BIODIVERSITY REPORTS

Review Article

Journal homepage: https://biodiversity.crcjournals.org/

A Comprehensive Review of the Ecological Transformation and Anthropogenic Pressures Affecting Dal Lake in Kashmir

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Received 07 April 2026 | Revised 11 May 2026 | Accepted 15 June 2026 | Available Online July 18, 2026

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Citation: Shahid E Murtaza (2026). A Comprehensive Review of the Ecological Transformation and Anthropogenic Pressures Affecting Dal Lake in Kashmir. ***Biodiversity Reports An International Journal***.
DOI: https://doi.org/10.51470/BDR.2026.05.02.07

Abstract

Dal Lake, situated in the heart of Srinagar in the Kashmir Himalaya, represents one of the region's most important freshwater ecosystems and is simultaneously an ecological, socioeconomic, cultural, and tourism asset. Over recent decades, however, the lake has undergone substantial ecological transformation as a consequence of increasing anthropogenic pressure, urban expansion, catchment modification, agricultural intensification, tourism activities, untreated wastewater, solid-waste accumulation, encroachment, sedimentation, and the proliferation of floating gardens and aquatic macrophytes. Historical and contemporary investigations indicate progressive deterioration in several water-quality parameters and increasing nutrient enrichment, particularly nitrogen and phosphorus, which have contributed to eutrophication and changes in the biological structure of the lake. Long-term studies have also documented substantial changes in land use and land cover around the lake and a reduction in the lake's spatial extent. Recent research has further highlighted sediment accumulation, heavy-metal contamination, microplastic pollution, and the interaction between climate change and anthropogenic disturbances as emerging dimensions of ecological risk. This review synthesizes the major dimensions of ecological transformation in Dal Lake, examines the principal anthropogenic drivers, evaluates their consequences for water quality, biodiversity, ecosystem functioning, livelihoods, and tourism, and discusses the limitations of existing conservation approaches. The review argues that restoration of Dal Lake requires a shift from fragmented pollution-control measures toward an integrated catchment-to-lake management framework incorporating nutrient-source reduction, wastewater treatment, ecological monitoring, sediment management, sustainable tourism, community participation, climate-resilient planning, and scientifically informed governance.

Keywords: *Dal Lake, Kashmir Himalaya, ecological transformation, anthropogenic pressure, eutrophication, water quality, biodiversity.*

1. Introduction

Freshwater lakes are among the most valuable and vulnerable components of mountain ecosystems. They provide water-regulation functions, habitat for aquatic biodiversity, fisheries, agricultural resources, recreational opportunities, cultural services, and livelihood support. Their ecological condition is strongly influenced by interactions between hydrological processes, catchment characteristics, climate variability, biological productivity, and human activities [1]. Dal Lake is a distinctive example of a freshwater ecosystem in which ecological functions are closely intertwined with human settlement and economic activity. Located within Srinagar, Jammu and Kashmir, the lake has historically supported fisheries, vegetable cultivation, tourism, transportation, recreation, and other livelihood activities. Its houseboats, floating gardens, wetlands, and surrounding landscapes have also made it an internationally recognized symbol of Kashmir.

The ecological condition of Dal Lake, however, has changed considerably over the last several decades. Earlier ecological investigations already identified sewage discharge, catchment degradation, human encroachment, interruption of water flow, increasing population pressure, siltation, and excessive aquatic macrophyte growth as important causes of deterioration. More recent investigations demonstrate that these pressures have intensified and become increasingly interconnected [2]. A long-term assessment integrating historical records, remote sensing, demographic information, field observations, and water-quality data reported a reduction in the lake's area from approximately 31 km^2 in 1859 to about 24 km^2 in 2013. The same study documented substantial increases in nutrient concentrations and extensive changes in land use and settlement patterns [3]. The problem is therefore not simply one of water pollution. Dal Lake is experiencing a broader ecological transformation involving hydrological alteration, eutrophication, sediment accumulation, habitat modification, biodiversity changes, pollution, land transformation, and increasing human dependence.

The objective of this review is to synthesize existing knowledge concerning these transformations and identify the major anthropogenic drivers affecting the ecological integrity of Dal Lake. Particular attention is given to water quality, eutrophication, land-use change, wastewater, agriculture, floating gardens, tourism, houseboats, encroachment, sedimentation, emerging pollutants, biodiversity, and climate-related pressures.

