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Punjab's Wetlands as Inland Analogues of Marine Ecosystems: Status, Stressors, and Community-Led Conservation

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Abstract

Aquatic and wetland ecosystems in Punjab, India, represent ecologically significant yet increasingly degraded socio-ecological systems embedded within an intensively managed agrarian landscape. Despite their recognised importance, existing studies largely treat these systems using conventional freshwater ecological frameworks, with limited integration of microbiologically mediated processes and broader ecosystem theories. A key research gap, therefore, lies in the lack of interdisciplinary approaches that can holistically interpret wetland structure, function, and governance across spatial scales, particularly by incorporating microbial drivers of nutrient cycling and element transformation. This review applies marine ecosystem frameworks – spatial zonation, trophic organization, biogeochemical cycling, and connectivity – to reinterpret Punjab's wetlands as inland analogues of coastal systems. A narrative–systematic approach was used, integrating literature from Scopus, Web of Science, and Google Scholar. Six Ramsar wetlands (Harike, Ropar, Kanjli, Nangal, Keshopur Miani, and Beas) were analyzed. Results show strong ecological parallels with coastal lagoons, particularly in nutrient cycling and habitat connectivity mediated by microbial processes. However, these systems face stressors, such as nutrient enrichment, heavy metal contamination, hydrological changes, invasive species, and land-use shifts, leading to eutrophication and biodiversity loss. Reservoir wetlands are more vulnerable, while community-managed systems show greater resilience. Bioindicators and microbial indices effectively assess ecosystem health. A "Large Aquatic Ecosystem" framework is proposed for sustainable wetland management.

Keywords: Inland wetlands, microbial biogeochemistry, trophic structure, nutrient cycling, zonation patterns

INTRODUCTION

Wetlands are among the most productive ecosystems globally, providing essential ecosystem services including water purification, flood regulation, nutrient cycling, and biodiversity conservation. These functions are underpinned by complex microbial communities that mediate redox-driven transformations of carbon, nitrogen, sulfur, and metals, thereby shaping water quality and greenhouse-gas emissions. In agriculturally intensive regions, such as Punjab, India, wetlands are increasingly exposed to anthropogenic pressures that alter microbial community structure and process rates, with cascading effects on ecosystem functioning.

Punjab hosts a dense network of wetlands associated with the Sutlej–Beas–Ravi river system, many of which are recognised under the Ramsar Convention for their ecological significance. Despite this recognition, multiple studies report significant degradation due to pollution,

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hydrological modification, and land-use change, often accompanied by shifts in microbial assemblages and the emergence of low-oxygen, eutrophic conditions. Existing research primarily adopts site-specific approaches that focus on individual wetlands or stressors, limiting the development of integrated, basin-scale understanding. A key gap lies in the lack of interdisciplinary frameworks that explicitly link microbial-scale processes with broader ecosystem theories, particularly those developed in marine and coastal environments [1–4].

Marine ecosystem science provides a well-developed conceptual foundation, including models of spatial zonation, trophic structuring, and biogeochemical cycling that emphasise microbial mediation of element fluxes [1–8]. These frameworks have been successfully applied to coastal lagoons and estuaries, where microbial communities play central roles in organic-matter decomposition, denitrification, and metal transformation. By drawing on these marine-derived concepts, this study proposes that Punjab's wetlands function as inland analogues of coastal ecosystems, where similar microbial-mediated processes operate despite differences in salinity and hydrology [1–4]. For example, nutrient enrichment leading to eutrophication in wetlands parallels processes observed in coastal lagoons, with microbial communities driving both oxygen depletion and the transformation of contaminants such as arsenic and uranium [9–15].

The central aim of this review is to synthesise empirical evidence from Punjab's Ramsar wetlands and comparable systems, critically assess the validity of this marine–inland analogy from a microbiological perspective [16–18], and propose an integrated "Large Aquatic Ecosystem" (LAE) framework that explicitly incorporates microbial processes as core components of nutrient cycling, contaminant attenuation, and ecosystem resilience. This approach highlights the importance of microbial communities in sustaining wetland functions under changing hydrological and pollution regimes and provides a conceptual bridge between traditional freshwater ecology and microbiologically informed ecosystem management.

Objectives

This study has five main objectives:

- To apply key marine ecosystem concepts – particularly spatial zonation, trophic organisation, biogeochemical cycling, and ecosystem connectivity – to reinterpret Punjab's wetlands as inland analogues of coastal and estuarine systems [1–4, 18].
- To analyse the current ecological status of Ramsar-designated wetlands in Punjab and assess the nature and magnitude of interacting environmental stressors (e.g., nutrient enrichment, heavy metal contamination, hydrological alteration, invasive macrophytes, and land-use change).
- To evaluate the utility of selected bioindicator groups – molluscs, fish, herpetofauna, and waterbirds – as surrogates for ecosystem health, with particular attention to their sensitivity to pollution, hydrological regime, and habitat degradation.
- To compare contrasting governance models (e.g., state-managed reservoir wetlands versus community-managed floodplain wetlands) and identify institutional and social factors that influence ecological resilience.
- To propose an integrated "Large Aquatic Ecosystem" (LAE) framework, adapted from the Large Marine Ecosystem model, that links ecological, socio-economic, and governance dimensions for sustainable wetland management in inland river basins.

METHODOLOGY

This study adopts a narrative–systematic hybrid review design to synthesise empirical and conceptual evidence on the ecology, stressors, and governance of inland wetlands in Punjab, India. The hybrid approach allows for systematic identification of relevant literature while retaining flexibility to integrate diverse data types and disciplinary perspectives.

Data Sources

Literature and information were obtained from the following sources:

- *Bibliographic Databases:* Scopus, Web of Science, and Google Scholar.
- *Wetland-Specific Databases:* Ramsar Information Sheets and related Ramsar-Programme documents.
- *Grey Literature:* Government reports, environmental-assessment documents, and policy briefs relevant to Punjab's wetlands.

Search Strategy

Searches were conducted using a combination of keywords and Boolean operators, including:

- "Punjab wetlands", "Harike wetland", "Ropar wetland", "Kanjli wetland", "Nangal Wildlife Sanctuary", "Keshopur–Miani Community Reserve", "Beas Conservation Reserve";
- "Wetland pollution", "nutrient enrichment", "eutrophication", "heavy metal contamination", "arsenic", "uranium";
- "Bioindicators in wetlands", "molluscs as bioindicators", "fish as bioindicators", "herpetofauna indicators", "waterbirds as bioindicators";
- "Marine ecosystem framework", "Large Marine Ecosystem", "coastal lagoon", "estuarine ecosystem", "inland analogues of coastal systems" [1–4, 18].

Inclusion Criteria

Studies were included if they met one or more of the following criteria:

- Peer-reviewed journal articles, monographs, or conference proceedings published between 2000 and 2025.
- Explicit focus on ecological processes, hydrology, biodiversity, pollution, or environmental stressors in Punjab's wetlands or in comparable inland freshwater systems.
- Relevance to at least one Ramsar-designated wetland in Punjab or to analogous inland/coastal systems that inform the marine–inland analogy.

Exclusion Criteria

Studies were excluded if they:

- Lacked empirical or conceptual ecological content (e.g., purely journalistic or promotional material, non-scientific sources).
- Were identified as duplicates (e.g., conference abstracts later superseded by full papers).
- Focused on entirely different ecosystems or geographic regions without clear relevance to inland wetlands or the marine–inland analogy.

The selected literature was then thematically synthesised to address the study objectives, with particular emphasis on microbial-mediated biogeochemical processes, bioindicator responses, and governance–outcome linkages in the six Ramsar wetlands of Punjab.

DATA ANALYSIS

Thematic synthesis was conducted under three broad categories: ecological structure, environmental stressors, and governance, supported by comparative analysis across the Ramsar wetlands and river stretches of Punjab.

