clear waters to forage (Davies-Colley and Smith, 2001). In Indian wetlands, agricultural runoff and urban effluents are major contributors to turbidity (Khan and Ansari, 2005). Research on Pallikaranai Marsh, Tamil Nadu, has reported that high turbidity levels degrade aquatic productivity and reduce foraging efficiency for wading birds (Saravanan *et al.*, 2022).

Transparency

Measured using a Secchi disk, transparency indicates the depth to which light can penetrate water. It is a direct measure of the water's optical clarity. High transparency favors the growth of benthic and pelagic diatoms by enabling better light availability, while reduced transparency often signals eutrophication or pollution (Carlson, 1977; Moss, 2010). In India, transparency has been a reliable indicator for trophic status in urban lakes such as Hussain Sagar (Kumar *et al.*, 2010). In Tamil Nadu, reduced transparency in Vedanthangal and Pulicat lakes has been linked to nutrient enrichment and algal blooms, affecting the carrying capacity for migratory birds (Nagarajan and Thiyagesan, 1996; Ramachandran *et al.*, 2020).

pH

The pH of lake water affects nutrient availability, metal solubility, and the survival of aquatic organisms (Wetzel, 2001; Kalff, 2002). Diatoms are particularly sensitive to pH fluctuations; different taxa thrive under acidic, neutral, or alkaline conditions (Battarbee *et al.*, 2010). Extreme pH values can disrupt cellular processes and lead to shifts in community composition. Indian studies, such as those from Loktak Lake and Dal Lake, demonstrate that pH fluctuations significantly influence phytoplankton diversity (Ramakrishnan *et al.*, 2006; Rather and Khan, 2013). In Tamil Nadu, variations in pH in Pulicat Lake have been linked to changes in fish populations and waterbird foraging efficiency (Ramachandran *et al.*, 2020).

Dissolved oxygen (DO)

Dissolved oxygen is vital for aerobic aquatic life. It is replenished through diffusion from the atmosphere and photosynthesis by algae, including diatoms (Wetzel, 2001). Low DO levels (hypoxia) often result from organic pollution and eutrophication, causing fish kills and the collapse of aerobic microbial activity (Dodds *et al.*, 2009). This has cascading effects on bird food sources such as fish and invertebrates

(Davidson, 2014). In Indian lakes, hypoxic conditions have been reported in Hussain Sagar and Vembanad, leading to biodiversity decline (Kumar *et al.*, 2010; Jyothibabu *et al.*, 2010). In Tamil Nadu, DO fluctuations in Pallikaranai Marsh and Vedanthangal Bird Sanctuary have been linked to seasonal bird abundance (Saravanan *et al.*, 2022; Nagarajan and Thiyagesan, 1996).

Nutrients (Nitrogen and Phosphorus)

Nitrogen (N) and phosphorus (P) are essential for primary productivity but also drive eutrophication when present in excess (Smith and Schindler, 2009). Nutrient enrichment often leads to shifts in algal communities—replacing beneficial diatoms with nuisance or toxic cyanobacteria (Carpenter *et al.*, 1998). This alters the food base for invertebrates and fish, ultimately affecting migratory birds (Green and Elmberg, 2014). In India, high nutrient loading has been recorded in lakes like Loktak, Chilika, and Hussain Sagar (Ramakrishnan *et al.*, 2006; Pattnaik *et al.*, 2007). In Tamil Nadu, Pulicat Lake and Pallikaranai Marsh face nutrient-driven eutrophication from agriculture and sewage, threatening biodiversity (Ramachandran *et al.*, 2020; Saravanan *et al.*, 2022).

Salinity

Salinity influences osmoregulation in aquatic organisms and shapes species composition in freshwater lakes (Hammer, 1986). Diatoms exhibit varying tolerance to salinity; some are restricted to freshwater, while others thrive in brackish environments (Smoland Stoermer, 2010).