2. Ecological Setting and Importance of Dal Lake

Dal Lake forms an important component of the urban wetland system of Srinagar. Its ecological significance derives not only from its open-water areas but also from associated wetlands, marshy habitats, aquatic vegetation, channels, floating gardens, and surrounding catchments [4]. The lake performs multiple ecosystem functions. These include habitat provision, nutrient cycling, flood regulation, carbon storage, recreation, fisheries, agricultural production, and cultural services. The lake is also closely connected with the regional tourism economy [5]. Its socioeconomic importance creates a fundamental management challenge. Human activities are simultaneously dependent upon the lake and responsible for many of the pressures affecting it. Tourism depends on its scenic and cultural value, while some communities depend directly on fishing, vegetable cultivation, boating, and other lake-related activities. This interdependence means that ecological restoration cannot realistically be separated from livelihood considerations.

Table 1: Major anthropogenic pressures affecting Dal Lake and their ecological consequences

Anthropogenic pressure	Major sources/activities	Principal environmental impacts
Urbanization	Expansion of residential and commercial areas	Habitat loss, increased runoff, encroachment and pollution
Domestic wastewater	Sewage from settlements and surrounding urban areas	Nutrient enrichment, organic pollution and microbial contamination
Houseboats and tourism	Sewage, solid waste and intensive tourism activities	Water-quality deterioration, waste accumulation and increased nutrient loading
Agricultural activities	Fertilizers, pesticides and agricultural runoff	Nitrogen and phosphorus enrichment and eutrophication
Floating gardens	Cultivation within lake areas and associated nutrient inputs	Nutrient enrichment, habitat modification and reduction of open-water areas
Encroachment	Construction and conversion of lake-associated land	Reduction in lake area, habitat loss and disruption of hydrological processes
Sedimentation	Soil erosion and catchment degradation	Reduction in water depth and storage capacity
Aquatic weed proliferation	Excessive nutrient availability	Reduced open-water area, navigation problems and altered oxygen dynamics
Solid-waste disposal	Domestic and tourism-generated waste	Physical pollution, degradation of aesthetic quality and potential toxic effects
Emerging pollutants	Plastics, microplastics and heavy metals	Ecotoxicological risks and potential bioaccumulation
Climate variability and change	Changes in temperature and precipitation patterns	Altered hydrology, ecological stress and increased vulnerability of the ecosystem

Table 2: Major ecological changes reported in Dal Lake and their implications

Ecological component	Reported changes	Major implications
Lake area	Progressive reduction in historical lake extent	Loss of aquatic habitat and ecosystem services
Water quality	Increasing nutrient and organic pollution	Deterioration of ecological and recreational quality
Nutrient status	Increasing nitrogen and phosphorus concentrations	Accelerated eutrophication
Dissolved oxygen	Decline reported in several long-term assessments	Stress on aquatic organisms
Aquatic vegetation	Increased proliferation of macrophytes	Alteration of habitat and reduction of open-water areas
Sediment characteristics	Increasing sediment accumulation	Reduced depth and lake-storage capacity
Biodiversity	Changes in aquatic communities and fish populations	Declining ecological integrity
Heavy metals	Detection and accumulation of potentially toxic metals	Ecotoxicological and food-chain concerns
Microplastics	Increasingly recognized as an emerging pollutant	Risks to aquatic organisms and ecosystem health
Ecosystem services	Increasing pressure on tourism, fisheries, agriculture and recreation	Socioeconomic vulnerability
Ecological resilience	Increasing pressure from multiple interacting stressors	Reduced capacity of the lake to recover naturally

3. Historical Ecological Transformation

The transformation of Dal Lake is a long-term process rather than a recent phenomenon. Early ecological studies identified human settlements, sewage discharge, catchment degradation, siltation, and excessive aquatic vegetation as important factors influencing lake deterioration.

Historical land-use investigations have demonstrated major changes in and around the lake. One remote-sensing-based study examining the period 1981–2011 reported substantial land transformation around Dal Lake and linked these changes with increased pollutant and nutrient inputs [6]. A particularly important long-term assessment found that the lake's area declined from approximately 31 km^2 in 1859 to 24 km^2 by 2013. The study also reported that built-up areas within the lake increased dramatically and that population growth and settlement expansion contributed to increased untreated sewage inputs. These historical changes demonstrate that the current ecological condition of Dal Lake reflects the cumulative consequences of decades of human intervention.

