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Wetland Birds at Risk: A Global Review of Anthropogenic Threats with a Regional Focus on Punjab, India

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Birds, diversity, threat, wetland, habitat

Abstract

Wetlands are among the world's most productive ecosystems, providing essential habitats for waterbirds while supporting critical ecosystem services, including water purification, flood regulation, carbon sequestration, and nutrient cycling. However, anthropogenic pressures have intensified wetland degradation across the globe, leading to declining numbers of resident and migratory waterbirds. This review critically synthesizes the current knowledge on the main anthropogenic factors that have an impact on wetland ecosystems, such as habitat loss and fragmentation, pollution, eutrophication, hydrological changes, climatic changes, invasive species, and human disturbance. A detailed literature survey of peer-reviewed publications and authoritative international reports has been conducted to assess global trends in wetland degradation and the link with the ecology of an important flyway region of Punjab, India. This review identifies that the major wetlands of Punjab, such as Harike, Ropar, Kanjli, Nangal, Keshopur-Miani, and Ranjit Sagar, face an increasing range of interacting pressures related to loss of habitat quality and reported changes in the abundance, species composition, and ecological functioning of waterbirds. This review brings together and synthesises international knowledge and experience with local examples of conservation actions, highlighting key knowledge gaps, examining current conservation policies and management practices, and emphasising site-specific conservation priorities, including habitat restoration, water-quality management, long-term ecological monitoring, invasive species control and hydrological rehabilitation, and community involvement. This study offers an evidence-based regional framework on

how regional conservation challenges relate to global wetlands sustainability and underscores the importance of coordinated, science-based management for the conservation of wetlands and migratory waterbirds in the Central Asian Flyway.

Keywords: Birds, diversity, threat, wetland, habitat

1. Introduction

Wetlands are highly productive and ecologically important ecosystems on the planet, which can offer vital services that benefit biodiversity as well as the livelihood of human beings. They act as a natural water filter, a flood regulator, groundwater recharge, carbon storage, and cycling of nutrients and sediment (Mitsch & Gosselink 2015; Junk et al. 2013). In addition to those ecosystem services, wetlands are important habitats for diverse organisms, including amphibians, fish, invertebrates, and, notably, waterbirds, which are highly sensitive to wetland conditions (Delany et al. 2006). Migratory and resident waterbirds bridge the ecology of the continents, and breeding, stopover, and wintering places of the flyways are connected to the major flyways like the Central Asian, East Asian-Australasian, and African-Eurasian Flyways (United Nations Environment Programme World Conservation Monitoring Centre [UNEP-WCMC] 2024). Due to their abundance and diversity, they are highly useful for monitoring and biodiversity conservation planning, given their indicative value for the ecological state of wetlands. Wetlands are among the most endangered ecosystems in the world, despite their ecological and socio-economic significance (Isaac et al. 2025). The aggregation of wetlands and their disappearance in the last century have been observed on a large scale and encompass almost half to a quarter of the existing wetlands (Davidson 2014; UNEP-WCMC 2024). This is even more acute for migratory waterbirds, whose populations are declining in much larger proportions, and many species are at high risk of extinction (UNEP-WCMC 2024). The combination of habitat loss, water contamination, altered hydrology, and changes in rainfall and temperatures caused by climate leads to a decrease in foraging opportunity, nesting success, and survival rates (BirdLife International 2022; UNEP-WCMC 2024). In arable lands, fertilizers and pesticides dissolved into waters cause the event of eutrophication, algal proliferation, and oxygen loss, which destabilise aquatic food chains and alter the bird population (Liu et al. 2025).

Wetlands are important biodiversity networks in India, which harbour more than 170 species of waterbirds, including threatened global species like the Sarus Crane (*Antigone antigone*), Common Pochard (*Aythya ferina*), and Ferruginous Duck (*Aythya nyroca*) (Wetlands International South Asia 2020). In addition to supporting resident waterbirds, these wetlands serve as important wintering grounds and stopover sites for migratory waterbirds travelling along the Central Asian Flyway. The survival of waterbirds in the region and globally depends on these ecosystems and their health and integrity; thus, the conservation of wetlands is interconnected.

Punjab in northwest India is an important case study of this border situation. The semi-arid to sub-humid climate and the high agricultural activity of the state allow several major wetlands, both natural and artificial, such as Harike, Ropar, Kanjli, Nangal, Keshopur-Miani, and Ranjit Sagar. Such wetlands offer important winter and staging grounds to migratory species of ducks, geese, cranes, and waders, as well as sustaining local species such as herons, egrets, and coots (Brraich & Kaur 2016; Singh & Brraich 2022). The Harike wildlife sanctuary and Ramsar site is of special significance as it is a regular habitat for thousands of migratory birds such as Northern Pintail (*Anas acuta*), Gadwall (*Mareca strepera*), and Painted Stork (*Mycteria leucocephala*) (Singh & Brraich 2022). Keshopur-Miani, run by local communities, is also an example of how participatory management could preserve biodiversity in wetlands. However, several anthropogenic stressors, such as agricultural intensification, urbanization, industrial development, alteration of hydrology, and other activities, are a growing threat to wetlands in Punjab. These complex stressors have led to the degradation of wetland habitats, changes in ecological processes, and negative impacts on waterbird populations and biodiversity throughout the region (Pandey et al. 2023; Naqash et al. 2023; BirdLife International 2024). The anthropogenic threats and their ecological impacts are explained in detail in the following sections.

The trends realized in Punjab are similar to world trends in the decline of waterbirds. Other groups that have suffered the most worldwide due to habitat loss, climate change, and pollution include dabbling ducks, diving ducks, waders, and cranes (Zhang et al. 2023; UNEP-WCMC 2024). In Punjab, other species, including the Common Pochard (*Aythya ferina*, Vulnerable), Northern Pintail (*Anas acuta*), Sarus Crane (*Antigone antigone*), and Ferruginous Duck (*Aythya nyroca*), are similarly declining across some wetlands (BirdLife International 2024; Wetlands International South Asia 2023). These observations on the local scale highlight the importance of considering regional conservation efforts in combination with flyway-scale efforts, and in this regard, wetland degradation in a single part of the world can have a ripple effect on the migrating populations of various continents.

To overcome these difficulties, conservation should be implemented through a multi-level approach. Habitat protection at a site scale should be integrated with catchment-scale mitigation of pollution, hydrology, and long-term monitoring. The results of the study offer significant insights into the intricate relationship between human activities and avian biodiversity, underscoring the need for data-driven conservation policies and practices to safeguard the conservation of wetland ecosystems in Punjab (Convention on Wetlands 2021; MoEFCC 2017). The community involvement, participatory observation, and reestablishing the habitat diversity, such as the open water, mudflats, and reedbeds, are very vital in ensuring the integrity of the ecosystem and the support of resident and migratory birds (Ramsar Convention Secretariat 2022; Gopal 2013).