Increased salinization due to climate change, seawater intrusion, or human activities can stress freshwater taxa and modify trophic interactions (Williams, 2001). In Indian wetlands like Sambhar Lake and Pulicat Lake, rising salinity has been shown to reduce freshwater biodiversity and affect migratory bird populations (Nagarajan andThiyagesan, 1996; Ramachandran *et al.*, 2020).

Conductivity

Conductivity measures the water's ability to conduct electricity, which correlates with ion concentration (e.g., Na^+, Cl^-, $SO_4{}^{2-}$). It provides a general indicator of water mineralization and anthropogenic inputs (APHA, 2017). Elevated conductivity often reflects pollution or land-use change and influences diatom assemblages and habitat quality (Karthick *et al.*, 2013). Studies from Indian wetlands, including Chilika and Pallikaranai, reveal that conductivity is strongly linked to urban effluents and agricultural runoff (Pattnaik *et al.*, 2007; Saravanan *et al.*, 2022). In Tamil Nadu, seasonal variations in conductivity at Vedanthangal and Pulicat lakes have been reported due to impact plankton communities and waterbird foraging grounds (Nagarajan and Thiyagesan, 1996; Ramachandran *et al.*, 2020).

Presence of algae

Algae, including diatoms, form the base of the aquatic food web and are widely recognized as reliable indicators of water quality and trophic status (Reynolds, 2006; Smoland Stoermer, 2010). Their abundance, species diversity, and community composition reflect nutrient levels and ecological balance in aquatic systems. A balanced algal population supports healthy food chains, while excessive growth, particularly cyanobacterial blooms, indicates nutrient enrichment and can produce toxins harmful to aquatic fauna and humans (Paerland Otten, 2013; Saha and Paul, 2020). In Indian freshwater ecosystems, phytoplankton composition has been directly linked to eutrophication and seasonal changes (Kaushik and Saksena, 1995; Singh and Singh, 2006). Studies from Tamil Nadu lakes have reported seasonal variation in phytoplankton, especially diatoms and cyanobacteria, as effective bioindicators of water quality (Arivoli and Mohanraj, 2013; Murugan and Santhanam, 2011).

Microbial activity

Microbial communities play a central role in decomposition of organic matter, nutrient cycling, and sustaining energy flow in aquatic systems (Wetzel, 2001). Shifts in microbial abundance and diversity provide early warnings of deteriorating water quality. Elevated organic loads often enhance microbial respiration, leading to depletion of dissolved oxygen and creating stress for fish and invertebrates (Jindal and Sharma, 2011). In India, microbial activity has been shown to increase significantly in sewage-fed and polluted water bodies, accelerating oxygen depletion (Reddy and Rao, 1986). In Tamil Nadu lakes, microbial communities such as heterotrophic bacteria have been found to correlate strongly with nutrient enrichment and organic pollution (Senthilkumar and Sivakumar, 2018). Such microbial responses highlight their significance as bioindicators of anthropogenic stress in freshwater ecosystems.

Eutrophication and its effects

Eutrophication is the process of nutrient enrichment, primarily with nitrogen and phosphorus, leading to excessive algal growth and loss of ecological balance in aquatic ecosystems (Wetzel, 2001; Smith *et al.*, 1999). While it may initially enhance primary productivity, chronic eutrophication disrupts lake ecology in multiple ways.

One of the most prominent impacts is the decline in diatom diversity, as fast-growing green algae and cyanobacteria dominate under high nutrient conditions (Reynolds, 2006; Saha and Paul, 2020). This dominance of cyanobacteria and green algae, which are less palatable or even toxic to grazerseventually allow diatoms to lose their dominance. This shift can lower the efficiency of energy transfer to zooplankton and invertebrates. This further reduces the nutritional quality of prey available to birds (Paerland Otten, 2013; Jeppesen *et al.*, 2020).