Aquatic and wetland ecosystems in Punjab (north-west India) form a critical inland analogue to marine and coastal systems in terms of habitat complexity, connectivity, and ecosystem services, yet they are under severe anthropogenic stress. This review applies concepts from marine ecosystem science – spatial zonation, trophic structure, biogeochemical cycling, ecosystem services, and Large Marine Ecosystem (LME) frameworks – to synthesise the status, threats, and community-based conservation responses across Punjab's major wetlands and river stretches, including Harike, Ropar, Kanjli–Kali Bein, Nangal Wildlife Sanctuary, Keshopur–Miani Community Reserve, and the Beas Conservation Reserve.

We first outline marine-derived analytical tools and demonstrate their relevance for categorising freshwater pelagic, benthic, and littoral zones in Punjab's reservoir and floodplain wetlands, and for interpreting trophic interactions and bioindicator assemblages (molluscs, herpetofauna, fishes, waterbirds) along the Sutlej–Beas–Ravi network [1–4, 12–30]. We then review hydrological modifications, pollution (nutrient enrichment, heavy metals, pesticides, plastics), land-use change, and governance gaps as cross-cutting pressures that parallel degradation patterns in estuaries and coastal lagoons globally. Case studies highlight both top–down policy instruments (Ramsar designation, wildlife sanctuaries, river and community reserves) and bottom–up initiatives (Kali Bein "Kar-Sewa", Keshopur community management, school- and CSR-supported stewardship at Kanjli) as emerging models for integrated conservation. We conclude that triangulating wildlife-centric monitoring with marine ecosystem frameworks and participatory governance can provide a robust basis for designing "Large Aquatic Ecosystem" (LAE) approaches in Punjab and similar inland regions worldwide.

Wetlands, Rivers, and Ecosystem Services

Wetlands and riverine ecosystems are widely recognised as global biodiversity hotspots that provide disproportionately high ecosystem services relative to their area, including water purification, flood regulation, carbon storage, fisheries, and cultural values. International frameworks, such as the Ramsar Convention and the Convention on Biological Diversity, explicitly identify wetlands as priority ecosystems, and recent Indian ecosystem-accounting assessments highlight their role in natural capital and ecosystem-service accounting.

In India, national wetland programmes and recent year-end reviews emphasise expansion of Ramsar coverage and state-level management plans, yet multiple analyses show that unprotected and community-managed wetlands continue to be drained, polluted, or converted, leading to major service losses. Punjab is particularly instructive in this context because an intensely irrigated agrarian economy coexists with a high density of Ramsar and other important wetlands within a relatively small area, creating strong parallels with coastal regions where dense human use and infrastructure intersect with high-value aquatic habitats. In both settings, ecosystem services are underpinned by microbially mediated processes (e.g., denitrification, organic-matter decomposition, metal transformation) whose disruption by pollution and hydrological change can rapidly degrade system functionality [1–4, 13, 17, 20, 23].

Marine Ecosystem Concepts as Framework

Marine ecosystem science has developed a sophisticated body of theory around spatial zonation (pelagic, benthic, and coastal wetlands), trophic structure, biogeochemical cycling, and ecosystem services that can be directly adapted to inland aquatic systems [1–4, 18]. Foundational work on Large Marine Ecosystems (LMEs) conceptualises coastal seas as functional units assessed through linked modules for productivity, fish and fisheries, pollution and ecosystem health, socio-economics, and governance, offering an integrative template for ecosystem-based management.

This approach is tightly coupled to the ecosystem-services framework that classifies marine and coastal contributions to human well-being into provisioning, regulating, supporting, and cultural services, reinforcing the need to connect ecological processes with social and economic outcomes. Applying these concepts to Punjab's aquatic and wetland mosaic allows reservoir and floodplain wetlands to be interpreted as freshwater analogues of coastal lagoons and marshes, and supports the development of a "Large Aquatic Ecosystem" (LAE) framing for the Sutlej–Beas–Ravi network that links wildlife, ecosystem functions (including microbial biogeochemistry), and governance within a single analytical structure. This framing is particularly useful for identifying critical control points where microbial-mediated nutrient and contaminant transformations intersect with hydrological and institutional arrangements [1–4, 13, 17, 21, 22, 23].

Punjab's Rivers and Wetland Inventory

Recent inventories identify roughly twenty ecologically significant wetlands in Punjab, with about eight classifieds as natural floodplain or depression wetlands and twelve as artificial or man-made

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systems, typically associated with dams and barrages. Six of these sites – Harike, Ropar, Kanjli, Nangal Wildlife Sanctuary, Keshopur–Miani Community Reserve, and the Beas Conservation Reserve – have been designated as Ramsar wetlands, reflecting their importance for waterbirds, fish, herpetofauna, and ecosystem services at state and flyway scales. These wetlands are embedded in a hydrological network dominated by the Sutlej, Beas, and Ravi rivers, whose flows are extensively regulated by large dams, headworks, and a dense network of irrigation canals, fundamentally altering natural flood pulses and sediment dynamics.

Official state briefs and national wetland portals note that many additional wetlands, including smaller Chhambs and village-level waterbodies, remain under-documented or unprotected, even as journalistic and civil-society accounts reveal substantial losses of wetland area and function in districts, such as Patiala, Mansa, and Fazilka, over recent decades. This pattern mirrors broader trends in inland-water governance, where designation and protection are concentrated on a few high-profile sites while numerous smaller, community-linked wetlands face ongoing degradation.

Case Studies and Site-Level Variation

Harike Wetland, the largest in northern India, is a barrage-created reservoir at the Sutlej–Beas confluence that supports tens of thousands of wintering waterbirds but is heavily impacted by nutrient and contaminant inputs, invasive macrophytes, and hydrological regulation. In contrast, Keshopur–Miani Community Reserve is a low-lying floodplain marsh owned and managed by village panchayats, where lotus and water chestnut cultivation and artisanal fisheries coexist with conservation of sarus cranes and large waterbird flocks under India's first community-reserve designation. The Kali Bein–Kanjli system illustrates a culturally driven restoration effort in which religious "Kar-Sewa", sewage-treatment interventions, and, more recently, a CSR-funded multi-stakeholder project have sought to rehabilitate a small but symbolically important river–wetland corridor [24, 25].

Nangal Wildlife Sanctuary and the Beas Conservation Reserve add Shivalik-reservoir and free-flowing river contexts, respectively, the latter harbouring India's only population of the Indus River dolphin and diverse mollusc and herpetofaunal assemblages proposed as bioindicators of river health. Together, these case studies illustrate a gradient from heavily regulated, large-scale reservoir wetlands to small-scale, community-managed systems, providing a natural experiment for comparing ecological responses and governance outcomes under similar biophysical and socio-political conditions.

Cross-Cutting Pressures and Indicators

Across these case studies, several cross-cutting pressures recur and interact. Multiple hydrological and geochemical studies document elevated concentrations of arsenic, uranium, nitrates, and other heavy metals in Punjab's ground and surface waters, linked to both geological factors and intense agricultural and industrial activity, with clear implications for wetlands receiving these flows. Nutrient loading and organic pollution from fertilisers, pesticides, and untreated sewage have contributed to eutrophication and invasive macrophyte proliferation in wetlands, such as Harike, while long-term siltation, encroachment, and land-use conversion have led to outright loss or severe shrinkage of several non-Ramsar wetlands.

In this context, the use of biotic assemblages as indicators has gained attention. Studies of molluscs and herpetofauna along the Beas, combined with broader work on macroinvertebrates and fish in Indian rivers, show that community composition and functional traits provide sensitive measures of ecological condition. Long-term waterbird counts at Harike and Keshopur increasingly serve as integrative indicators of wetland health and flyway-scale change, reflecting shifts in food–web structure, habitat quality, and hydrological regime. These indicators, when linked to microbial biogeochemical processes (e.g., denitrification, metal-transforming microbes), offer a multi-level lens for assessing the combined impacts of pollution, hydrological alteration, and governance interventions on Punjab's wetland mosaics [1–4, 13, 17, 23, 30].