Although there has been an increase in literature addressing wetland degradation and the conservation of waterbirds in recent years, this knowledge is scattered, and most are of a descriptive nature, addressing one anthropogenic factor or one specific geographical area. A comprehensive knowledge of the combined effect of various anthropogenic drivers on waterbird biodiversity at both spatial and temporal scales is therefore still missing. Moreover, there has been no thorough attempt to critically review the scientific evidence from around the world and to place these threats in the specific ecological and socio-environmental context of Punjab, India. This review aims to fill this gap by bringing together lessons learnt from international and regional experiences, highlighting new research priorities, and offering an evidence-based framework for integrated sustainable wetland management and waterbird conservation. This review will generalize the global and regional pattern of waterbird species, analyse human pressure on wetlands in Punjab, name species on the conservation priority list, and review the available policy framework and conservation management strategies. Through connecting the local phenomena to the international trends, this research will seek to give an all-inclusive assessment of the threat that is posed to waterbirds, as well as give a recommendation in the form of evidence that will help in protecting such essential ecosystems in the future

2. Review Methodology

A comprehensive literature search was performed in the Scopus, Web of Science, ScienceDirect, SpringerLink, and Google Scholar databases. Additional relevant reports were consulted from the Ramsar Convention Secretariat, BirdLife International, the International Union for Conservation of Nature (IUCN), the Convention on Migratory Species (CMS), and the Convention on the Conservation of World-Wide Endangered Birds (CWWEB), which is now known as the UNEP World Conservation Monitoring Centre (UNEP-WCMC).

The search was done using combinations of the following keywords: wetland birds, waterbirds, avian diversity, wetland ecosystems, anthropogenic threats, habitat degradation, pollution, climate change, human disturbance, invasive species, wetland conservation, India, and Punjab wetlands. The publications were mainly taken from the period 2000-2025, and, where they were necessary for background information, earlier publications were included. This review comprised English-language peer-reviewed research articles, review papers, book chapters, and reports of relevance to wetlands, waterbirds, anthropogenic impacts, and conservation.

3. Global Perspective on Anthropogenic Threats

Global waterbirds are declining significantly in numbers due to the growing anthropogenic impacts on wetland ecosystems. BirdLife International (2024) indicates that about 56% of the waterbird species assessed have declined in population trend, and 17% are listed as globally threatened. In addition, BirdLife International (2022) states that close to 60% of all waterbird species assessed in Asia are in

decline, and this is putting increasing pressure on wetlands across the region. The State of the World's Migratory Species report by UNEP-WCMC (2024) shows that some 44% of monitored migratory species have declining populations as a result of habitat loss and degradation, pollution, climate change, and overexploitation. This crisis is most acutely experienced by the shorebirds, whose percentage of the number of threatened migratory shorebird species in the world has increased (BirdLife International 2024; IUCN 2024; van de Pol et al. 2024). The Convention on Wetlands (2025) estimates that around 22% of the world's wetlands have been lost since 1970, driven mainly by the expansion of agriculture, changing land use, and urban development. These are compounded by climate change: IPCC AR6 estimates rising drought frequency, changing monsoon patterns, and faster sea-level rise, which will play a role in causing extensive losses in the coastal and inland wetland area, with ecological modelling research estimating that by the mid-century, ecologically vulnerable deltaic systems would have lost up to 70% of their habitat (IPCC 2022; van de Pol et al. 2024). All these accumulating stresses, habitat conversion, changed hydrology, pollution, invasive species, direct disturbance, and climate-driven degradation are currently driving several wetland-dependent species to higher threat levels, necessitating collective conservation efforts on a global scale.

2.1 Habitat Loss and Degradation: Impacts of Urbanization, Agriculture, and Industrial Expansion

The most common and acute threat to wetlands and their associated bird populations in the world is habitat loss and degradation. The wetlands, which are one of the richest ecosystems on Earth, act as decisive breeding, feeding, and stopover areas of waterbirds, shorebirds, and other animals. The rapid destruction of wetlands with anthropogenic land-use change is happening despite their ecological significance. The Convention on Wetlands (2025) shows that about 22% of all the wetlands in the world have been lost since 1970, which is about 411 million hectares. This significant loss is indicative of the fact that wetlands are one of the most rapidly disappearing ecosystems in the world and are losing ground at a faster rate than forests and grasslands. Moreover, 25% of wetlands that do not disappear are now in a degraded state, which is affecting the ecological processes and the quality of the wetland habitats of waterbirds (Convention on Wetlands 2021; IPBES 2019). Reconstructions of the past show that the global wetlands suffered 3.4 million km^2 of inland wetlands (about 21% of all wetlands globally) degraded between 1700 and 2020, mostly through conversion into crop and urban areas (Fluet-Chouinard et al. 2023). Such losses have a direct negative impact on the habitat of waterbirds, most of which have very specific ecological needs and are vulnerable to the alteration of wetland size, connectivity, and quality.

Urbanization has a complex effect on wetland loss that changes hydrological conditions, disintegrates habitat, and reduces the integrity of the ecosystem (Anaba et al. 2026). The most common forms of rapid urbanization include the drainage, filling in or transforming wetlands into housing, infrastructure, and commercial projects to interfere with water levels and eradicate critical bird habitats. A study conducted in Delhi, India, found that the total wetland area decreased by 8.2% between 1991 and 2021, whereas in

South Delhi, the decrease was almost 97% because of the uncontrolled urban sprawl (Prasad et al. 2002; Xu et al. 2022). Urbanization is another factor that brings high loads of pollutants, such as nutrients, heavy metals, sediments, and wastewater, to degrade the water quality, change the vegetation, and decrease prey availability to waterbirds (Xu et al. 2022). Wetlands are also fragmented, further isolating populations, limiting movement corridors and population breeding of the waterbirds that rely on an intact landscape. Figure 1 presents some of the main factors responsible for the loss of wetland biodiversity worldwide, including anthropogenic factors.