The excessive organic matter produced leads to oxygen depletion, particularly in bottom waters, due to microbial decomposition of algal biomass (Carpenter *et al.*, 1998; Jindal and Sharma, 2011) as a result of microbial respiration which consumes large amounts of dissolved oxygen, leading to hypoxic or anoxic conditions. This process often triggers fish kills or increased mortality rates, reducing prey availability for piscivorous birdsand insectivorous birds (Schindler, 2001; Kaushik and Saksena, 1995). Bird species such as terns, gulls, and grebes may abandon degraded sites or suffer reproductive failure (Diaz and Rosenberg, 2008; Rabalais *et al.*, 2014).

Eutrophication also causes habitat degradation, making lakes unsuitable for foraging and nesting of migratory waterbirds (Arivoli and Mohanraj, 2013). The emergence of harmful algal blooms (HABs), dominated by toxin-producing cyanobacteria, poses direct health threats to fish, birds, and even humans (Paerland Otten, 2013). Long-term eutrophication alters species composition and food web dynamics, undermining the ability of lakes to sustain biodiversity, with severe consequences for sensitive groups such as migratory waterbirds that depend on stable, nutrient-balanced ecosystems (Murugan and Santhanam, 2011; Senthilkumar and Sivakumar, 2018).

Diatoms as ecological indicators

Biology and ecology of diatoms

Diatoms are unicellular, photosynthetic algae belonging to the class Bacillariophyceae. They are characterized by intricately patterned, silica-based cell walls called frustules, which make them both ecologically significant and taxonomically identifiable under a microscope (Round *et al.*, 1990; Smoland Stoermer, 2010). Diatoms occur in a wide range of aquatic habitats—from pristine mountain streams to nutrient-rich lakes—and can be found in planktonic (free-floating) and benthic (attached to surfaces) forms (Wetzel, 2001; Saha and Paul, 2020).

Ecologically, diatoms are primary producers, forming the foundation of aquatic food webs. They exhibit rapid reproduction under favorable conditions, allowing them to respond quickly to environmental changes (Stoermer andSmol, 1999; Reynolds, 2006). Their sensitivity to specific environmental parameters such as nutrient levels, salinity, temperature, and pH makes them reliable indicators of ecological shifts (Ramakrishnan and Kumar, 2018; Arivoli and Mohanraj, 2013; Murugan and Santhanam, 2011).

Sensitivity to water quality changes

Diatoms are widely recognized as one of the most responsive groups of microorganisms to changes in water quality (Smoland Stoermer, 2010; Wetzel, 2001). Different species have distinct ecological tolerances and optima, which allow for fine-scale detection of alterations in environmental conditions (Stoermer and Smol, 1999; Ramakrishnan and Kumar, 2018). For example, Eutrophic conditions known as high nutrient levels favor species like *Cyclotella meneghiniana* and *Nitzschia palea* (Reynolds, 2006; Saha and Paul, 2020). However, oligotrophic environments which are low nutrient conditionssupport species such as *Fragilaria crotonensis* or *Achnanthes* spp. (Round *et al.*, 1990; Singh and Singh, 2006) and acidic waters promote acid-tolerant diatoms like Tabellariafenestrata, while alkaline waters favor *Navicula* and *Gomphonema* species (Battarbee *et al.*, 2010; Arivoli and Mohanraj, 2013).

Since diatoms have short generation times, they can rapidly colonize new habitats or shift in composition in response to stressors, offering a real-time assessment of lake health (Murugan and Santhanam, 2011; Senthilkumar and Sivakumar, 2018).