Community-Based Conservation and Governance Analogies

Punjab's wetlands also offer important examples of community-based conservation that parallel marine and coastal co-management models. The Kali Bein revival, led by Sant Balbir Singh Seechewal and volunteers through "Kar Sewa", has combined religious motivation, manual restoration, pressure on authorities to install sewage-treatment infrastructure, and sustained public awareness, and is frequently cited as a national model of community-led river restoration. Keshopur–Miani Community Reserve represents an institutionalised form of local stewardship under the Wildlife (Protection) Act, with village panchayats sharing responsibility for managing wetland resources and conservation outcomes, akin to community-managed coastal fisheries or mangrove reserves elsewhere.

More recently, NGO and CSR partnerships, such as the Danone–WWF initiative at Kanjli, have sought to formalise multi-stakeholder governance through management plans, school-based "Water Programmes", and "Wetland Mitras" networks, although transparent, independent evaluations of ecological impact remain limited. These experiences sit alongside a formal governance architecture of Ramsar designations, wildlife sanctuaries, conservation and community reserves, and state wetland rules, which together resemble, in inward-facing form, the layered protection regimes found in large marine ecosystem and marine protected area networks [26, 27].

Towards a "Large Aquatic Ecosystem" Approach

Synthesising these strands suggests that Punjab's Sutlej–Beas–Ravi–wetland complex can productively be conceptualised as a "Large Aquatic Ecosystem" (LAE) in the sense used for coastal LMEs, with distinct but interacting sub-units linked by hydrological flow, species movements, and shared governance challenges. Under such a framing, monitoring and management would explicitly integrate modules on productivity and primary production, multi-taxon biodiversity (fish, invertebrates, amphibians, reptiles, birds, and mammals), pollution and ecosystem health, socio-economic dependence of local communities, and the effectiveness of governance arrangements, rather than treating each wetland in isolation.

This would help align wetland conservation with emerging ecosystem-services assessments and natural-capital accounting in India, which call for linking ecological data with economic and policy decision-making. It also generates a clear research agenda for wildlife and conservation scientists in Punjab: long-term, multi-site monitoring programmes; development of integrated ecosystem-health indices; comparative evaluations of community-managed versus state-managed wetlands; and scenario analyses for climate and land-use change that inform adaptive, basin-scale planning [28].

Concepts from Marine Ecosystem Science Relevant to Punjab

Marine ecosystem science provides a rich conceptual toolkit for understanding the structure, function, and conservation of Punjab's aquatic and wetland systems, even though these are inland and largely freshwater [1–4, 18]. Marine ecologists routinely analyse ecosystems in terms of spatial zoning, trophic organisation, biogeochemical cycles, ecosystem services, and large-scale management units, all of which can be productively transferred to riverine and wetland contexts in north-west India [1–4, 18]. This section outlines key marine concepts and shows how they can frame wildlife-oriented research and management of Punjab's wetlands.

Spatial Zoning and Habitat Analogues

Marine environments are classically divided into pelagic (open-water), benthic (bottom-associated), and coastal zones, with further refinement into neritic, oceanic, intertidal, estuarine, and coastal wetland habitats [1–4]. Each zone is characterised by distinct physical conditions, productivity regimes, and biological communities; for example, shallow coastal waters and estuaries typically support high primary productivity, nursery habitats for fish and invertebrates, and dense aggregations of waterbirds [1–4, 18].

Punjab's wetlands and rivers lack true marine salinity, but analogous spatial zonation is evident. Large reservoir–wetlands, such as Harike, Ropar, Nangal, and Keshopur–Miani, exhibit open-water pelagic zones supporting plankton, fish, and diving waterbirds; littoral and emergent macrophyte belts functioning like coastal marshes; and benthic zones of soft sediment inhabited by benthic invertebrates, molluscs, and herpetofauna. Riverine segments (e.g., Beas, Sutlej, Kali Bein) show longitudinal gradients in depth, velocity, and substrate that parallel marine nearshore–offshore gradients, influencing community composition and habitat use by fish, turtles, and birds. For wildlife scholars, explicitly mapping these "freshwater pelagic–benthic–littoral" zones facilitate habitat-specific monitoring and impact assessment, much as in coastal and shelf-sea studies [1–4, 18].

Biogeochemical Cycles and Ecosystem Services

Marine systems are key actors in global carbon, nitrogen, and phosphorus cycles, with oceans storing vast amounts of carbon and mediating nutrient transformations through processes such as upwelling, denitrification, and sedimentation [1–4, 18]. These biogeochemical processes underpin ecosystem services including climate regulation, nutrient retention, and fisheries productivity, and have strongly influenced the broader ecosystem-services framework, which classifies services into provisioning, regulating, supporting, and cultural categories.

Punjab's wetlands provide analogous services at regional scales. Floodplain and reservoir wetlands act as sinks and transformers of nutrients and pollutants entering from agricultural and urban catchments, moderating downstream loads and supporting fisheries, grazing, and plant-based livelihoods. Carbon storage in wetland soils and sediments, regulation of local microclimate, and support of pollinators and pest-controlling species extend their ecological importance beyond open water. Culturally, sites, like Kali Bein–Kanjli and Harike, serve as religious, recreational, and educational spaces, mirroring the cultural services often highlighted for coastal and marine ecosystems. Using a marine-inspired ecosystem-services lens can help wildlife scholars quantify and communicate the multi-dimensional value of Punjab's wetlands to decision-makers [28].

Connectivity and Meta-Ecosystem Thinking

Marine ecology has long dealt with connectivity, given the fluidity of seawater and the long-distance dispersal of larvae, nutrients, and pollutants [1–4, 18]. Concepts, such as source–sink dynamics, metapopulations, and meta-ecosystems, are central to understanding how populations and processes are linked across spatial scales, from estuaries to offshore reefs. This thinking informs the design of marine protected area (MPA) networks and large marine ecosystem (LME) management units.

Punjab's rivers and wetlands are likewise embedded in connected catchment networks. The Kali Bein–Kanjli–Harike continuum, the chain of Beas wetlands, and the linkage of Nangal to downstream Ropar illustrate how hydrological connectivity couples water quality, nutrient fluxes, fish movements, and migratory bird use across multiple sites. Pollution incidents or flow alterations upstream propagate to Ramsar wetlands, just as land-based pollution affects downstream estuaries and coastal seas. For wildlife scholars, adopting connectivity and meta-ecosystem perspectives encourages multi-site monitoring designs, analyses of movement ecology (e.g., banding or telemetry of birds and turtles), and assessment of cumulative impacts along river–wetland corridors rather than isolated sites.

Large Marine Ecosystems (LMEs) and Integrated Management Modules

The Large Marine Ecosystem (LME) framework divides the global coastal ocean into ecologically and oceanographically distinct units managed through five linked modules: productivity, fish and fisheries, pollution and ecosystem health, socio-economics, and governance. This approach integrates biophysical monitoring with socio-economic analysis and institutional strengthening and has influenced regional seas programmes and marine spatial planning.

Although designed for coastal seas, the LME modular logic is directly applicable to Punjab's aquatic landscapes. A "Large Aquatic Ecosystem" perspective on the Sutlej–Beas–Ravi–wetland complex could, for example, organise research and management around: (i) productivity and primary production in rivers and wetlands; (ii) fish and fishery dynamics in reservoirs and marshes; (iii) pollution and ecosystem-health metrics (water quality, bioindicators, disease in wildlife); (iv) socio-economic dependence of local communities (fisheries, lotus and Singhara harvest, eco-tourism); and (v) governance arrangements (Ramsar, community reserves, river–basin institutions). Framing Punjab's wetlands through an adapted LME lens can help wildlife scholars structure interdisciplinary studies and propose integrated management plans that resonate with global marine conservation discourse.

Marine-Inspired Indicators and Monitoring Approaches

Marine ecosystem science has developed a suite of bioindicators and composite indices to assess ecosystem health, including multi-species fish indices, benthic quality indices, plankton-based eutrophication metrics, and seagrass condition scores. These tools integrate species-level information into ecosystem-level assessments that can be tracked over time and linked to management targets.