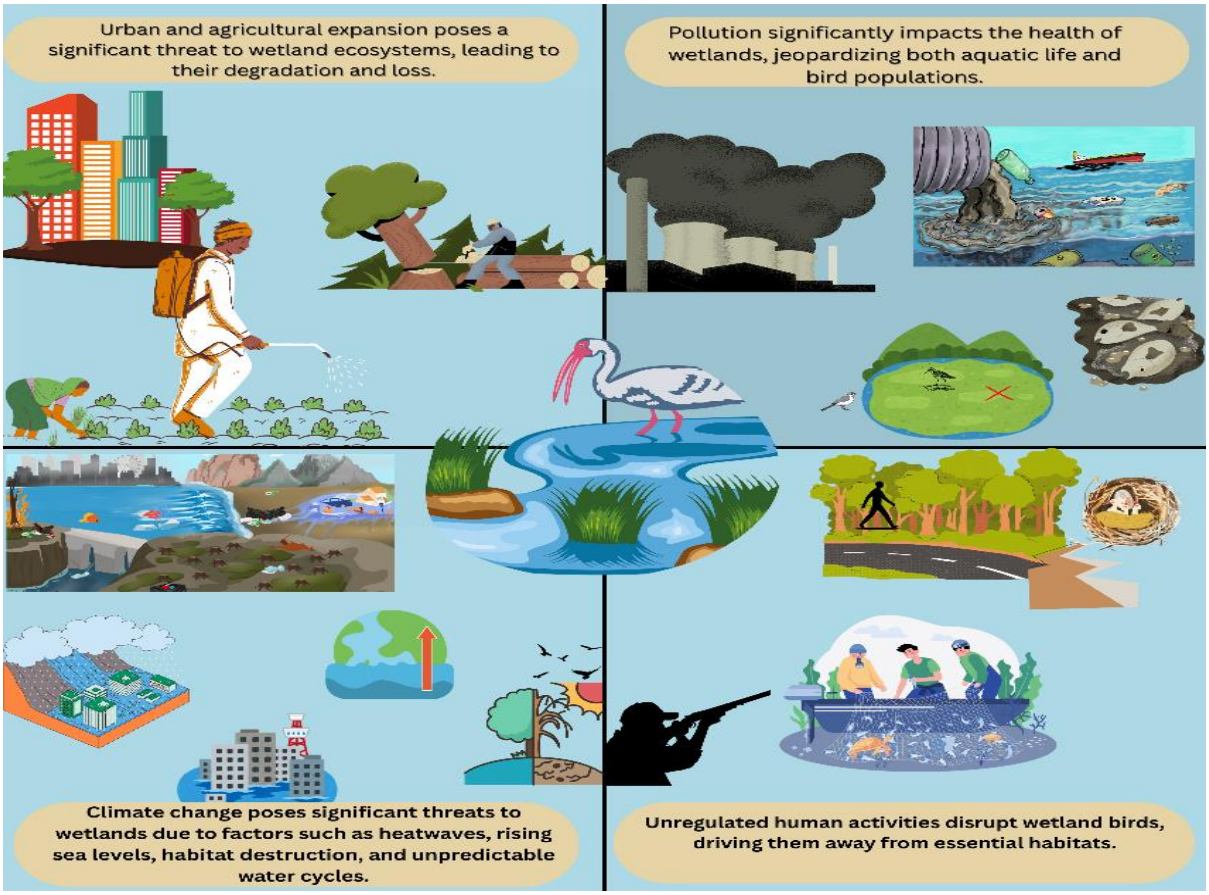

Fig.1: Visual Representation of Anthropogenic Threats to Wetland Ecosystems, highlighting the Impacts of Habitat Loss, Pollution, Climate Change, and Human Disturbance on Avian Diversity.

Source: Developed by the authors based on published literature (Convention on Wetlands 2021; IPBES 2019; MoEFCC 2017; UNEP-WCMC 2024).

One of the biggest causes of wetland habitat loss worldwide is agricultural expansion and intensification (Livinus et al. 2025). Natural wetlands being converted to croplands and pastures destroy habitat and disturb hydrological processes with drainage, levees, and water abstraction. The current world farmlands

cover about 70% of freshwater abstractions, which exert heavy pressure on wetland water resources and seasonal floods required by migratory and resident birds (FAO 2022; Convention on Wetlands 2021). Agricultural drainage of wetlands is associated with eutrophication caused by the runoff of fertilizers and pesticides, and decreases the habitats of waterbirds. In China, in the Sanjiang Plain, agriculturalization was found to result in high levels of wetland depletion and fragmentation, which resulted in decreased waterbird habitat quality, and abandoned farmland (ecological restoration) showed greater bird richness over time (Xu et al. 2022). The same tendencies are stated in the Gediz Delta, Turkiye, where the intensive farming landscapes had less diversity of the specialist wetland species than the less-disturbed wetlands.

The expansion of industries contributes towards the degradation of wetlands by turning wetlands into mining areas, power generation, transport, and manufacturing industries. Industries demand a lot of water to operate, thus modifying the natural flow regime and wetland, lessening hydroperiods. The effluents bring in toxic substances and nutrient discharge that negatively affect the water quality, and bioaccumulation in the wetland food webs that influences the reproduction and survival of birds (UNEP-WCMC 2024; IPBES 2019). Wetland landscapes are broken by industrial infrastructure (roads and railways), which isolates the bird populations and reduces habitat connectivity. In places with a high rate of industrialization, the threat to wetlands is usually increased by the nearby urban and agricultural developments, which underscores the compound effect of anthropogenic pressures.

External to all these elements of urbanization, agriculture and industrialization have contributed to widespread habitat loss and degradation, resulting in wetlands that are smaller, fragmented and less ecologically functional. The changes have a direct impact on the populations of waterbirds, particularly those species that have limited habitat preferences. Since it has been found that wetlands disappear 3 times faster than forests and sustain about 40% of all the world's species, degradation of wetlands not only endangers biodiversity but also compromises essential ecosystem functions, including water purification, flood treatment, and carbon storage (Ramsar Convention Secretariat 2021; IPBES 2019). These tendencies highlight the fact that there is a dire need to have more robust conservation policies, integrated land-use planning, and restoration projects that use wetland protection and sustainable development as the priority.

Rapid agricultural expansion, urbanisation, infrastructure construction and encroachment are the key drivers of habitat loss and degradation in the vicinity of the major wetlands of Punjab, such as Harike, Kanjli, Ropar and Nangal. These land-use switching events have been linked to habitat fragmentation, hydrological changes, loss of breeding, foraging, and roosting habitat. Together, these changes are thought to be important factors contributing to the observed changes in waterbird communities, but their relative importance varies among wetlands. The region is facing a similar situation as the world, and the need for

integrated land-use planning and habitat improvement is the key to maintaining the ecological value of the wetlands of Punjab.

2.2 Contamination of the Wetland Ecosystems: Eutrophication and Chemical Contaminants.

Wetlands are extremely productive ecosystems, yet they are becoming more and more exposed to the threat of chemical pollution and nutrient overload, which have a devastating impact on their health and the species reliant on them. Farms, factories, cities, and even air supply chemicals, which in turn are accumulated in wetlands, water, soil, and wildlife. The heavy metals that are of particular concern include lead, cadmium, chromium, zinc, and copper, which accumulate in sediments and organisms and lead to toxicity and influence the reproduction and survival of aquatic organisms (Panda et al. 2023). Emerging contaminants like Polyfluoroalkyl Substances **(**PFAS) and pharmaceuticals have also been of importance in recent years and can remain in wetlands and change microbial communities and the well-being of aquatic life (Zhao et al. 2025).

The other significant threat to wetlands is eutrophication. Once excessive amounts of nitrogen and phosphorus find their way into such systems, primarily due to fertilizers, sewage, and animal waste, it may cause algae and cyanobacteria to grow with explosive force. These flowers lower water clarity, drain oxygen and might result in hypoxia, which is fatal to fish and invertebrates (Akinnawo 2023). In addition to the negative impact of nutrient overload on water quality, there is also a change in the structure of wetland habitats, which are no longer conducive to such species as waterbirds that require clean and oxygen-sufficient water and healthy vegetation (Wetzel 2001; Jeppesen et al. 2020).

The recent studies put forward the necessity to combine the approaches of control and restoration of the wetlands to sustain them. The tools, such as a reduction of nutrient and chemical input sources, the use of constructed wetlands to treat the water, and frequent monitoring, can assist in the preservation of the water quality and biodiversity (Mitsch & Gosselink 2015; Wu et al. 2023). Preservation of wetlands against chemical contamination and eutrophication is not just essential to the survival of wildlife, but it is equally important to the continued existence of the ecosystem services, such as water purification and flood control, that are essential to human survival. Unless something is done, these precious ecosystems are on the verge of being further degraded at the expense of nature and society.

Available data suggest impacts that are both direct and indirect, but vary greatly in scope and magnitude of the impacts across the studies (Wetzel 2001; Mitsch & Gosselink 2015; Jeppesen et al. 2020). These opposing findings are primarily attributed to differences in pollutant emissions, pollutant levels, and hydrological conditions (Panda et al. 2023; Zhao et al. 2025). Similar issues are observed in Punjab, where the quality of the water in some wetlands has been affected by agricultural runoff, untreated domestic sewage, and industrial effluents, potentially affecting aquatic food resources and, thereby,

wetland bird communities. Integrated monitoring strategies that integrate ecotoxicological assessments, water-quality monitoring, and spatial analyses are thus increasingly needed to facilitate effective wetland management (Akinnawo 2023; Wu et al. 2023).

2.3 Climate Change and Wetland Dynamics: Altered Hydrology and Sea-Level Rise

Climate change is having a significant impact on wetlands, changing their hydrological cycles and physical frameworks with dire effects on biodiversity and ecosystem processes. Also, due to an increase in temperatures, evaporation increases, and because of this, the water levels of many inland wetlands decrease. Meanwhile, changing rainfall patterns, which are characterised by unpredictable storms, extended dry seasons, and extremes in seasons, cause hydrological instability. Such alterations interfere with the nutrient cycling, depositional processes of sediments, and vegetation, and lead to a reduced quality of habitats of wetland-dependent species such as birds, amphibians, and aquatic invertebrates (Mitsch & Gosselink 2015; IPCC 2022).