Diatom indices and bioassessment

Diatoms are extensively used in bioassessment protocols due to their sensitivity, diversity, and persistence in the sediments (Smoland Stoermer, 2010; Wetzel, 2001). Quantitative diatom indices have been developed to assess the trophic status, organic pollution, and acidification of freshwater systems (Stoermer andSmol, 1999; Ramakrishnan and Kumar, 2018). Some of the widely used indices include:

1. Trophic Diatom Index (TDI): Assesses nutrient enrichment in rivers and lakes (Kelly and Whitton, 1995; Saha and Paul, 2020).
2. Paleoecological Diatom Index: Reconstructs historical water quality using fossil diatoms from sediment cores (Battarbee *et al.*, 2010; Singh and Singh, 2006).
3. Specific Pollution Sensitivity Index (IPS): Scores diatoms based on their tolerance to organic pollution (Coste, 1982; Arivoli and Mohanraj, 2013).

These indices are instrumental in regulatory monitoring frameworks such as the European Union Water Framework Directive (WFD) and can inform conservation and management actions (Kelly *et al.*, 1998; Murugan and Santhanam, 2011).

Diatoms as a link between water quality and bird ecology

Diatoms form the base of many freshwater food webs where their health directly influences the availability of resources for invertebrates and fish—critical prey for migratory birds. A decline in diatom diversity or productivity can disrupt trophic pathways, reducing biomass at higher levels (Stoermer andSmol, 1999; Battarbee *et al.*, 2010). This can also affect the timing and quality of food during bird migration periods (Jeppesen *et al.*, 2011; Kumar *et al.*, 2019), lead to habitat unsuitability, causing changes in bird distribution or decline in populations (Mukherjee and Borad, 2001; Arivoli and Mohanraj, 2013).Thus, monitoring diatom communities provides not only a measure of water quality but also an indirect indicator of bird habitat quality and sustainability (Soininen, 2007; Murugan and Santhanam, 2011).

Lakes and wetlands serve as complex ecological networks where energy and nutrients are transferred across multiple trophic levels formingtrophic linkages between diatoms and migratorybirds. Diatoms, as primary producers, form the base of this aquatic food web. Though birds do not directly consume diatoms, the trophic influence of diatoms cascades through invertebrates and fish to shape food availability and habitat conditions for migratory bird species (Reynolds, 2006; Jeppesen *et al.*, 2010). Understanding these linkages is critical for assessing how changes in lake water quality can impact bird populations (Mukherjee and Borad, 2001; Arivoli and Mohanraj, 2013).

Diatoms as primary producersplay an important role in food web dynamics, where theycontribute significantly to primary productivity in lakes. Through photosynthesis, they convert sunlight into biomass and oxygen, forming a major part of the phytoplankton and periphyton community. Their production supports the diet ofZooplankton like copepods and rotifers, Macro-invertebrates for e.g., insect larvae, mollusks and amphipods and also for small fish and fish larvae that graze on invertebrates or plankton. These lower trophic organisms are essential food resources for migratory waterbirds, such as ducks, shorebirds, and herons (Reynolds, 2006; Jeppesen *et al.*, 2010; Arivoli and Mohanraj, 2013).

Energy transfer to birds is witnessed especially in migratory bird populations. Based on their feeding preferences migratory birds are categorized as Planktivores,such as some ducks, that consume zooplankton supported by diatom blooms; Invertivores that feed on invertebrates that rely on benthic diatoms(e.g., sandpipers, storks) and piscivores that depend on fish that are indirectly sustained by diatom-based primary production(e.g., pelicans, cormorants). Disruptions at the diatom level, due to pollution, eutrophication, or salinity changes, can therefore reduce prey abundance and quality, diminishing bird foraging success (Mukherjee and Borad, 2001; Ramachandran and Rajkumar, 2018).

Diatoms not only support food webs but also contribute to habitat structuring where benthic diatoms form biofilms on submerged surfaces, supporting invertebrate communities in mudflats and shallow water zones—critical feeding areas for wading birds.This critically determines the foraging behavior and habitat suitability of migratory birds as they select feeding and stopover sites based on prey availability, which is a function of underlying productivity and water quality.The periphytic diatoms influence macrophyte growth, which provides shelter and breeding grounds for aquatic organisms and nesting areas for birds.When diatom-based productivity is high and stable, these sites support higher bird abundance, diversity, and reproductive success (Waiser and Robarts, 2004; Kumar *et al.*, 2019; Murugan and Santhanam, 2011).

