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Drivers of Wetland Faunal Decline: Climate Change and Anthropogenic Pressures with Special Reference to Kolleru Lake-Andhra Pradesh, India

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Abstract
This study analyzes the primary drivers of faunal decline in wetland ecosystems, with a focused case study on Kolleru Lake, Andhra Pradesh. Wetlands are ecologically critical systems that support high biodiversity, regulate hydrological cycles, and contribute significantly to global carbon sequestration (Dalu et al., 2021; Li et al., 2024). However, these ecosystems are undergoing rapid degradation due to the combined impacts of climate change and anthropogenic pressures. Climate-induced alterations such as temperature rise, hydrological variability, extreme weather events, and phenological shifts disrupt ecological balance, leading to habitat loss, reduced dissolved oxygen levels, and trophic mismatches (Schoeman et al., 2023). Simultaneously, human activities—including aquaculture expansion, pollution, habitat fragmentation, and invasive species introduction—exert immediate and localized pressures that accelerate biodiversity loss. The case of Kolleru Lake highlights how these stressors interact synergistically, intensifying ecosystem degradation and faunal decline. The study emphasizes that while climate change acts as a long-term modifier, anthropogenic factors are often the dominant drivers. Effective conservation requires integrated management approaches combining hydrological restoration, sustainable resource use, climate-resilient planning, and stronger policy enforcement.

Keywords: *Wetland degradation, Faunal decline, Climate change impacts, Anthropogenic stressors, Kolleru Lake, Biodiversity loss, Aquaculture expansion, Ecosystem management*

Introduction

Wetlands are indispensable ecosystems globally, providing a myriad of ecological services such as hydrological regulation, water purification, and nutrient cycling, alongside supporting immense biodiversity (Dalu et al., 2021, p. 151685). These vital habitats are crucial for a diverse array of fauna, including various species of mammals, fish, crustaceans, reptiles, amphibians, and avian species, many of which rely on wetlands for breeding, feeding, and shelter (Nyandwi & Ndikubwimana, 2024; Olive et al., 2023, p. 51). Beyond their intrinsic biodiversity value, wetlands also serve as critical stepping stones for migratory species, including millions of waterbirds that traverse continents annually, underscoring their international ecological significance (Breiner et al., 2021, p. 740). However, these highly productive yet fragile ecosystems are experiencing unprecedented rates of degradation and loss globally, with significant implications for faunal populations and the ecosystem services they provide (Garba et al., 2025).

Importance of Wetland Ecosystems and Services

Wetlands contribute substantially to global biodiversity, acting as critical habitats that support a disproportionately high number of species relative to their areal extent (Nyandwi & Ndikubwimana, 2024). Their ecological significance extends to regulating hydrological cycles and maintaining climate stability (Hashemi et al., 2026). Moreover, the intricate biogeochemical processes occurring within wetlands, such as carbon sequestration by autotrophic microorganisms, play a substantial role in global carbon cycling (Li et al., 2024, p. 8). Despite their profound ecological importance, these ecosystems are under increasing threat from a confluence of anthropogenic pressures and climate change impacts (Garba et al., 2025).

Machine learning techniques are widely used in gene prediction, disease diagnosis, and biomarker discovery. These methods enhance data analysis efficiency and accuracy (Nalina et al., 2025).

Deep Learning

Deep learning models, including neural networks, are applied in protein structure prediction and genomic analysis.

Large Language Models

Large language models have shown potential in analyzing biological sequences and improving predictive modeling (Wang et al., 2025).

Wetland Ecosystems and Faunal Diversity

Classifications of wetlands generally delineate them based on their hydrological characteristics, vegetation types, and dominant biogeochemical processes, encompassing a wide array of environments from marine and estuarine systems to lacustrine, palustrine, and riverine habitats. These diverse wetland types support distinct faunal assemblages, each with specialized adaptations to their specific hydrological regimes and trophic structures. For example, Ramsar-designated wetlands, recognized for their international importance, often host critical populations of migratory birds and endemic aquatic species (Nyirangirimana & Nyandwi, 2024). The ecological roles of various faunal groups, from microscopic plankton to large apex predators, are intricately interwoven within wetland food webs, contributing to nutrient cycling, energy transfer, and overall ecosystem stability. Plankton, as primary producers and consumers, form the base of many aquatic food webs, influencing nutrient dynamics and supporting higher trophic levels including various fish species. These fish, in turn, serve as crucial food sources for piscivorous birds, amphibians, and reptiles, creating complex interdependencies within the wetland ecosystem. However, the delicate balance of these trophic interactions can be significantly disrupted by environmental perturbations, leading to cascading effects throughout the entire faunal community. Changes in water quality, habitat structure, or species composition can therefore profoundly alter these trophic linkages, potentially leading to biodiversity loss and compromised ecosystem functions.

Classification and Characteristics of Wetlands

Wetlands are broadly categorized into five main types: marine, estuarine, lacustrine, riverine, and palustrine, each characterized by specific geomorphological features, hydrologic regimes, and dominant vegetation, which collectively define the ecological niches available to diverse faunal communities. These classifications are critical for understanding the distribution and adaptation of wetland fauna, as hydrological connectivity, water depth, and salinity gradients directly influence species richness and community structure. Estuaries, for instance, exhibit a unique longitudinal salinity gradient and significant tidal fluctuations, fostering a community of specialist species adapted to these dynamic conditions, despite often having lower species richness overall (Ridel et al., 2024, p. 112958). Conversely, freshwater wetlands, including marshes and peatlands, are defined by their emergent vegetation and play a crucial role in carbon sequestration and water purification (Garba et al., 2025; Hambäck et al., 2022, p. 160751). The physicochemical characteristics of these wetlands, such as temperature, dissolved oxygen levels, and nutrient availability, are pivotal in determining faunal community composition and structuring trophic interactions (Dalu et al., 2021, p. 151687).