Sea-level rise threatens coastal wetlands, especially by intruding onto saltwater, flooding marshlands and depleting freshwater marshes. In place of urban development or other obstacles, wetlands become irreversibly submerged, causing the loss of the most important habitats and changes in plant and animal communities (Enwright et al. 2016; Thorne et al. 2025). Hydrological alteration is also responsible for wetland processes like carbon storage and oxygen availability, which may impact the productivity of the ecosystem and the survival of the species reliant on wetlands (Junk et al. 2013; IPCC 2023; Guan et al. 2025).

The only solution to the climate pressures on wetlands to ensure wetland health and biodiversity is to restore natural water flows, protect buffer areas, and provide room to migrate to other wetlands. These are steps that allow wetlands to maintain their ecological processes and remain useful in their water purification, flood control, and animal habitat despite climate change, that are altering their hydrology (Convention on Wetlands 2025).

The same issue has also been reported in Punjab, where agricultural activities with fertilisers and pesticides, domestic untreated sewage and industrial effluents have caused degradation of water quality in some wetlands. This can result in changes to wetland food webs and habitat quality, and thus impact the abundance and diversity of wetland birds. The need to improve pollution control and periodic water quality monitoring to support wetland conservation is emphasized by these regional observations.

2.4 Human Disturbance: Fishing, Recreation, Tourism and Hunting

There is increased pressure on wetlands by direct human activities, including hunting, fishing, tourism and other recreation activities, which may have a significant impact on their structure and biodiversity.

Besides decreasing the population of waterbirds, amphibians, and other birds, hunting and poaching disturb the natural balance of predator-prey relationships, changing the dynamics of the wetland community (Ramachandran et al. 2017). Likewise, inefficient fishing methods, such as overfishing and destructive fishing equipment, cause a decrease in fish numbers, disruption of sediments and aquatic plants, and a decrease in the food supply of birds and other species relying on fish (Ramsar Convention on Wetlands 2018).

Wetland ecosystems may also be stressed by tourism and recreational activities like boating, watching birds and trekking. Stress on wildlife, behaviours, and habitat displacement can occur due to heavy human activity. There is also a high level of habitat degradation due to trampling, littering and noise pollution. Tourism infrastructure such as trails, boardwalks and visitor facilities can also affect wetland habitats by decreasing the ability of the wetland to support a variety of species (Steven et al. 2011). Research suggests that a combination of these forces commonly results in species losses in the long term and changes in the composition of wetland communities. Regulated hunting and fishing, controlled tourism, habitat protection, and environmental education are some of the measures that are needed to counter such impacts. These measures will preserve the biodiversity of wetlands and permit sustainable human exploitation of wetlands so that the ecosystems remain valuable in offering important ecological services (Arya 2024).

The effects of fishing, recreation, tourism and hunting on the ecology are dependent on the intensity, frequency and management of these activities. Whilst there is generally a trade-off between human disturbance and the feeding, breeding and roosting behaviour of wetland birds, appropriate ecotourism and control of recreational activities can minimise impacts (Steven et al. 2011; Ramachandran et al. 2017). The same is observed in Punjab, where the high rate of visitors visiting major wetlands during the migratory period and recreation activities have great potential to affect the birds if these are not managed properly. The recommendations of the wise-use concept of the Ramsar Convention on Wetlands (Ramsar Convention on Wetlands 2018; Arya 2024) were also reinforced by these observations, which include: regulating visitation; zoning habitats; and involving communities.

3 Biodiversity-Ecosystem Functioning (BEF) Relationship

3.1 *Description of BEF concept and its applicability to the wetland ecosystem*

The BEF concept emphasizes the correlation between species diversity and ecosystem functioning that ecosystems with greater biodiversity tend to be more productive, stable, and resilient. The biodiversity in wetlands includes plants, microbes, invertebrates, fish and waterbirds, which are involved in the important functions of nutrient cycling, water purification, storage of carbon and energy flow. The research shows that wetlands with a greater variety of plants generate greater biomass and more effectively eliminate

nutrients such as nitrogen, which is essential to ensure the quality of water and sustain a healthy ecosystem (Song et al. 2024; Liu et al. 2024).

BEF in wetlands is an important aspect in terms of functional diversity and redundancy. If several species carry out comparable ecological functions, essential ecosystem functions may persist despite alterations in the environment, including fluctuations in water level or human disturbances. This is to provide stability and resilience to support lower and higher trophic levels. As an example, the various plant systems and microclimates present appropriate conditions that support the populations of waterbirds, and biodiversity at the plant and invertebrate levels is correlated with the upper-tier ecosystems (Qiu et al. 2024). Knowledge of the BEF relationship in wetlands shows that species richness and functional diversity play a crucial role in maintaining ecosystem processes and ecological balance within the wetland ecosystem, which forms the foundation of the health of the wetland. Bird biodiversity enhances habitat heterogeneity and provides a range of ecosystem services, while human activities can reduce these ecological connections and negatively affect the functioning of wetlands, as shown in Figure 2.

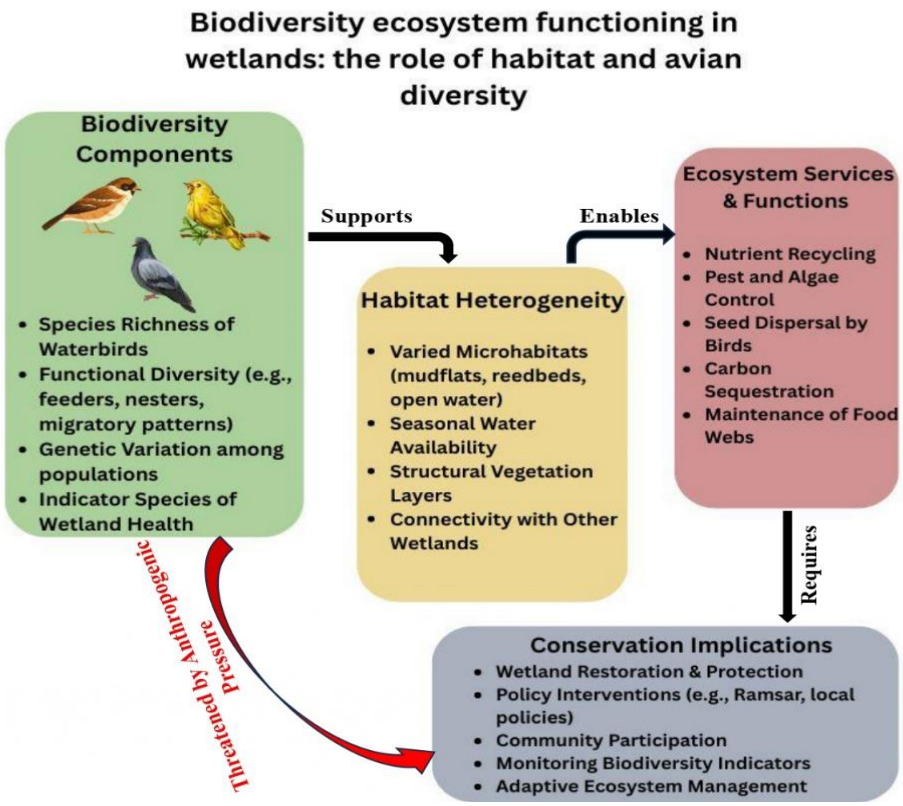

Fig 2: Conceptual diagram showing how avian biodiversity supports habitat heterogeneity in wetlands, enabling key ecosystem functions and services, while anthropogenic pressures disrupt these linkages and inform conservation strategies

Source: Developed by the authors based on published literature (MEA 2005; Convention on Wetlands 2021; IPBES 2019; MoEFCC 2017).