Above all theseasonal dynamics and migration timing play a significant role as the seasonal variation in diatom productivity also influences the timing of bird arrival and departure at wetlands, their body condition and fat reserves needed for long-distance flight and the reproductive readiness in species that nest near lakes. For instance, pre-migratory staging birds rely on nutrient-rich foraging grounds to accumulate energy. A collapse in diatom populations during critical migratory windows which can happen due to thermal stress or nutrient imbalance often delaying migration or reducing survival rates (Smoland Stoermer, 2010; Balachandran, 2006; Samikannu *et al.*, 2020).

Feedback loops between birds and lake ecosystems

Migratory birds also contribute to nutrient cycling in lakes through excretion of guano, enriching shallow zones with nitrogen and phosphorus, Bioturbation from foraging, influencing sediment mixing and diatom resuspension and Seed dispersal and habitat engineering, which affects aquatic plant–diatom interactions. This creates feedback loops, where bird activity can influence the composition and productivity of diatoms, and vice versa, making the relationship between diatoms and birds mutually interdependent and dynamic (Post *et al.*, 1998; Hahn *et al.*, 2007; Ramachandran *et al.*, 2017).

Influence of lake degradation on migratory bird populations, conservation implications and management strategies

Lakes and associated wetlands are crucial stopover, wintering, and breeding sites for millions of migratory birds worldwide. However, degradation of these habitats, especially due to declining water quality, poses serious threats to bird populations. As diatoms play a major role in sustaining lake habitats for migratory birds, any negative impact will lead to trophic disruption (Finlayson *et al.*, 2018; Ramsar Convention Secretariat, 2021). When diatom communities are degraded, the zooplankton and macroinvertebrate populations decline and survival of fish larvae drops due to food shortage. Birds exhibit changes in feeding patterns, site fidelity, or migrate longer distances to find suitable habitats where some species may suffer population declines or altered migratory pathways.

This trophic disruption can be especially harmful in regions where lakes serve as critical migratory flyways or breeding grounds, such as Ramsar wetlands or transcontinental bird routes (e.g., Central Asian Flyway, East Asia–Australasia Flyway) (Davidson, 2014; Balachandran, 2006; Samikannu *et al.*, 2020).

Therefore, changes in trophic dynamics, habitat structure, and food web stability resulting from pollution, eutrophication, or salinization can significantly alter bird behavior, foraging success, and survival as shown in Table 1.

Table 1. Evidence from case studies linking diatoms and migratory birds

Region	Key stressors	Ecological Impact on diatoms / Food web	Consequences for migratory birds	References
Chilika Lake, Odisha, India	Sedimentation, eutrophication	Algal blooms; reduced fish population	Decline in piscivorous birds (pelicans and cormorants)	Balachandra *et al.*, 2020; Sundar and Subramanya, 2010.
Keoladeo National park, Bharathpur, India	Water diversion, pollution, wetland drying	Habitat loss; reduced prey availability	Decline in migratory waterfowl; Siberian crane (Grus leucogeranus)	Vijayan, 1991; BirdLife International, 2020
Danube delta and Lake, Europe	Eutrophication, industrial discharges	Shift from diatoms to Cyanobacteria dominance	Reduced food resource for benthic-feeding birds (snipes and sandpipers)	Ibelings, 2016; Donohue *et al.*, 2019
Great Lakes region, North America	Nutrient imbalance, habitat alteration	Loss of diatom-based productivity; decline in invertebrates	Migratory ducks and shorebirds impacted during spring/fall migrations	Smith *et al.*, 2015; Schindler, 2019

Other impacts

Some cyanobacteria produce neurotoxins or hepatotoxins that can accumulate in aquatic organisms and pose direct toxic effects orhealth risks to birds. Documented bird die-offs due to cyanotoxins have occurred in several wetlands globally (Metcalf *et al.*, 2012; Burford *et al.*, 2020). Sub-lethal effects include impaired navigation, reproduction, or immunity (Carmichael, 2001; Miller *et al.*, 2010).