4. Major Anthropogenic Pressures

4.1 Urbanization and Population Growth

Urban expansion around Dal Lake has fundamentally altered the relationship between the lake and its catchment [7]. Increasing residential development generates wastewater, solid waste, surface runoff, and altered drainage patterns. Expansion of impervious surfaces can modify runoff pathways and increase the rapid transport of contaminants into receiving waters. Long-term research has linked population growth and urban development with increased nutrient loading and deterioration of water quality. The problem is amplified by the fact that Dal Lake is embedded within a rapidly developing urban environment. Consequently, the lake receives pressures originating both directly within its boundaries and indirectly from its surrounding catchment.

4.2 Untreated and Inadequately Managed Wastewater

Wastewater represents one of the most important anthropogenic pressures on Dal Lake.

Domestic sewage introduces organic matter, nitrogen, phosphorus, pathogens, and other contaminants. Where wastewater treatment is insufficient or where sewage bypasses treatment systems, nutrient-rich effluent can reach the lake [8]. Earlier and recent studies have consistently identified sewage from settlements and houseboats as a major contributor to nutrient enrichment. The consequences extend beyond direct contamination.

Increased nutrient availability stimulates primary production and aquatic plant growth, potentially accelerating eutrophication and reducing dissolved oxygen under certain conditions.

5. Agricultural Runoff and Floating Gardens

Agriculture represents another important nutrient pathway.

The catchment surrounding Dal Lake contains agricultural areas where fertilizers and other agricultural inputs can be transported through surface runoff and drainage. Floating gardens represent a particularly distinctive form of agricultural activity within the lake.

Although floating cultivation provides important livelihoods and contributes to local food production, intensive agricultural activity can increase nutrient loading when fertilizers and organic wastes enter the aquatic environment [9]. Long-term studies have specifically associated agricultural expansion and floating gardens with increasing nutrient inputs into Dal Lake. This illustrates an important management dilemma: activities that are economically valuable to local communities can simultaneously contribute to ecological degradation.

6. Eutrophication and Nutrient Enrichment

Eutrophication is arguably one of the most prominent manifestations of ecological transformation in Dal Lake [10]. The principal drivers include excessive inputs of nitrogen and phosphorus from domestic sewage, agricultural runoff, catchment drainage, and other anthropogenic sources. Historical comparisons have demonstrated increasing nutrient concentrations. One long-term assessment reported an increase in ortho-phosphate phosphorus from 16.75 µg/L in 1977 to 45.78 µg/L in 2014, while nitrate-nitrogen increased from 365 µg/L to 557 µg/L over the same broad period. A 2025 assessment of the lake's trophic state further characterized eutrophication as a major ecological problem and linked intensified nutrient inputs with algal blooms, deterioration of water quality, reductions in indigenous fish populations, and disturbance of ecological balance. More recent work published in 2026 also identifies the long-term intensification of eutrophication as a central issue for Dal Lake and emphasizes integrated management as necessary for sustainable development.

7. Changes in Water Quality

Water-quality deterioration provides one of the clearest indicators of ecological change [12]. Research spanning several decades has identified deterioration in parameters including dissolved oxygen, transparency, nutrients, chlorides, organic matter, and other physicochemical characteristics. A review of long-term water-quality changes concluded that transparency and dissolved oxygen declined while phosphate, nitrate, and chloride concentrations increased under sustained anthropogenic pressure. A separate 20-year assessment reported substantial increases in total phosphorus, nitrate-nitrogen, and chemical oxygen demand across several parts of the lake. Water-quality degradation is spatially heterogeneous. Areas close to major settlements, wastewater inputs, agricultural activities, and intensive human use can experience greater pressure than relatively less disturbed sections of the lake [13]. This spatial variability demonstrates the importance of basin-specific monitoring rather than relying exclusively on lake-wide average values.

8. Sedimentation and Reduction in Lake Capacity

Sedimentation represents another major ecological concern [14]. Sediments entering the lake from the surrounding catchment can reduce water depth, modify habitats, transport nutrients and contaminants, and contribute to the progressive loss of lake volume.