3.2 *The Habitat Diversity and Waterbird Diversity Co-existence*

Habitat diversity is among the best predictors of waterbird richness owing to variation in microhabitat used by various species to forage, nest, roost and shelter. More species are supported in wetlands having a mosaic of shallow pools, open water, emergent vegetation, mudflats and grassy margins as compared to uniform habitats. Recent research indicates that increased habitat heterogeneity increases species richness and functional diversity because waterbirds react to the changes in water depth, vegetation structure, and prey availability (Hartman et al. 2025). Studies of Asian and European wetlands reveal that spatially diverse habitats contribute to the lowering of the niche overlap and enable species to coexist that have various feeding behaviours, including dabbling ducks, herons, waders, and geese (Chen et al. 2025, Xia et al. 2025).

Waterbird communities are also enhanced by landscape-level diversity. Fields with mixed types of land use, i.e., cropland, grassland, and patches of forests, were more likely to have more and more diverse waterbird populations since they provide more feeding ground and better overall habitat quality (Hartman et al. 2025). The restoration experimentation also indicates that with the introduction of complexity in the habitat by manipulating water levels and vegetation cover, wintering waterbirds become more diverse and well-functioning (Xia et al. 2025).

4. Case Studies: Waterbirds in Punjab, India

India hosts one of the world's richest wetland-associated bird communities, supporting more than 240 species of waterbirds, including globally threatened cranes, storks, ducks and waders that depend on diverse wetland habitats across the country. Large wetland complexes such as Bharatpur (Rajasthan), Chilika (Odisha), and Loktak (Manipur) serve as critical wintering and stopover sites for birds migrating along the Central Asian Flyway, and long-term monitoring shows that waterbird populations respond strongly to changes in water quality, hydrology, habitat diversity, and human disturbance (Ameta et al. 2022; Mehta et al. 2024; Yadav et al. 2024). Recent assessments highlight that many Indian wetlands are under pressure from urban expansion, eutrophication, and altered inflow regimes, which have contributed to population declines in several migratory species since 2015 (Government of Punjab 2023). Table 1 presents an integrated overview of selected wetlands of Punjab, India, summarizing their protection status, major anthropogenic pressures, documented ecological impacts (including heavy-metal contamination,

toxic elements, and ecological health risks), supporting analytical evidence, and corresponding literature sources.

Table 1: Integrated overview of selected wetlands of Punjab, India, summarizing their protection status, major anthropogenic pressures, documented impacts on wetland condition and habitat quality, implications for avian diversity, evidence type (measured or inferred), and supporting literature.

Wetland	Major anthropogenic pressure	Effect on wetland condition	Bird-related impact	Evidence type	Key reference(s)
Harike Wetland	Agricultural runoff, industrial effluents, eutrophication, invasive macrophytes, hydrological alteration	Water-quality deterioration, eutrophication, reduced open-water habitat, habitat degradation	Decline in waterbird abundance; reduced wintering and foraging habitat	Measured	Kaur et al. (2017); Chaudhary et al. (2023); Ladhar (2002)
Ropar Wetland	Siltation, agricultural runoff, invasive aquatic vegetation, altered hydrology	Habitat degradation, reduced water quality, shrinking open-water areas	Reduced waterbird abundance and species richness	Measured	Pandey et al. (2023); Punjab Bird Census (2023)
Kanjli Wetland	Reduced water inflow, eutrophication, water hyacinth invasion	Dense weed infestation, reduced habitat heterogeneity, poor water quality	Loss of suitable foraging habitat; decline in waterbird diversity	Inferred from habitat assessment	Ramsar Convention Secretariat (2023); Pandey et al. (2023)

Wetland	Major anthropogenic pressure	Effect on wetland condition	Bird-related impact	Evidence type	Key reference(s)
Keshopur–Miani Community Reserve	Agricultural intensification, pesticide and fertilizer runoff	Habitat degradation, declining semi-natural feeding grounds	Decline of habitat-sensitive bird species; reduced habitat suitability	Inferred from ecological assessment	Jangral & Vashishat (2021)
Nangal Wetland	Flow regulation by Bhakra–Nangal Dam altered hydrology	Fluctuating water levels, shoreline modification, habitat homogenization	Shift in bird community composition; decline in specialist species	Measured	Kaur & Brraich (2021)
Beas Conservation Reserve	Sand mining, fishing disturbance, river regulation, habitat fragmentation	Riverine habitat alteration and disturbance	Disturbance to migratory birds and aquatic bird habitats	Inferred	Ramsar Secretariat (2019); WII (2020)
Ranjit Sagar Wetland	Water-level fluctuations, fishing disturbance	Altered shoreline habitats and reduced shallow-water feeding areas	Lower abundance of migratory ducks and other waterbirds	Measured	Brraich et al. (2023)

Source: Compiled by the authors based on published literature, including Ramsar Convention Secretariat (2019, 2020, 2023), Kaur et al. (2017), Ladhar (2002), Jangral & Vashishat (2021), Kaur & Brraich (2021), Brraich et al. (2023), Pandey et al. (2023), Chaudhary et al. (2023), Punjab Forest and Wildlife Preservation Department reports, and related references cited in the manuscript.

The Punjab occupies a very special ecological location on the northwestern Indo-Gangetic Plains due to its high river density, floodplain and irrigation systems. The topography of marshes, oxbow lakes and shallow water bodies has been created naturally along the rivers Beas, Sutlej and Ravi and has a variety of

wetlands. The state has several ecologically significant wetlands that have been altered or lost due to the expansion of agricultural fields and regulation of water bodies, but remain protected (MoEFCC 2017; Punjab State Wetland Authority 2022; Convention on Wetlands 2021). The sites are critical wintering and staging areas for migratory birds on the Central Asian Flyway, and Punjab is one of the first and most reliable stopovers for waterbirds moving through Central and Western Asia. Each winter, the wetlands of Punjab feed and provide a resting place to large numbers of ducks, geese, waders, herons, cormorants, and storks. The existing evaluation indicates that the state sustains more than 90 species of waterbirds, which demonstrates the diversity of the habitats created by the open waters, reed beds, marshes, and riparian vegetation. Human disturbance has increased pressure on hydrological processes like agricultural intensification, water diversion, pollution, siltation, and has worsened the quality of the habitat. Winter temperature changes and rainfall are also climate-related variants that influence the arrival of migratory species in time and quantity. Nevertheless, Punjab is a very important stronghold of wetland biodiversity and conservation planning; habitat restoration and water management must be strengthened in a bid to protect the waterbird communities. To facilitate comparison among Punjab's major wetlands, Table 2 synthesizes the available information on waterbird census records, reported changes in abundance and species richness, documented anthropogenic threats, supporting evidence, and current knowledge limitations. Rather than replacing the detailed case studies presented below, this comparative synthesis highlights common regional patterns while acknowledging differences in data availability among wetlands.