Emerging work along the Beas and in Punjab's wetlands on mollusc and herpetofaunal diversity, fish assemblages, and waterbird counts provides a starting point for similar indicator development in inland systems. For example, mollusc and amphibian richness and abundance can be used to flag habitat degradation and pollution, paralleling benthic indices in marine systems; likewise, trends in migratory waterbirds at Harike, Kanjli, and Keshopur can function as integrative indicators of hydrological and water-quality change. Adopting marine-inspired indicator frameworks can make wildlife monitoring in Punjab more comparable across sites and more policy-relevant, particularly when linked to microbial-mediated biogeochemical processes that underpin nutrient and contaminant dynamics [1–4, 13, 17, 30]. Marine-to-Punjab conceptual analogies depicted in Table 1.

Table 1. Marine-to-Punjab conceptual analogies.

Marine concept	Punjab application	Practical use for wildlife research	Citation
Coastal lagoon with river inflow	Harike as a barrage-created lagoon-like wetland at the Sutlej–Beas confluence.	Supports use of estuarine sampling designs, eutrophication metrics and lagoon-type habitat models in inland setting [1.8].	5, 13, 18, 1.8
Seagrass meadow	Macrophyte-rich marshes at Keshopur–Miani and other Chhambs dominated by emergent and floating vegetation.	Encourages use of vegetation condition and spatial extent as structural indicators of habitat quality, like seagrass-based indices [1.8].	5, 18, 28, 1.8
Large Marine Ecosystem (LME)	"Large Aquatic Ecosystem" framing of Sutlej–Beas–Ravi River network and associated wetlands [1.7] [1.8].	Provides template for structuring monitoring around productivity, biodiversity, pollution, socio-economics and governance modules [1.7] [1.8].	1.7, 1.8, 17
Marine Protected Area (MPA) network	Network of Ramsar sites, wildlife sanctuaries, conservation and community reserves across Punjab.	Promotes thinking in terms of connected protected sites and ecological corridors rather than isolated wetlands [1.6].	5, 18, 28, 1.6
Coastal bioindicators (benthic indices, fish IBI, seabird trends)	Multi-taxon indicators using molluscs, herpetofauna, fish assemblages and waterbird count at sites such as Harike, Beas, Kanjli, Keshopur, and Nangal [1.9].	Encourages development of integrated wetland–health indices, moving beyond single-species monitoring towards ecosystem-level assessment [1.9].	12, 17, 23, 26, 1.9

CROSS-CUTTING PRESSURES AND BIOINDICATORS IN PUNJAB'S AQUATIC AND WETLAND ECOSYSTEMS

Aquatic and wetland ecosystems in Punjab are shaped by a suite of cross-cutting anthropogenic pressures that act simultaneously and often synergistically across river basins and wetland types. These pressures span chemical pollution, hydrological modification, land-use and land-cover change, biological invasions, and climate-linked stressors, all operating within a context of intensive agriculture and dense infrastructure. Rather than affecting individual sites in isolation, they propagate along the Sutlej–Beas–Ravi network and its associated reservoirs and marshes, producing basin-scale patterns analogous to those documented in many estuarine and coastal marine systems. Understanding these cross-cutting drivers, and the extent to which biological assemblages can function as integrated indicators of ecosystem health, is central to designing an effective "large aquatic ecosystem" approach for Punjab.

Chemical Pollution and Contamination

A large body of work has highlighted the role of chemical contamination in degrading freshwater and wetland ecosystems in Punjab, with particular attention to heavy metals, pesticides, nutrients, and emerging pollutants. Groundwater and floodplain studies in the Ravi–Beas–Sutlej corridors have demonstrated elevated concentrations of arsenic and other trace elements in many shallow aquifers, attributed to both geogenic sources and intensive agricultural practices. Reviews of groundwater across Malwa, Doaba, and Majha regions similarly report high levels of uranium, selenium, chromium, and other metals in drinking-water wells, often linked to excessive fertiliser and pesticide application and industrial effluents, prompting descriptions of groundwater contamination as a "man-made curse".

Because these aquifers discharge into rivers and wetlands, and because contaminated irrigation water is recycled through fields and drainage channels, the contamination footprint extends into surface aquatic systems, including Ramsar sites. Within wetlands themselves, case studies at Harike and other reservoir wetlands document significant nutrient loading and toxic inputs. Reports from Harike describe long-term "slow poisoning" through industrial effluents and municipal sewage entering via the Sutlej and Beas, contributing to elevated nutrient levels, organic loading, and contamination of sediments. These conditions promote the proliferation of water hyacinth and other opportunistic macrophytes, which form dense mats that deplete dissolved oxygen, shade out native vegetation, and impede fishing and navigation.

Beyond nutrients and metals, pesticide residues and agrochemicals pose additional risks. Punjab's high-input agriculture has led to persistent concerns about organophosphate, organochlorine, and newer pesticide residues in surface waters, sediments, and biota. While detailed multi-pollutant surveys remain limited compared to some coastal and estuarine regions, the available data from groundwater, soils, and selected river stretches indicate that agricultural chemicals contribute significantly to overall contaminant loads. From a wildlife perspective, these contaminants can cause sub-lethal effects, such as endocrine disruption, reproductive impairment, and immunosuppression in fishes, amphibians, reptiles, and birds, as well as bioaccumulation up food chains.

Nutrient Enrichment, Eutrophication and Invasive Macrophytes

Nutrient enrichment – particularly from nitrogen and phosphorus—is a pervasive pressure across Punjab's aquatic landscape, driven by fertiliser runoff, manure, and untreated or partially treated sewage. In reservoir wetlands, like Harike, nutrient inputs from the Sutlej and Beas promote high phytoplankton productivity and favour fast-growing macrophytes such as water hyacinth. The resulting eutrophic conditions can create diurnal swings in dissolved oxygen, with high daytime levels due to photosynthesis and nighttime declines as plant and algal respiration dominates. Under calm, warm conditions these swings may lead to episodic hypoxia or anoxia, causing fish kills and stressing benthic invertebrates.

From an ecological standpoint, eutrophication and invasive macrophytes alter habitat structure and food–web dynamics. Dense hyacinth mats and thick stands of emergent vegetation reduce open water area, affecting diving ducks, terns, and other species that require unobstructed surfaces and water columns. They also change the composition of invertebrate communities, favouring taxa tolerant of low oxygen or high organic loads, and may reduce habitat suitability for some fish and amphibians. Over time, as macrophyte biomass dies and decomposes, it contributes to sediment accretion and shallowing, accelerating the infilling and potential terrestrialisation of shallow wetland zones. These processes mirror eutrophication-driven vegetation shifts observed in many coastal lagoons and estuaries, where nutrient enrichment promotes macroalgal blooms, seagrass loss, and altered benthic communities.

Hydrological Alteration and Flow Modification

Hydrological alteration is another cross-cutting pressure with profound ecological consequences. Large dams and barrages on the Sutlej and Beas, along with an extensive canal network and numerous smaller headworks, have re-shaped seasonal flow regimes, flood pulses, and connectivity between channels and floodplains. Harike Wetland is itself a product of such engineering, created by the Harike barrage, with water levels influenced by irrigation demands and operational decisions. Ropar, Nangal, and Ranjit Sagar are similar examples where reservoir operations determine the timing and magnitude of water-level changes, often decoupled from natural monsoon cycles.

For wetlands, altered hydrology affects the frequency, duration, and timing of inundation, which are key determinants of vegetation zonation, breeding success, and habitat availability. Rapid drawdowns or prolonged high-water conditions can disrupt nesting in emergent vegetation, affect spawning cues for fish, and change the composition of amphibian communities. In floodplain marshes and Chhambs, canalisation and embankments can reduce natural flooding, cutting off sediment and nutrient inputs and accelerating ecological isolation. Over decades, such alterations have contributed to the shrinkage or disappearance of numerous small wetlands in Punjab, as documented by state and national assessments that note a loss of thousands of hectares of wetland area across multiple districts.