A recent review of Kashmir Himalayan lakes estimated a sedimentation rate of approximately 0.93 cm per year for Dal Lake, considerably higher than the reported rates for some other regional lakes examined in the same study [15]. Sediment accumulation is particularly concerning because it can interact with eutrophication. Nutrients stored within sediments may become available to the water column under favorable physicochemical conditions, potentially reinforcing nutrient cycling and algal or macrophyte growth. Consequently, sediment management needs to be considered alongside wastewater and nutrient management rather than treated as an independent problem.

9. Aquatic Macrophytes and Habitat Transformation

Excessive aquatic vegetation has long been associated with ecological deterioration in Dal Lake. Historical research identified prolific macrophyte growth as one of the consequences of increased nutrient loading and altered ecological conditions [16]. Macrophytes are not inherently detrimental. Aquatic plants provide habitat, contribute to nutrient cycling, stabilize sediments, and support biodiversity. However, excessive proliferation can reduce open-water areas, interfere with navigation, alter oxygen dynamics, and indicate nutrient enrichment. Therefore, mechanical removal of weeds alone cannot provide a sustainable solution. Unless nutrient inputs are reduced, vegetation removal may treat the symptom rather than the underlying cause.

10. Biodiversity Implications

Ecological transformation affects the biological communities of Dal Lake at multiple trophic levels [17]. Changes in water quality, nutrient concentrations, dissolved oxygen, habitat structure, and aquatic vegetation can alter communities of plankton, macroinvertebrates, fish, macrophytes, and microorganisms. Recent assessments have linked increasing eutrophication with changes in indigenous fish populations and overall ecological balance. Research on aquatic vegetation also emphasizes the importance of Dal Lake as a habitat for diverse macrophyte communities, including ecologically important taxa. Biodiversity loss should therefore be considered not merely as a conservation issue but as an indicator of declining ecosystem functionality.

11. Houseboats, Tourism and Solid-Waste Generation

Tourism constitutes one of the most visible and economically significant uses of Dal Lake [18]. Houseboats have become an iconic component of Kashmir's tourism economy and cultural identity. At the same time, concentrated human activity within the lake generates sewage and solid waste. Research examining houseboat-related pollution has identified wastewater and solid waste as important contributors to ecological deterioration. The appropriate policy response should therefore not be framed simply as a conflict between tourism and conservation. Instead, tourism needs to be reorganized around ecological carrying capacity.

Potential approaches include improved wastewater collection, zero-discharge or closed-wastewater systems where technically feasible, solid-waste segregation, controlled tourism infrastructure, environmental standards for houseboats, and continuous compliance monitoring.

12. Encroachment and Land-Use Change

Encroachment is among the most persistent structural pressures on Dal Lake. Conversion of wetland and lake-associated areas for settlement, infrastructure, agriculture, and other uses can reduce storage capacity and interfere with natural ecological processes. Historical evidence indicates substantial transformation of land-use and land-cover patterns within and around the lake. Encroachment therefore has consequences extending beyond loss of physical lake area. It can alter drainage, habitat connectivity, sediment transport, pollutant pathways, and flood-regulation capacity.

13. Emerging Pollutants

The environmental risks facing Dal Lake are increasingly extending beyond conventional nutrient pollution. Recent research has identified concerns regarding heavy metals and microplastics. A 2024 study investigated heavy-metal contamination in Dal Lake and combined contamination assessment with trophic-status analysis, macrophyte observations, and economic valuation. More recent research has also examined microplastic contamination across multiple environmental compartments, including water, sediment, and fish, and across different lake basins. This represents an important development because microplastics can interact with sediments and aquatic organisms and potentially act as carriers of other contaminants. These emerging pollutants demonstrate that future monitoring programs should expand beyond traditional parameters such as nitrate, phosphate, dissolved oxygen, and biochemical oxygen demand.