Degraded water quality often coincides with increased sedimentation and vegetation overgrowth.

Loss of mudflats and shallow feeding areas are critical for waders (Ma *et al.*, 2010; Sundar and Subramanya, 2010) and encroachment of invasive species lead to altering nesting habitats (Sharma *et al.*, 2016). Pollution and water abstraction alter hydrological regimes, affecting the availability and timing of suitable foraging habitats. Early drying of wetlands limits resource availability during migration windows (Vijayan, 1991; Pattnaik *et al.*, 2021). Increased salinity excludes freshwater species, reducing prey diversity (Zhang *et al.*, 2019).

Climate-induced changes—such as increased temperatures, altered precipitation patterns, and salinization—affect both diatom communities and migratory bird behavior (IPCC, 2022; Smoland Douglas, 2007). However, climate-mediated interactions across trophic levels are poorly understood (Adrian *et al.*, 2009; Hassan *et al.*, 2021 – Indian wetlands; Both *et al.*, 2009; Pearce-Higgins and Green, 2014; Thackeray *et al.*, 2016).

Conservation concerns

Degraded lake systems not only threaten individual species but also disrupt entire migratory flyways. Lakes serve as stepping stones across continents for millions of birds. The degradation of one or more of these critical sites can have cascading consequences across the entire migration network, especially for species already facing climate and land-use pressures (BirdLife International, 2020; Harris *et al.*, 2019). Given the critical role of lake ecosystems in supporting biodiversity—particularly primary producers like diatoms and migratory birds at higher trophic levels—it is imperative to adopt integrated conservation and management approaches. The degradation of water quality and its cascading ecological impacts necessitate multi-pronged strategies combining restoration, monitoring, policy, and community participation (Jeppesen *et al.*, 2020; Kumar *et al.*, 2022; Ramsar Convention Secretariat, 2021). Consequences in behavioral and demographical changes must be addressed. Birds experiencing habitat degradation may extend migratory routes in search of suitable alternatives (Newton, 2008). They delay migration or show poor body condition due to reduced food (Davidson and Stroud, 2016). Population rates suffer due to declines in breeding success as a result of inadequate nourishment (Finlayson *et al.*, 2018).Cumulatively, these stressors can lead to population declines, loss of genetic diversity, and changes in migration corridors, threatening the long-term viability of migratory species (Kirby *et al.*, 2008; Ramsar Convention Secretariat, 2021). Establishing bird sanctuaries and no-disturbance zones during peak migration and nesting periods. Habitat enhancement projects such as the creation of mudflats, shallow pools, and nesting islands can improve foraging and breeding opportunities (Ma *et al.*, 2010; Rahmani, 2012 – India).

Restoring water quality is most required to reduce nutrient load. One of the most effective measures to restore water quality is limiting nutrient inputs, particularly nitrogen and phosphorus, from agricultural runoff, sewage, and industrial waste. Reducing nutrient loads helps in restoring diatom diversity and minimizing the dominance of harmful algae (Jeppesen *et al.*, 2005; Paerland Otten, 2013). Buffer zones and vegetative filters around lakes to trap sediments and nutrients can be planned (Carpenter *et al.*, 1998; Withers and Jarvie, 2008) along with constructed wetlands for tertiary wastewater treatment (Vymazal, 2011; Mitsch and Gosselink, 2015). Regulations on fertilizer use, especially near ecologically sensitive zones can be mandated (Smith and Schindler, 2009).