Table 2: Comparative summary of waterbird population trends, documented threats, evidence sources, and data limitations across major wetlands of Punjab

Wetland	Available census period	Reported change in abundance/species richness	Major documented threats	Evidence source	Data limitations
Harike	2019–2023	Waterbird abundance declined from approximately 123,000 to 65,624 individuals, a decline reported in several migratory species	Eutrophication, invasive macrophytes, hydrological alteration, nutrient enrichment, human disturbance	Punjab Bird Census, Chaudhary et al. (2023), Kaur et al. (2017), Ladhar (2002)	Most studies are observational; the contributions of individual stressors have not been quantified independently
Ropar	2020–2023	Decline from 3,808 birds (56 species) to 1,764 birds (43 species)	Siltation, invasive vegetation, altered hydrology, agricultural runoff	Punjab Bird Census, Pandey et al. (2023), Times of India (2024)	Limited long-term monitoring; causal relationships remain uncertain
Kanjli	Multiple surveys (2013–2023)	Declining habitat quality and reduced waterbird diversity	Reduced water inflow, eutrophication, and	Ramsar Convention Secretariat	Quantitative long-term census data are limited

Wetland	Available census period	Reported change in abundance/species richness	Major documented threats	Evidence source	Data limitations
		reported	invasive water hyacinth	(2023); Pandey et al. (2023)	
Keshopur-Miani	Community monitoring (2010–2023)	Overall richness is relatively stable, but declines are reported for habitat-sensitive species	Agricultural intensification, pesticide and fertilizer runoff	Jangral & Vashishat (2021); Ramsar Convention Secretariat (2023)	Functional-group and long-term abundance data remain scarce
Nangal	Periodic surveys	Changes in community composition; decline of specialist species reported	Dam-regulated hydrology, shoreline erosion, habitat homogenization	Kaur & Brraich (2021)	Continuous standardized monitoring is unavailable
Ranjit Sagar	Recent surveys (2020–2023)	Reduced abundance of migratory ducks reported	Water-level fluctuations, fishing disturbance	Brraich et al. (2023); regional bird surveys	Limited published long-term datasets; impacts inferred from observational studies

4.1.1 *Harike Wetland: A Case Study*

The largest wetland in Punjab and one of the most ecologically important Ramsar sites in India is Harike Wetland, which was created in the area of the convergence of the Sutlej and Beas rivers. It covers an area of approximately 86 km^2 with a mix of open-water areas, reed beds, shallow marshes, and mudflats, which in combination provide perfect wintering conditions for a wide diversity of. The location hosts thousands of migratory species in the Central Asian Flyway every year, which include northern pintails, gadwalls, common teals, northern shovelers, greylag geese, Eurasian coots, black-tailed godwits, redshanks, spoonbills and painted storks (Chaudhary et al. 2023).

In the last several years, Harike has, however, demonstrated a distinct decrease in the population of birds. The winter counts, which had registered more than 123,000 individuals in 2019-20, have declined to around 65,624 birds in 2023, which indicates distress to the species' number and total abundance (Punjab State Wetland Authority 2022). This decreasing trend has become a cause for worry for the sustainability of the ecosystem of the wetland in the long run. This is being driven by some interacting pressures.

The observed loss in waterbirds at Harike Wetland is concurrent with several anthropogenic factors from the literature, such as nutrient enrichment, hydrological alteration, invasive macrophyte expansion, and greater human disturbance. These stressors and their associated habitat quality deterioration have been

documented previously, but have not been evaluated independently as a contribution to changes in waterbird abundance. These factors should therefore be considered potential, interacting causes of the observed declines and not established causes. These measures are, however, supported by the available evidence, which also highlights the need for the adoption of integrated conservation measures such as water quality management (Chaudhary et al. 2023; Kaur et al. 2017), control over invasive species, restoration of natural hydrological regimes, disturbance free zones during the migratory season (Ladhar 2002).

4.1.2 *Ropar Wetland: A Case Study*

The Ropar Wetland is an artificial but rich in biodiversity wetland located along the river Sutlej in Rupnagar district, which came up after the construction of the Ropar Head Regulator. It is a significant stopover and wintering ground for many migratory and resident waterbirds, such as Northern Pintail, Common Teal, Gadwall, Eurasian Coot, Grey Heron and a range of migratory waders, and covers an area of ~1,365ha. Hence, it is considered one of the important wintering habitats for waterbirds in Punjab. Though some studies have reported declines in waterbird abundance and diversity in recent years, the latest bird census data show that this situation has worsened over time, from 3,808 individuals from 56 species in 2020 to 1,764 individuals and 43 species in 2023, signaling growing ecological stress (Brraich et al. 2023).

Thus, the overall quality of the habitat at Ropar Wetland has declined, owing to the combined effects of siltation, nutrient enrichment, hydrological alteration, invasive aquatic vegetation and disturbance by humans, as discussed in previous sections. The interacting pressures are believed to be likely factors for the declining trend of waterbirds and the ecological worth of the wetland (Pandey et al. 2023). The Ropar case has shown that even a protected wetland can lose its conservation value if anthropogenic activities are sustained for too long. Thus, to provide long-term ecological protection to this vital wetland, strengthening habitat restoration, better water-quality management, invasive plant control, hydrological reconnections and limiting disturbance during the migratory season are critical.

4.1.3 *Kanjli Wetland: A Case Study*

The Kanjli Wetland is an ecologically and culturally important, relatively small Ramsar site located on the banks of the river Kali Bein in Kapurthala district. It is an important site for marsh birds, waders and winter migratory water birds, including Common Teal, Moorhen, Little Grebe (Dabchick), egrets and herons (Ramsar Convention Secretariat 2023), covering an area of approximately 183ha. Although it is an ecologically significant habitat, the wetland has undergone a progressive deterioration in habitat quality and avian diversity over the last ten years. Decreasing water flow, nutrient enrichment, invasive aquatic vegetation, and hydrologic changes have been linked to decreasing habitat quality, as mentioned in the

previous sections. These synergistic factors have led to a decrease in the amount of available open water and have negatively impacted foraging opportunities for waterbirds, especially dabbling waterfowl, which rely on shallow, unpolluted water. In the Kanjli case study, small wetlands are found to be highly vulnerable to cumulative anthropogenic pressures and the importance of effective hydrological restoration, invasive species management, and continued conservation to ensure the ecological integrity of these wetlands is emphasized (Ramsar Convention Secretariat 2023; Pandey et al. 2023).

4.1.4 *Keshopur-Miani Community Reserve: A Case Study*

The first Community Reserve in India is Keshopur-Miani in Gurdaspur district, which includes approximately 850 ha of marshes, paddy fields and seasonal pools. This wetland is recognized in terms of high habitat diversity, and it has been known to host a wide variety of species, which include bar-headed geese, ruddy shelducks, painted storks, black-headed ibises and various raptor species during migration (Ramsar Convention Secretariat 2023; Jangral & Vashishat 2021).

The site has increasing environmental pressures, even though it has a powerful community-managed model. Intensification of agriculture in the area surrounding the wetland has increased pesticide and fertilizer runoff, which may influence water quality and the population of invertebrates. The process of changing the traditional paddy fields around the cities to commercial farming systems has also decreased the size of semi-natural feeding grounds. The bird richness has not changed significantly in contrast with the other wetlands in Punjab, but recent surveys indicate that sensitive species, big waders and diving ducks, among others, have been reported to decline in recent surveys, because of shrinking patches of open water. Keshopur-Miani emphasizes the need - and precariousness - of conservation directed by communities in preserving the biodiversity of wetlands (Jangral & Vashishat 2021).