In a marine framing, these changes are analogous to upstream damming and flow regulation in estuarine and coastal systems, where altered freshwater inflows modify salinity gradients, sediment delivery, and estuarine circulation, with cascading effects on fisheries, vegetation, and water quality. Applying this analogy to Punjab highlights the importance of treating flow management not just as an engineering problem but as a core element of ecosystem-based wetland management.

Land-Use Change, Encroachment and Habitat Loss

Land-use and land-cover change – particularly agricultural expansion, urbanisation, and infrastructure development – have led to direct loss and fragmentation of wetland habitats in Punjab. Recent journalistic analyses and official inventories suggest that at least eight significant wetlands have been severely degraded or lost over the past three decades, with more than 2,800 ha disappearing in districts such as Patiala, Mansa, Gurdaspur, Hoshiarpur, Jalandhar, Ferozepur, and Fazilka. Many of these sites lie on private land or in a grey zone of tenure where regulatory mechanisms were weak, and were gradually converted to cropland, brick kilns, industrial uses, or built-up areas.

Even where wetlands formally persist, encroachment at the margins is common. Agriculture on wetland fringes reduces buffer zones that can filter pollutants, increases disturbance to birds and other wildlife, and may involve drainage works that alter local hydrology. Urban growth near smaller wetlands and along rivers brings solid-waste dumping, increased sewage loads, and hardening of banks, further diminishing habitat quality. These patterns mirror the "dying traditional water bodies" documented across India, where unplanned development and lack of recognition of ecosystem functions drive piecemeal loss. The cumulative effect is not only a reduction in total wetland area but also increased fragmentation and isolation of remaining sites, which is problematic for migratory species and for maintaining genetic exchange in aquatic organisms.

Climate Variability and Emerging Stressors

While detailed climate-change attribution studies for Punjab's wetlands remain limited, there is growing recognition that climate variability and long-term trends may exacerbate existing pressures. Changes in monsoon patterns, increased frequency of extreme rainfall events, and heatwaves can interact with hydrological regulation and water demand to alter water levels and temperature regimes in rivers and wetlands. For example, lower base flows combined with high evaporation and increased water extraction can concentrate pollutants and raise water temperatures, stressing cold-water-tolerant species. Heatwaves and droughts may intensify conflicts between irrigation and environmental flow requirements, particularly in systems, like Harike and Ropar, where water allocation decisions directly affect wetland hydrology.

From a biological perspective, climate-linked shifts in phenology may alter migration timing, breeding seasons, and species distributions. Migratory waterbirds may adjust arrival or departure dates in response to temperature and resource availability, while fish and amphibians may experience mismatches between breeding cues and habitat conditions. These dynamics add a layer of uncertainty to management, and underscore the need for flexible, adaptive approaches that incorporate climate scenarios into wetland planning, as is increasingly common in coastal and marine ecosystem management.

Bioindicators and Multi-Taxon Assessment

Given this complex mixture of pressures, there is growing interest in using biological assemblages as integrated indicators of ecosystem health, drawing on approaches developed for rivers, estuaries, and coastal seas. In Punjab, one foundational line of work has examined mollusc and herpetofaunal diversity along the River Beas, demonstrating that species richness and community composition vary systematically with habitat condition and disturbance, and can be used to detect degradation. This aligns with broader Indian and international studies showing that benthic macroinvertebrates are sensitive indicators of changes in water quality, organic pollution, and habitat structure in wetlands and streams.

Fish assemblages offer another window into cumulative impacts of flow alteration, habitat modification, and exploitation. In many regulated rivers and reservoirs, shifts from rheophilic species adapted to flowing water towards more generalist or lentic species can signal changes in hydrological regime and habitat simplification. While comprehensive fish-based indices have not yet been standardised for Punjab's wetlands, experience from other basins indicates that multi-metric indices combining species richness, trophic structure, and life-history traits can provide robust assessments of ecological condition [28].

Waterbirds represent perhaps the most visible and widely monitored indicator group. Mid-winter counts at Harike and Keshopur–Miani document trends in total waterbird numbers and species composition, with declines in some years linked to water-level fluctuations, habitat changes, and reported pollution episodes. Because many migratory species depend on networks of sites along the Central Asian Flyway, local declines can reflect both local pressures and broader flyway-scale changes. From a management standpoint, waterbird monitoring has the advantage of strong public interest and existing census frameworks, making it a practical component of long-term ecosystem-health assessment.

Taken together, these bioindicator groups provide complementary perspectives: invertebrates and herpetofauna offer fine-scale, often local signals of water and habitat quality; fish assemblages integrate flow, habitat, and exploitation effects; and waterbirds integrate conditions at broader spatial scales. An explicit "large aquatic ecosystem" framework would seek to combine these into a multi-taxon indicator suite, akin to multi-component indices used in marine ecosystem assessment, to support evidence-based management decisions.

Here is a tightened, citation-ready version of your Section 3 (Keshopur–Miani) and the Harike Wetland case-study text, with in-text references woven in for key claims, while preserving the marine–inland analogy and the "large aquatic ecosystem" framing:

KESHOPUR–MIANI COMMUNITY RESERVE: A CASE STUDY OF COMMUNITY-MANAGED WETLAND CONSERVATION IN PUNJAB

Keshopur–Miani Community Reserve (often referred to as Keshopur Chhamb) is a unique floodplain wetland system in Gurdaspur district, Punjab, and is widely recognised as India's first formally notified community reserve and one of the state's last remaining natural wetlands of substantial size. The site occupies a low-lying depression in the Ravi–Beas interfluve, about 6–7 km from Gurdaspur town and close to the Indo-Pakistan border, and encompasses a mosaic of marshes, shallow open water, managed aquaculture ponds and surrounding agricultural fields distributed across several villages, notably

Keshopur, Miani, Dalla, Matwa and Magarmudian. The wetland complex covers roughly 340–344 ha and is owned largely by village panchayats, with the Punjab Wildlife and Forest Department holding regulatory authority as part of the community-reserve designation. In 2019, Keshopur–Miani was designated as a Ramsar site (no. 2414), further underscoring its biological and socio-ecological importance at national and international levels.

Within the "large aquatic ecosystem" framing developed for Punjab's Sutlej–Beas–Ravi–wetland mosaics [17–19, 26], Keshopur–Miani serves as a critical node of connectivity for migratory waterbirds along the Central Asian Flyway, as well as a sentinel site for community-based wetland governance analogous to marine and coastal co-management models [1–4, 18, 28]. Avifaunal surveys and long-term waterbird counts indicate that the reserve supports tens of thousands of migratory birds each winter, including threatened species, such as the sarus crane and common crane, and that local community-based stewardship has helped maintain habitat quality despite broader pressures of nutrient loading, hydrological alteration and land-use change across the Ravi–Beas floodplain [13, 17, 28, 21–24].

From a marine-ecosystem perspective, Keshopur–Miani closely resembles a coastal wetland or lagoon in its functional role: it provides high-productivity pelagic and littoral zones, supports nursery functions for fish and invertebrates, and mediates nutrient and contaminant fluxes through sedimentation and microbial transformations, much like estuarine and coastal systems described in marine ecosystem science [1–4, 18, 26]. Its community-reserve status, under the Wildlife (Protection) Act, mirrors principles of local co-management seen in community-managed mangrove reserves and small-scale marine protected areas, where village institutions share responsibility for resource use and conservation, while state agencies retain regulatory oversight [18, 28, 16].

Applying marine-inspired bioindicator and monitoring approaches, conservation practitioners at Keshopur–Miani have begun to track trends in waterbird assemblages, fish and invertebrate communities, and habitat structure, using these as integrative indicators of ecosystem health and hydrological change [13, 17, 28, 26]. When embedded within a basin-scale "large aquatic ecosystem" framework for the Ravi–Beas corridor, Keshopur–Miani becomes not only a Ramsar wetland but also a key reference site for evaluating the cumulative impacts of pollution, land-use change, and climate-linked stressors on wetland mosaics that parallel patterns documented in coastal and estuarine systems [1–4, 17–19, 21–25].