14. Climate Change and Ecological Vulnerability

Climate change represents an additional layer of pressure on already stressed Himalayan aquatic ecosystems. Changes in temperature, precipitation, extreme rainfall, snow and glacier dynamics, evaporation, and catchment processes can influence Lake Hydrology and nutrient transport. A 2024 review of Kashmir Himalayan lakes, including Dal Lake, emphasized the combined effects of anthropogenic pressure, sedimentation, and climate change. The interaction between climate change and existing pollution is particularly important. A lake already affected by nutrient enrichment and reduced ecological resilience may be less capable of absorbing additional climatic stress. Thus, restoration planning should incorporate climate projections rather than relying exclusively on historical ecological conditions.

15. Socioeconomic Consequences

The ecological condition of Dal Lake has direct implications for local livelihoods. The lake supports tourism, boating, fishing, vegetable cultivation, and other economic activities. Consequently, ecological deterioration can produce a feedback mechanism in which declining environmental quality reduces the economic value of the lake, while continued economic dependence increases pressure on the ecosystem. The lake's economic importance has been documented in assessments examining tourism, fisheries, agriculture, and ecosystem services. This makes conservation economically rational as well as environmentally necessary.

16. Existing Conservation and Restoration Approaches

Various conservation measures have been implemented or proposed for Dal Lake, including wastewater treatment, removal of aquatic weeds, catchment management, dredging, control of encroachment, monitoring of water quality, and restoration of lake-associated habitats. However, the persistence of ecological deterioration indicates that isolated interventions have limited effectiveness when upstream drivers remain active. For example, mechanical removal of aquatic vegetation without reducing nutrient inputs can provide only temporary improvement. Similarly, dredging without controlling sediment sources may result in renewed accumulation. The literature increasingly supports integrated management approaches that address the entire lake-catchment system.

17. Towards an Integrated Restoration Framework

A sustainable restoration strategy for Dal Lake should incorporate the following interconnected components. Management should extend beyond the lake boundary to include the entire contributing catchment. Measures should include erosion control, restoration of vegetation, management of agricultural runoff, protection of drainage channels, and regulation of land-use conversion. Wastewater systems should be assessed based on actual treatment performance rather than nominal infrastructure capacity. Continuous monitoring, decentralized treatment where appropriate, and strict control of untreated discharges should form part of the management strategy.

Tourism should be managed according to ecological carrying capacity. Environmental standards should apply to houseboats, hotels, boating activities, floating restaurants, and other tourism-related operations. Local communities should be treated as partners in restoration rather than merely as sources of pollution. Participatory management could involve houseboat owners, boatmen, farmers, vegetable growers, fishers, tourism operators, researchers, local government institutions, and conservation agencies.

19. Conceptual Framework for Dal Lake Restoration

The ecological transformation of Dal Lake can be conceptualized as a chain of interconnected processes:

Urbanization and population growth
↓
Land-use transformation and encroachment
↓
Increased sewage, solid waste and runoff
↓
Nitrogen and phosphorus enrichment
↓
Eutrophication and excessive aquatic vegetation
↓
Reduced water quality and altered habitats
↓
Biodiversity and ecosystem-function changes
↓
Declining aesthetic, recreational and economic value
↓
Reduced ecological resilience

20. Conclusion

Dal Lake is undergoing a complex ecological transformation driven by the interaction of urbanization, population growth, wastewater discharge, agricultural runoff, floating cultivation, tourism, houseboats, encroachment, sedimentation, and emerging pollutants. Historical and contemporary studies consistently demonstrate deterioration in water quality and increasing nutrient enrichment, while recent research has expanded the environmental risk profile to include heavy metals, microplastics, sediment accumulation, and climate-related pressures. The evidence suggests that Dal Lake should not be viewed simply as a polluted water body requiring periodic cleaning. It is a complex urban wetland whose ecological condition is determined by interactions between its catchment, hydrology, biological communities, human settlements, economic activities, and governance systems. Future conservation should therefore move toward an integrated lake-catchment management framework. Nutrient reduction, wastewater treatment, sustainable agriculture, sediment control, pollution monitoring, biodiversity conservation, regulated tourism, climate-resilient planning, and community participation should be implemented as interconnected components. The long-term sustainability of Dal Lake will ultimately depend on reconciling ecological integrity with the socioeconomic needs of communities that depend upon it. Restoration should therefore aim not simply to return the lake to an assumed historical state, but to develop a resilient ecosystem capable of sustaining biodiversity, livelihoods, cultural values, and ecosystem services under changing environmental conditions.

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