4.1.5 *Nangal Wetland: A Case Study*

Nangal Wetland is located below the Bakhra Dam and is a hotspot of conservation, which sustains riverine and other reservoir-related bird communities. The wetland is rather small (approximately 116 ha), but it is an important wintering place of ruddy shelducks, bar-headed geese, pochards, and different cormorants. Its ecology is closely connected with the hydrological activities of the dam. Changing water levels, sudden flows and flow patterns are likely to influence the nesting and feeding sites of some species. Bank erosion and siltation have shifted shoreline profiles, eliminating the shallow feeding habitats that waders like. Recent studies report the change in bird community structure, where generalist species have been rising, and specialist species have been decreasing, which is a sign of habitat homogenization consistent with hydrological alterations reported for the wetland (Kaur & Brraich 2021). Nangal provides a strict illustration of the effect of controlled river systems and modified flow regimes on waterbird assemblies.

4.1.6 *Ranjit Sagar Wetland: A Case Study*

Ranjit Sagar Wetland, which is linked to the Thein Dam on the Ravi River, creates an extensive reservoir that sustains huge populations of waterbirds, particularly in winter. The common species of birds include great cormorants, grey herons, tufted ducks, bar-headed geese, and gull species. The main stresses in this area include changes in the water level, fishing disturbance and loss of shore habitat (Brraich et al. 2023). Shifts in the level of the reserve to either make or cover feeding areas influence the distribution of waterbirds. More disturbance has been recognized with the rise of fishing activity in the past years, most especially in the morning and late evening feeding hours. The most recent surveys show decreases in migratory duck numbers, which is probably associated with the lack of shallow-water habitats and the inconveniences of mechanised boats (Government of Punjab 2023). Ranjit Sagar shows how it is possible that even big reservoirs, which contain a lot of water, may become ecologically unstable under changing hydrological conditions.

4.2 ***Evaluation of regional risks, such as alterations in land use and pollution***

Punjab's wetlands are under great danger due to the rapid land-use change and escalating anthropogenic pressures in their catchments. Floodplains, marshes, and seasonal wetlands have been altered over the last 20 years with agricultural intensification, urban development and infrastructure, leading to habitat fragmentation and loss of critical feeding, breeding and roosting habitats for migratory and resident waterbirds (Bassi et al. 2014).

These wetlands are also subjected to several concurrent stressors such as nutrient enrichment, pollution, hydrological alteration, siltation and invasive vegetation as discussed earlier. These pressures are not separately identifiable, but rather are frequently linked to habitat degradation, are altering ecosystem processes, and are decreasing the wetlands' suitability for waterbirds. The impacts are seen in the decreasing occurrence of some waterbirds in the major wetlands of Harike, Ropar and Kanjli. The above-mentioned regional trends underscore the importance of integrated catchment-scale management involving sustainable land use, pollution control, hydrological rehabilitation, management of invasive plant species, and long-term ecological monitoring to help conserve Punjab's wetland ecosystem and its associated avifauna.

Functional Roles of Wetland Birds in Punjab Ecosystems

Wetland birds undertake vital ecological roles which contribute to the productivity, stability and resilience of wetland ecosystems. Wetlands of Punjab include Harike, Kanjli, Ropar, Nangal and Keshopur-Miani and host a variety of resident and migratory waterbirds of different functional groups, including herbivores, piscivores, insectivores, raptors and scavengers. Together they play a role in important ecosystem processes which support biodiversity in wetlands (Mitsch and Gosselink 2015; IPBES 2019).

The seeds of aquatic plants are dispersed by endozoochory and epizoochory (Lovas-Kiss et al. 2019), which is promoted by herbivorous waterbirds, leading to vegetation regeneration and habitat connectivity (Green et al. 2002; Lovas-Kiss et al. 2019). Birds of prey control insect populations, and piscivorous birds like cormorants, herons and kingfishers control balanced fish communities and trophic interactions in aquatic food webs (Weller 1999, Jeppesen et al. 2020). Waterbirds are also important for their role in nutrient cycling, through redistribution via the feeding activities and guano deposition that supports primary production and ecosystem functioning (Mitsch & Gosselink 2015). The scavenging birds further contribute to the breakdown of the carcass and recycling of nutrients, all the while minimizing transmission risk of disease. Habitat degradation, pollution, hydrological changes, intensification of agriculture and urban sprawl are increasingly impacting these ecosystem functions in Punjab wetlands (Ladhar 2002; Kaur et al. 2017; Pandey et al. 2023). Thus, shifts in abundance or composition of functional types of birds can affect nutrient cycling, seed dispersal and food-web regulation, which in turn can lead to decreased ecosystem resilience. While regional studies have mainly concentrated on species richness and abundance, there has been relatively little work on functional diversity and ecosystem processes, thus emphasizing the importance of long-term studies that combine functional trait analyses with wetland conservation planning.

4.3 *Waterbird population trend and species of concern*

Recent evaluations indicate that the waterbird populations in Punjab are experiencing some apparent alterations, and the changes are highly indicative of the world trends of degradation. The number of migratory waterbirds has declined significantly in recent years all over the world. The UNEP-WCMC (2024) State of the World's Migratory Species report shows that about 44% of all monitored migratory species are in decline, with habitat loss and degradation, pollution, climate change and other human activities taking a toll on migratory species. Furthermore, BirdLife International (2024) states that some 17% of waterbird species are now considered to be globally threatened. Long-term analyses also show that waterbirds are indicators of wetland health, and that habitat loss, pollution, and hydrological alteration are key factors driving declines in many waterbird groups (BirdLife International 2025).

In India, the wetlands of Punjab (which are situated along the Central Asian Flyway) exhibit such weaknesses. The situation is reflected by long-term control of the sites such as Harike, Ropar, Kanjli, and Keshopur-Miani, which show the decreased overall abundance, particularly of dabbling and diving ducks, which are becoming less abundant in the world due to lost wetlands, changing water regimes, and escalating eutrophication. Early warning signals of species of concern in the world are also being experienced in Punjab. An example is the Common Pochard, which is Vulnerable; this species has shown varying but overall declining winter counts, which mirror the flyway-wide decline associated with the

poor quality of water and simplification of wetlands. Likewise, Northern Pintail and Garganey, which have already gone on a downward trend in Asia, are less represented in recent Punjab surveys.

There is also an overall decline in the presence of wader populations, including Black-tailed Godwits and Common Redshanks, that are susceptible to hydrological instability, which is also reported in other intensively cultivated areas of India and Southeast Asia. Such reiterating trends imply that the wetlands of Punjab are undergoing the same forces that push the rest of the world into decline: agricultural intensification, rich runoff, invasive vegetation, and unreliable water levels. Since migratory birds require a series of connected habitats across the migratory route, the destruction of even some of them, like the ones in Punjab, amounts to the larger deterioration that has been observed on various continents. This is why to analyse the local impact of the anthropogenic threats on the global conservation picture; it is crucial to comprehend the state-level population trends.

4.4 *Evaluation of current conservation efforts and policy frameworks*

The conservation strategy of wetlands in India is mainly guided by the Wetlands (Conservation and Management) Rules, 2017, which also present procedures for wetlands notification, the principles of wise use, integrated management planning, and limitations of the activities that can destroy wetlands (MoEFCC 2017). In such regulations, every state is required to form a State Wetland Authority that deals with mapping, monitoring, and the formulation of management plans. This change of policy has enhanced coordination at the national level and introduced more scientific standards in the governance of wetlands.

The state of Punjab has made efforts to fit into this structure by putting up the Punjab State Wetland Authority, which recently finished the assessment of over 1,143 wetlands, suggesting 72 sites to be formally recognized as wetlands. The preparation of Integrated Management Plans (IMPs) of large wetlands like Harike, Kanjli and Beas Conservation Reserve is also being done in parallel. The plans are aiming at the control of pollution, restoration of the habitat, hydrological enhancement, and community engagement- a strategy that aligns with national recommendations and the Ramsar guidelines.