Hydrological and Geomorphic Setting

Hydrologically, Keshopur–Miani is a freshwater marsh system primarily supported by local rainfall, catchment runoff and residual flooding, rather than by direct perennial river inflows. Historically, the area functioned as a floodplain depression that captured seasonal floodwaters from nearby streams and drainage channels, providing temporary storage and slowly releasing water back into the landscape. Over time, canal development, drainage works and changes in agricultural practices have modified inundation patterns, but the basic hydrological character – a shallow, seasonally variable marsh – remains.

Unlike reservoir wetlands, such as Harike or Ropar, which are dominated by deep open-water zones and strong vertical stratification, Keshopur–Miani is characterised by extensive shallow zones, with water depth typically ranging from a few centimetres to about two metres depending on season and management. The geomorphic setting as a floodplain depression means that the wetland is particularly sensitive to changes in catchment land-use and local hydrological engineering. Small bunds, sluice gates and field channels constructed by villagers and local authorities regulate inflow and outflow of water, allowing some control over water levels for fisheries and crop production while maintaining habitat for waterbirds and other wildlife. This fine-grained hydrological management contrasts with the top–down reservoir operations of larger barrages and aligns more closely with the managed wetland systems described in coastal and estuarine literature, where communities adjust water regimes to balance production and conservation objectives [1–4].

Habitat Structure and Vegetation

Ecologically, Keshopur–Miani comprises a heterogeneous mosaic of habitat types that together support high biodiversity. The core wetland includes patches of relatively open water interspersed with dense stands of emergent macrophytes such as *Typha* and *Phragmites*, floating-leaved species such as lotus (*Nelumbo nucifera*) and water chestnut (*Trapa*), and submerged vegetation in some zones, particularly during certain water-level phases. Seasonal variations in water depth and extent create a dynamic pattern of exposed mudflats, shallow inundated grasslands and deeper pools, which in turn provide habitats for different guilds of birds, fish, amphibians and invertebrates at different times of the year.

Surrounding the core marsh are a series of managed ponds (often used for aquaculture) and agricultural fields where wetland-dependent crops, like lotus and water chestnut, are cultivated, along with more conventional crops in slightly elevated areas. This landscape configuration aligns closely with the “wise use” concept emphasised by the Ramsar Convention, in which wetlands are managed to allow sustainable resource use while maintaining ecological character. The Ramsar Information Sheet for Keshopur–Miani notes that the site supports around 344 plant species, including a range of hydrophytes, emergent and terrestrial vegetation, reflecting both natural diversity and centuries of human use and management.

Faunal Assemblages and Wildlife Significance

Keshopur–Miani is of exceptional importance for avifauna, particularly waterbirds. The wetland lies on the Central Asian Flyway and is reported to support an estimated 15,000–20,000 migratory waterbirds in winter in favourable years, alongside diverse resident species. It is widely cited as the last stronghold of the sarus crane (*Antigone antigone*) in Punjab, with regular records of pairs and small groups using the wetland and surrounding agricultural fields for feeding and breeding [28, 11–12]. Other notable waterbird taxa include various ducks, geese, storks, ibises, herons, egrets, rails, moorhens, jacanas and waders, making the site a critical refuge in an otherwise intensively cultivated landscape.

Beyond birds, Keshopur–Miani supports diverse assemblages of fish, amphibians, reptiles and invertebrates. Fish communities benefit from the combination of natural marsh habitat and managed ponds, which provide spawning grounds, feeding areas and refuge from harsh conditions. Amphibians and semi-aquatic reptiles use shallow margins, mudflats and vegetated zones for breeding and foraging, contributing to overall trophic complexity. While comprehensive taxonomic surveys are still limited compared to better-studied river stretches, like the Beas, the combination of habitat diversity and relatively low levels of industrial pollution suggests that Keshopur–Miani may harbour significant unrecorded biodiversity, including invertebrate taxa such as molluscs and odonates (Table 2) [1, 9, 2, 6].

Livelihoods, Provisioning Services and “Wise Use”

A defining feature of Keshopur–Miani is the close integration of conservation and local livelihoods. Village panchayats and community members derive direct benefits from the wetland through fisheries, harvest of lotus stems and seeds, water chestnut cultivation and, to some extent, livestock grazing in peripheral areas. These provisioning services provide essential income and subsistence resources for local households, particularly landless or marginal farmers, and create a strong everyday dependence on the wetland’s ecological functioning. The Ramsar documentation explicitly recognises Keshopur–Miani as a demonstration of “wise use”, where sustainable resource use and biodiversity conservation are pursued in tandem.

Economically, the sale of lotus and water chestnut has become a notable component of local livelihoods, with produce marketed in nearby towns and beyond. Fisheries yield both subsistence catch and marketable fish, although detailed production statistics are not systematically reported. The presence of wildlife and the site's increasing recognition as a birdwatching destination also offer potential for eco-tourism-based income, particularly for local guides and homestay providers, though this remains underdeveloped relative to its potential. From an ecosystem-services perspective, Keshopur–Miani thus delivers a suite of provisioning, regulating (e.g., flood buffering, nutrient retention), supporting (e.g., habitat for biodiversity), and cultural services, aligning well with broader frameworks used for coastal and inland wetlands [1–4].

Table 2. Major bioindicator groups in Punjab's aquatic and wetland ecosystems.

Indicator group	Typical habitats	Sensitivity / signal	Use in assessment	Citation
Molluscs (gastropods, bivalves)	Riverbeds, reservoir and wetland sediments, macrophyte beds along Beas and associated wetlands.	Sensitive to substrate quality, organic loading and some pollutants; diversity declines with severe habitat degradation.	Species richness and community structure used as indicators of habitat condition and contamination levels in river stretches and wetlands.	12, 17, 28
Herpetofauna (amphibians and aquatic reptiles)	Shallow marshes, slow-flowing river margins, vegetated fringes of reservoirs and Chhambs.	Sensitive to water quality, hydroperiod and habitat structure; many species decline rapidly under pollution and hydrological change.	Presence/absence and assemblage composition provide early-warning signals of hydrological and pollution stress in aquatic habitats.	12, 28
Fish assemblages	Main river channels, reservoir bodies, marsh channels and inlets/outlets.	Respond to flow regimes, habitat heterogeneity, water quality and exploitation pressure.	Changes in species composition, size structure and trophic guilds reveal cumulative impacts on river and wetland ecosystems.	14, 17, 28
Waterbirds	Open water, mudflats, emergent marshes, riparian and agricultural interfaces around wetlands.	Integrate habitat, food–web and disturbance changes at landscape scales; migratory species particularly sensitive to habitat loss and pollution.	Mid-winter counts and breeding records used as integrative indicators of wetland health and flyway-level status.	5, 13, 23, 26
Aquatic macrophytes	Littoral zones of reservoirs, marsh interiors, slow-flowing channels.	Respond to nutrient levels, hydrology and competition/ invasion; composition reflects eutrophication and disturbance gradients.	Species composition and areal coverage used to classify trophic status and track habitat alteration over time.	13, 18

Community Ownership, Governance and Institutional Innovation

Governance at Keshopur–Miani is characterised by a combination of local ownership and formal state recognition. The wetland is owned by multiple village panchayats, with land parcels collectively managed under customary and statutory arrangements. In 2007, the area was notified as a community reserve under the Wildlife (Protection) Act, making it the first such reserve in India and legally establishing a management committee comprising local community representatives and state officials. This committee is empowered to conserve, maintain and manage the reserve, and to regulate sustainable use activities under agreed rules.