Maintaining natural hydrological regimes through environmental flow releases and water level control ensures habitat availability during critical migratory periods. Periodic flushing of lakes can also help remove excess nutrients and prevent stagnation (Poff *et al.*, 1997; Bunn and Arthington, 2002). Excessive sedimentation degrades benthic habitats crucial for periphytic diatoms and invertebrates. Desiltation efforts, when well-managed and ecologically informed, can help restore both the feeding grounds for benthic-feeding birds (Finlayson *et al.*, 2018) as well as improve light penetration for diatom photosynthesis (Likens, 2010; Wetzel, 2001).

Conservation planning should integrate Long-Term Diatom Monitoring Programs and Sediment Core Analysis. This can be successful by establishing diatom sampling stations at strategic locations in lake systems (Kelly *et al.*, 1998; Dixit *et al.*, 1999), creating reference libraries of diatom assemblages from pristine and degraded lakes (Soininen, 2007; Stevenson *et al.*, 2010), including diatom indices (e.g., TDI, IPS) in national water quality monitoring protocols (Kelly and Whitton, 1995; Pandey *et al.*, 2014 – India), studying fossil diatoms in sediment cores offers insights into historical ecological conditions, helping track changes due to land use, pollution, or climate over decades or centuries (Battarbee *et al.*, 2001; Smoland Stoermer, 2010). This supports adaptive lake management based on long-term ecological trends (Agnihotri and Mishra, 2021 – India).

Technological gaps in diatom monitoring

Traditional diatom identification is labor-intensive and requires taxonomic expertise. This limits widespread adoption in routine monitoring programs (Round *et al.*, 1990).

Protecting migratory bird habitats requires conserving wetland–lake complexes, regulating tourism and development near sensitive zones, establishing sanctuaries with no-disturbance periods, and undertaking habitat enhancement through mudflats, shallow pools, and nesting islands. A systems-based, integrated approach linking water quality monitoring, diatom studies, and avian surveys under ecosystem-based management enhances resilience and early detection of degradation. Community participation through capacity-building, citizen science, sustainable farming, and ecotourism strengthens conservation outcomes while supplementing formal datasets. At the policy level, enforcing wetland laws, expanding Ramsar site management, and engaging in international agreements like the CMS and Central Asian Flyway, alongside regional collaboration on diatom monitoring, are essential. However, major research gaps remain: the absence of integrated long-term monitoring of water chemistry, diatoms, and bird dynamics; poor understanding of diatom–bird trophic pathways via intermediate consumers; and the neglect of small or seasonal lakes that act as critical migratory stopovers along key flyways. Lack of Integrated Long-Term Monitoring Despite numerous short-term studies, integrated, long-term datasets that link lake water chemistry, diatom assemblages, and bird population dynamics are rare, particularly in tropical and developing regions (Smol, 2008; Battarbee *et al.*, 2005).

Addressing these gaps demands long-term ecological research stations, holistic monitoring frameworks, data-sharing platforms, isotope and food web studies, and coordinated international research across understudied wetlands, particularly in tropical and developing regions.

Encouraging regional collaboration in diatom monitoring and habitat restoration (UNEP, 2018; Anbumozhi and Reddy, 2019 – Tamil Nadu case study on water governance).

CONCLUSION

Lakes function as vital ecological hubs where microscopic diatoms and migratory birds are linked through intricate food web relationships. The health of these ecosystems is tightly bound to water quality, which regulates diatom productivity and, in turn, influences higher trophic levels. When water quality declines, the stability of these networks unravels, threatening both biodiversity and ecosystem services. Conservation must therefore integrate scientific monitoring, habitat restoration, and sustainable community practices to ensure resilience. Policy frameworks and international cooperation are equally critical, given the transboundary nature of migratory bird movements. Long-term, interdisciplinary research will be key to addressing existing knowledge gaps and preparing for climate-driven challenges. Ultimately, protecting lakes safeguards not just water bodies but the living migratory corridors that connect species, ecosystems, and people across regions.

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