Several conservation activities are on the ground already. Restoration of the habitat and the control of the invasive species in Harike and Kanjli wetlands are being supported by the Forest Department and NGOs such as WWF-India, which have assisted in systematic bird monitoring and awareness programmes (WWF-India 2022; Forest Department Punjab 2023). Other robust efforts undertaken by the state include river desiltation, wetland revitalization, and catchment restoration to enhance the ecological circulation and decrease the quantity of silt (Government of Punjab 2023). Nevertheless, professionals warn that such interventions as desiltation should be performed based on ecological standards to prevent the unwanted disruption of the habitats (MoEFCC 2021).

Even in the light of these developments, there are still several setbacks. There have been inconsistencies in the implementation of the Wetland Rules and slow notification, inadequate technical capacity at the district level, and lack of long-term funding. The inflow of pollution caused by agriculture and industry into Ramsar sites is still diminishing, which means that all policy tools have not been properly transferred into practice to protect the site (CPCB 2022; MoEFCC 2021). Moreover, the lack of communication between the departments, including forests, irrigation, pollution control, and local governance retards conservation action. Such limitations are based on the results of national assessments that highlight the fact that legal designation, without integrated catchment management and robust enforcement alone, cannot provide ecological recovery (Thoker & Marwaha 2026).

On the whole, the conservation system of Punjab is evidencing promising progress, yet its success in the long term will be based on enhanced enforcement, the improvement of the pollution regulation, the scientifically oriented restoration, and the constant ecological monitoring to preserve the population of waterbirds on the Central Asian Flyway.

5. Conservation Strategies and Recommendations

5.1 Site-specific Management Priorities for Punjab Wetlands

Effective conservation of Punjab's wetlands requires management strategies that are tailored to the dominant ecological pressures affecting each site. Although several conservation measures, including habitat restoration, hydrological management, pollution control, invasive species management, and community participation, are broadly applicable across wetlands, their implementation should be prioritized according to site-specific threats and conservation needs. Based on the evidence synthesized in this review, Table 3 presents the major anthropogenic threats, corresponding management actions, and their relative conservation priority for the principal wetlands of Punjab.

Table 3: Site-specific management priorities and recommended conservation actions for the major wetlands of Punjab based on the dominant anthropogenic threats identified in this review

Wetland	Major Threat(s)	Priority Management Action	Priority
Harike	Eutrophication, invasive macrophytes, and human disturbance	Control invasive vegetation, reduce nutrient inflow, and establish disturbance-free zones during migration	High
Ropar	Siltation, hydrological alteration	Restore hydrological connectivity, maintain shallow-water habitats, and manage sediment deposition.	High

Kanjli	Reduced water inflow, pollution, and invasive vegetation	Ensure environmental flow, improve sewage treatment, and remove invasive aquatic weeds	High
Nangal	Dam-regulated water fluctuations, shoreline erosion	Coordinate ecological flow releases, stabilize shoreline habitats, and protect nesting sites	Medium
Keshopur-Miani	Agricultural runoff, habitat loss	Promote sustainable farming, establish vegetative buffer strips, and strengthen community-based conservation.	Medium
Ranjit Sagar	Water-level fluctuations, fishing disturbance	Regulate fishing during the migratory season, maintain suitable water levels, protect feeding habitats	Medium

Source: Compiled by the authors based on published literature, including Ladhar (2002), Kaur et al. (2017), Jangral and Vashishat (2021), Kaur and Brraich (2021), Brraich et al. (2023), Pandey et al. (2023), Chaudhary et al. (2023), Ramsar Convention Secretariat (2023), MoEFCC (2021, 2022), Punjab Forest and Wildlife Preservation Department reports, and other references cited in this review.

5.2 General Conservation Strategies

A multi-lens approach is needed to conserve waterbirds in Punjab: wetland habitat must be complemented by conservation of the surrounding catchments. Timely notification of wetlands, establishment of buffer zones and support of financial resources for the management plans should be a priority to strengthen the implementation of the Wetlands (Conservation and Management) Rules, 2017 (MoEFCC 2017). These measures implemented at priority wetlands, such as Harike, Ropar, Kanjli, Nangal and Keshopur-Miani, will contribute to long-term conservation of the waterbirds that migrate and reside there.

A catchment-based management approach should support site-specific conservation measures, for sustainable agricultural methods, wastewater management, industrial effluent and the restoration of natural hydrology. Effective implementation of these integrated measures has shown to improve the health of wetlands and waterbirds at various locations across the world (Amano et al. 2018; CPCB 2022; MoEFCC 2021).

Conservation programmes should also ensure habitat diversity by using adaptive hydrological management, the scientific guidance of desiltation and appropriate management of invasive species, to protect a mosaic of open water, mudflats, reedbeds and shallow marshes. Adaptive management and enhancement of conservation outcomes should be based on regular monitoring of vegetation, water quality, hydrology and aquatic biodiversity (MoEFCC 2021).

Long-term conservation will also rely on the participation of the community. The Wetland Mitra programme, community-based bird monitoring, and sustainable ecotourism can enhance local stewardship and minimize human disturbance. Promoting farmers to use water-efficient irrigation and sustainable agriculture practices around wetlands will contribute in tandem to the conservation of habitats (WWF-India 2023).

In conclusion, there is a need to strengthen long-term ecological monitoring further and to incorporate waterbird, hydrological, and land-use data into national monitoring programmes and Central Asian Flyway conservation initiatives to ensure high-quality, evidence-based decision-making that will foster the long-term conservation of the wetlands and their avifaunal diversity in Punjab (UNEP-WCMC 2024).

6. Research Gaps and Future Research Directions

Although research about anthropogenic impacts on ecosystems and biodiversity of wetlands and on birds is progressing rapidly, there are still some key gaps. Most studies have studied one threat at a time, such as habitat degradation, pollution, climate change, or human disturbance, with relatively few studies addressing multiple and combined threats. These stressors frequently occur together, so multi-stressor responses should be integrated into understanding how stressors interact when determining impacts on wetland ecosystem functioning and the bird community. A second drawback is the absence of standardized monitoring protocols and long-term ecological data to help compare studies and lead to a consensus about the impacts of anthropogenic pressures. The reliability of assessments of biodiversity and conservation planning should therefore be strengthened in the future by the use of harmonised survey methodologies and long-term monitoring.

The recent developments in remote sensing and Geographic Information Systems (GIS), Environmental DNA (eDNA), Unmanned Aerial Vehicles (UAVs), Artificial Intelligence (AI) and Machine Learning (ML) provide great potential to assist the monitoring and habitat assessment of wetlands. The technologies will be integrated with traditional field surveys to get a better understanding of the dynamics of the ecosystem and support adaptive management. While research on wetland conservation has increased greatly at the global level, there is much less work at the regional level, especially in Punjab, India. Future research could benefit from using an ecological, hydrological, geospatial, and socioeconomic approach to assessing the combined effects of anthropogenic and climatic stressors on wetland birds. These multi-disciplinary approaches will enhance evidence-based conservation measures, and aid long-term protection and sustainable management of wetland ecosystems.

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All authors have read and approved the final version of the manuscript.

Conflict of Interest

The authors declare that there are no known competing financial or personal interests that could have appeared to influence the work reported in this paper.

Ethics Statement

This study is a review based exclusively on previously published literature and publicly available secondary data. Figures and tables included in the manuscript were prepared by the authors for synthesis and illustrative purposes using information from cited sources. No primary data were collected, and no experiments or observations involving animals or human participants were conducted. Therefore, ethical approval was not required.

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