The community-reserve model at Keshopur–Miani shares key features with community-managed marine and coastal areas, such as locally-led decision-making, integration of livelihood needs and conservation goals, and legal backing for participatory governance [1–6]. WWF–India and other organisations have highlighted Keshopur–Miani as a case study in community-based wetland management, noting that local involvement has been crucial in enforcing seasonal restrictions, preventing encroachment and maintaining habitat suitable for sarus cranes and other sensitive species. At the same time, the model depends on sustained engagement and capacity within the community and on supportive policy frameworks at the state level, raising questions about long-term institutional resilience. Community-based actions at selected sites depicted in Table 3.

Anthropogenic Pressures and Management Challenges

Despite its relative success-story status, Keshopur–Miani is not immune to broader pressures affecting Punjab's wetlands. Changes in cropping patterns, intensification of agriculture in surrounding catchments and potential future infrastructure developments pose risks of altered runoff, nutrient loading and encroachment [21–22]. Climate variability, particularly shifts in monsoon patterns and the occurrence of droughts or extreme rainfall events, may affect water availability and complicate the delicate hydrological balance that underpins both livelihoods and habitat quality [25]. There are also concerns that increased tourism, if not carefully managed, could lead to disturbance of birds and habitat degradation.

Table 3. Community-based actions at selected sites.

Site	Community actions	Conservation significance	Citation
Kali Bein–Kanjli system	"Kar Sewa" initiatives led by religious and local leaders; manual removal of garbage, weeds and silt; ghat construction; sustained awareness campaigns linking river health to spiritual values.	Demonstrates power of faith-based, volunteer-driven restoration in improving water quality and maintaining flow, indirectly benefiting Kanjli Wetland fed by the Kali Bein.	15, 19, 20
Keshopur–Miani Community Reserve	Panchayat-dominated management committee; community regulation of fishing and harvest of lotus and water chestnut; local monitoring of bird use and water levels; participation in management planning.	India's first community reserve; showcases how livelihoods and biodiversity conservation can co-exist under formal recognition and shared governance.	5, 9, 11, 28
Kanjli Wetland	Local participation in sanitation and cleanliness drives; engagement of schools and "Wetland Mitras" in awareness and monitoring activities under NGO/CSR programmes.	Strengthens stewardship and builds local constituency for protection of a small but culturally important Ramsar site.	19, 20, 22
Harike Wetland	Involvement of local guides and boat operators in birdwatching and nature-based tourism; episodic community clean-up efforts; advocacy by local groups and media against upstream pollution.	Early steps towards linking economic benefits from eco-tourism with conservation incentives, though constrained by basin-scale pollution drivers.	13, 23, 25, 26

From a governance perspective, key challenges include ensuring stable financial support for community-based management, maintaining effective participation of all stakeholder villages in the management committee, and integrating Keshopur–Miani's management with broader basin-level planning for the Ravi–Beas region [27]. As with many community-managed systems, there is a risk of over-exploitation if market demands for fish or wetland crops increase without adequate regulation. Ensuring that benefits are equitably distributed and that vulnerable groups are not marginalised is also critical for maintaining local support.

Lessons and Implications for "Large Aquatic Ecosystem" Management

Keshopur–Miani offers several important lessons for designing integrated management of Punjab's wider aquatic landscape. First, it demonstrates that formal recognition of community rights and responsibilities, backed by strong local institutions, can support effective conservation of a biologically rich wetland in a highly modified agrarian landscape [16]. Second, the site illustrates how provisioning services – fisheries and wetland crops – can be aligned with conservation objectives under a wise-use framework, reducing the perceived trade-off between livelihoods and biodiversity that often characterises debates around protected areas. Third, the mosaic of natural marsh and managed ponds provides a tangible example of how habitat heterogeneity can be maintained under human use, supporting high species diversity and resilient ecosystem functions.

In the context of a "large aquatic ecosystem" approach for the Sutlej–Beas–Ravi system,

Keshopur–Miani can be seen as a critical node in a network of wetlands and river stretches that together sustain migratory birds, fish assemblages and other taxa [17, 18, 26]. Its success suggests that integrating community-managed sites into broader basin-scale governance, alongside state-managed sanctuaries and Ramsar wetlands, can enhance both ecological and social outcomes [27]. Comparative studies between Keshopur–Miani and more top–down managed wetlands, such as Harike and Ropar, could yield valuable insights into the relative effectiveness of different governance models under similar environmental pressures [27]. For wildlife and conservation science, Keshopur–Miani thus functions both as a key habitat and as a living laboratory for community-based wetland management in an intensively used landscape.

Keshopur–Miani in Regional Flyway Context

Keshopur–Miani lies on the Central Asian Flyway, a major migratory corridor linking breeding grounds in Central Asia and Siberia with non-breeding areas across the Indian subcontinent and beyond. Its shallow marshes, mudflats and mixed crop–wetland matrix provide critical refuelling and roosting habitats for a wide spectrum of waterbirds, including dabbling and diving ducks, geese, cranes, storks, ibises, herons, rails, moorhens, jacanas and waders. In a landscape dominated by intensively cultivated fields and canal infrastructure, the wetland functions as one of the very few remaining large, semi-natural freshwater marshes in north-western Punjab, effectively serving as a "stepping-stone" site within broader migratory networks that also include Harike and trans-boundary wetlands in Pakistan.

The presence of sarus crane and substantial wintering waterfowl assemblages underscores Keshopur–Miani's importance for species of high conservation concern at flyway scale. For many of these taxa, the site offers not only safe roosting habitat but also access to abundant foraging opportunities in adjacent fields, where post-harvest grain and invertebrates supplement wetland food resources. This tight coupling between wetland and agricultural habitats means that changes in farming practices, pesticide regimes or disturbance levels can have direct implications for the quality of the site as a migratory stopover and wintering ground [21]. In the context of international initiatives under the Ramsar Convention and flyway programmes, Keshopur–Miani, therefore, represents a strategically important node where local community-based management decisions contribute to the resilience of wider migratory bird populations.

Research Gaps and Monitoring Needs at Keshopur–Miani

Despite its recognised importance, Keshopur–Miani remains comparatively under-studied relative to better-known wetlands, such as Harike, particularly with respect to long-term quantitative data. Systematic, multi-taxon monitoring of birds, fishes, amphibians, reptiles and invertebrates is limited, making it difficult to assess temporal trends in biodiversity, detect early warning signs of degradation, or evaluate the ecological outcomes of community-based management interventions [26]. Existing bird counts and species lists, while valuable, are often sporadic and methodologically heterogeneous, constraining their use for robust trend analysis or for integration into broader Central Asian Flyway assessments. Similarly, there are few published data on fish community structure, productivity of fisheries and aquaculture ponds, or the status of key herpetofaunal groups that could serve as sensitive bioindicators [2, 6].

Hydrological and water-quality monitoring is another critical gap. Detailed time-series data on water levels, inflows and outflows, nutrient concentrations, pesticides and other contaminants are needed to understand how catchment-scale drivers, climate variability and local management decisions affect habitat conditions within the marsh [21–22]. Without such data, it is difficult to design adaptive management measures or to quantify the regulating services (such as nutrient retention and flood buffering) that the wetland provides [26]. Social-science work on governance processes and livelihood outcomes is also relatively sparse, despite the site's status as a flagship community reserve, limiting understanding of how institutional arrangements, benefit-sharing mechanisms and external policy changes influence conservation effectiveness over time.

Addressing these gaps will require coordinated efforts by state agencies, academic institutions, NGOs and the community-reserve management committee [27]. Priority actions include establishing standardised, seasonal biodiversity surveys (with an emphasis on waterbirds, fish and herpetofauna), installing simple hydrological and water-quality monitoring systems, and integrating these datasets into a shared information platform that can inform both local decisions and state-level planning [26]. Participatory research approaches – such as involving local fishers, farmers and bird guides in data collection – could enhance monitoring coverage while strengthening community ownership of conservation outcomes [16]. Over the longer term, comparative studies between Keshopur–Miani and other Punjab wetlands, including more centrally managed sites, would help clarify the specific strengths and limitations of the community-reserve model and provide evidence to guide its replication or adaptation elsewhere [27]. Key wetlands of Punjab and their ecological roles depicted in Table 4.

Table 4. Key wetlands of Punjab and their ecological roles.

Wetland / system	Type & location	Key ecological roles	Wildlife highlights	Citation
Harike Wetland	Barrage-created reservoir at the Sutlej–Beas confluence in south-western Punjab (Tarn Taran, Ferozepur, Kapurthala districts).	Large-scale water storage, flood buffering, nutrient and sediment trapping, nursery habitat for fish and invertebrates, major staging and wintering site on the Central Asian Flyway.	Supports tens of thousands of wintering waterbirds in favourable years, including ducks, geese, waders and raptors; important for river-linked fauna.	5, 10, 13, 18, 23, 25, 30
Ropar Wetland	Barrage-created reservoir on the Sutlej near the Shivalik foothills in Rupnagar district.	Regulation of downstream flows, sediment and nutrient trapping, interface between hill and plains riverine biota.	Over 150 bird species and more than 35 fish species recorded; important link for migratory waterbirds and riverine fishes.	5, 13, 16
Kanjli–Kali Bein	Small bund-created wetland on the Kali Bein, a tributary of the Beas, in Kapurthala district.	Cultural-religious corridor, local flood moderation, habitat for waterbirds and fishes within an intensively cultivated landscape.	Regular use by waterbirds; part of a historically and religiously significant river–wetland system.	5, 15, 19
Nangal Wildlife Sanctuary	Reservoir-based wetland downstream of the Bhakra–Nangal dam on the Sutlej, in Rupnagar district.	Reservoir habitat with surrounding dry-deciduous and foothill forest, refuge in the Shivalik landscape, staging area for migratory birds.	Migratory waterbirds, diverse fish assemblages, and threatened mammals (e.g., Indian pangolin) and raptors reported.	5, 13, 16
Keshopur-Miani Community Reserve	Community-managed floodplain marsh complex near Gurdaspur town in north-western Punjab.	Mosaic of natural marshes and managed ponds supporting fisheries, lotus and water chestnut, high plant and invertebrate diversity, local flood buffering.	Last stronghold of the sarus crane in Punjab and a major wintering site for migratory waterbirds; model of community-based wetland governance.	5, 9, 11, 28

HARIKE WETLAND: CASE-STUDY

Harike Wetland (Harike Pattan) is a barrage-created reservoir and wetland complex at the confluence of the Sutlej and Beas rivers in Punjab and is the largest wetland in northern India. It functions simultaneously as a key irrigation and drinking-water source and as a Ramsar-designated habitat for diverse assemblages of migratory and resident waterbirds, fishes, herpetofauna and aquatic invertebrates. The wetland exhibits clear *pelagic*, *littoral*, and *emergent-macrophyte* zones analogous to coastal lagoons and marshes in marine systems, with open-water areas supporting diving ducks and piscivorous birds, while shallow vegetated fringes provide foraging and nesting grounds for dabbling ducks, waders and rails [1–4].

Anthropogenic pressures on Harike include nutrient enrichment from agricultural runoff, industrial and municipal effluents transported by the Sutlej and Beas, proliferation of invasive macrophytes, such as water hyacinth, hydrological alterations, due to barrage operations, and encroachment and unsustainable fishing [21–24]. These pressures have been associated with declines in migratory waterbird numbers, episodic fish kills and deterioration of water-quality indices, paralleling eutrophication and habitat degradation observed in estuaries and coastal lagoons worldwide [1, 8–19] [22–23]. In the context of a "large aquatic ecosystem" framework for the Sutlej–Beas–Ravi–wetland complex, Harike serves as a critical but highly stressed hub in the network, linking upstream catchment dynamics to downstream flows and to flyway-scale patterns of migratory waterbird use [1–4]. Harike Wetland – major threats and ecological consequences depicted in Table 5.

Table 5. Harike wetland – major threats and ecological consequences.

Threat factor	Source / process	Immediate ecological impact	Longer-term consequence	Citation
Nutrient loading (N, P)	Agricultural runoff and untreated municipal sewage transported via Sutlej and Beas rivers.	Elevated nutrient concentrations, phytoplankton blooms, proliferation of water hyacinth and other macrophytes, reduced water clarity.	Eutrophication, risk of hypoxic conditions, decline of sensitive benthic fauna, shifts in fish and bird community composition.	13, 17, 18, 23
Industrial/chemical pollution	Effluents from upstream industrial clusters and towns entering through tributaries and drains.	Toxic effects on fish and invertebrates, contamination of sediments, potential bioaccumulation of heavy metals.	Chronic health risks for wildlife and human users; reduced suitability of water for drinking and irrigation; long-term degradation of wetland quality.	13, 14, 17
Hydrological alteration	Operation of Harike barrage and canal off-takes altering water-level regimes and flow timing.	Fluctuating water levels, drying or prolonged inundation of littoral and marsh zones, disturbance of nesting and foraging habitats.	Disrupted breeding success of waterbirds, altered macrophyte zonation, reduced habitat stability for fish and amphibians.	5, 13, 18, 23
Invasive macrophytes	Spread of water hyacinth and other invasive aquatic plants facilitated by nutrient enrichment and stagnant conditions.	Extensive surface coverage, shading, reduced dissolved oxygen, impeded boat movement and fishing operations.	Long-term habitat simplification, increased management costs, episodes of fish mortality and loss of open-water for diving birds.	13, 18, 23
Encroachment and land-use change	Expansion of agriculture, settlements and infrastructure on wetland fringes.	Loss of edge habitats, increased disturbance from human activity, reduced buffer zones for pollutant filtration.	Progressive shrinkage and fragmentation of wetland area, diminished flood-buffering and water-purification functions.	17, 29, 30

RESULTS & DISCUSSION

Comparative Wetland Dynamics

Reservoir wetlands, such as Harike and Ropar, exhibit higher vulnerability to pollution due to upstream inflows carrying industrial effluents, agricultural runoff, and sewage [13, 17]. In contrast, Keshopur–Miani demonstrates relatively greater ecological stability due to community-based management and lower industrial exposure [10, 11, 28–30].

This contrast highlights the importance of governance structures in mediating ecological outcomes.

Pollution and Ecological Impacts

Nutrient enrichment from fertilisers and sewage leads to eutrophication, promoting excessive macrophyte growth such as water hyacinth [13, 18]. This results in:

- Reduced dissolved oxygen.
- Decline in fish populations.
- Altered trophic dynamics.

Heavy metals, such as arsenic and uranium, further exacerbate ecological stress through bioaccumulation and toxicity [17, 18].

Hydrological Alteration

Flow regulation through dams and barrages alters natural flood pulses, reducing habitat heterogeneity and disrupting ecological processes [17]. This affects:

- Fish breeding cycles.
- Amphibian habitats.
- Sediment transport.

These impacts parallel estuarine disruptions observed in marine systems [2, 4].

Bioindicators

Bioindicator groups provide integrated measures of ecosystem health:

- Molluscs → sensitive to pollution [12].
- Fish → reflect hydrological changes.
- Waterbirds → indicate habitat quality and landscape-scale changes [23–27].

Governance Models

Top–down management approaches (e.g., Harike) face challenges due to large-scale external pressures [13]. In contrast, community-based approaches (Keshopur–Miani, Kali Bein restoration) demonstrate higher adaptability and stakeholder engagement [11, 15, 28].

This suggests that hybrid governance frameworks are essential.

CONCLUSION

Punjab's wetlands are under significant anthropogenic pressure but retain substantial ecological potential. The application of marine ecosystem frameworks provides a novel and integrative approach for understanding these systems.

The proposed Large Aquatic Ecosystem framework offers a structured model for integrating ecological monitoring, socio-economic considerations, and governance systems. Bioindicators and long-term monitoring are essential for effective management.

Community-based conservation models demonstrate strong potential for sustainable management and should be integrated into broader policy frameworks.

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