Ecological Roles of Key Faunal Groups

The diverse faunal groups within wetlands, including plankton, fish, amphibians, reptiles, and birds, each play distinct and indispensable roles in maintaining ecosystem health and functionality. Plankton, forming the foundational trophic level, are instrumental in primary production and nutrient cycling, directly impacting the availability of resources for higher consumers such as fish and invertebrates. Fish, occupying various trophic levels, mediate energy transfer throughout the food web, influencing both bottom-up processes through their consumption of plankton and detritus, and top-down regulation of invertebrate populations (Li et al., 2023, p. 1).

Climate Change Impacts on Wetland Fauna: A Mechanistic Approach

The mechanistic approach to understanding climate change impacts necessitates a detailed examination of how altered climatic variables, such as precipitation patterns and rising temperatures, directly modify the physiological processes and ecological interactions of wetland fauna.

Hydrological Alterations: Rainfall Variability, Droughts, and Floods

Such alterations can lead to a significant reduction in wetland area and disrupt seasonal hydrological regimes, profoundly impacting species that depend on consistent water levels for survival (Xu et al., 2024, p. 1). Prolonged droughts, for instance, can lead to hypersalinity and desiccation, while increased flooding can scour habitats and displace fauna, thereby altering community structure and ecosystem function (Mellin et al., 2022, p. 1811).

Temperature Rise and Dissolved Oxygen Dynamics

Elevated water temperatures directly reduce the saturation capacity of dissolved oxygen, leading to hypoxic or anoxic conditions that severely stress aquatic organisms and can induce widespread mortality events, particularly for species with narrow physiological tolerances. Furthermore, increased metabolic rates in ectothermic wetland fauna due to higher temperatures exacerbate oxygen demand, intensifying the physiological burden in already oxygen-depleted environments (Larsen et al., 2023, p. 11).

Phenological Shifts and Migration Disruptions

Changes in temperature and precipitation regimes can disrupt the precise timing of critical life-history events, such as breeding, hatching, and migration, leading to trophic mismatches between interdependent species and potentially reducing reproductive success. This asynchronous shifting in phenology can particularly impact migratory bird species that rely on synchronized resource availability along their routes and at breeding grounds (Schoeman et al., 2023, p. 5).

Impacts of Extreme Weather Events

Increased frequency and intensity of extreme weather events, such as severe storms, heatwaves, and prolonged cold snaps, directly inflict acute mortality and significant habitat destruction, thereby fundamentally reshaping wetland community composition and altering successional pathways (Wild et al., 2024, p. 175055). These events can also trigger cascading effects, such as large-scale vegetation dieback and increased salinity intrusion, which further degrade critical habitats and exacerbate stress on faunal populations (Elsey-Quirk et al., 2024, p. 8).

Anthropogenic Stressors on Wetland Fauna

Beyond the direct ramifications of climate change, anthropogenic pressures represent a critical and often synergistic threat to wetland fauna, frequently exerting more immediate and localized impacts that can confound the effects of climatic shifts (Schoeman et al., 2023, p. 9). These human-induced disturbances, including habitat conversion, pollution, and overexploitation, often interact complexly with climate change, accelerating biodiversity loss and undermining ecosystem resilience.

Aquaculture Expansion and Intensification

The proliferation of aquaculture operations, particularly in tropical and subtropical regions, frequently entails the conversion of natural wetlands into fish or shrimp ponds, resulting in irreversible habitat loss and fragmentation for native wetland fauna. This conversion often involves extensive hydrological modifications, altering natural water flow and chemistry, and the introduction of non-native species, which can outcompete or prey upon indigenous populations. Furthermore, effluent from aquaculture facilities, laden with uneaten feed, faeces, and chemical treatments, introduces significant nutrient loading and pollutants into adjacent natural wetland systems, leading to eutrophication and subsequent degradation of water quality (Hambäck et al., 2022, p. 160753).

Pollution: Agricultural Runoff and Industrial Discharge

Diffuse pollution from agricultural runoff, rich in pesticides, herbicides, and fertilizers, along with point source industrial discharges containing heavy metals and persistent organic pollutants, critically impairs water quality, bioaccumulates in the food web, and directly poisons wetland fauna, often leading to reduced reproductive success and increased mortality rates. These pollutants can also indirectly degrade habitats by altering sediment composition and fostering the growth of harmful algal blooms, further exacerbating stress on sensitive aquatic species (Hambäck et al., 2022, p. 160753)

Habitat Fragmentation and Encroachment

These processes physically divide contiguous wetland ecosystems into smaller, isolated patches, restricting species dispersal, gene flow, and access to essential resources, thereby diminishing population viability and increasing extinction risk for many specialized wetland inhabitants. This fragmentation exacerbates the vulnerability of faunal communities to stochastic environmental events and limits their adaptive capacity to climate change (Fluet-Chouinard et al., 2023; Keck et al., 2025).

Impact of Invasive Species

Invasive alien species, defined as non-native taxa that establish self-sustaining populations and spread widely, pose significant threats to wetland ecosystems through direct trophic interactions, competition, and alterations to community structure (Tasker et al., 2023, p. 169669). For instance, invasive macrophytes like water hyacinth can form dense monocultures that outcompete native vegetation, reduce light penetration, and deplete dissolved oxygen, thereby degrading critical habitat for fish, amphibians, and aquatic invertebrates (Zambrano-Fernández et al., 2021, p. 132351).

Kolleru Lake: A Critical Case Study

Highlighting the importance of understanding localized impacts, Kolleru Lake, a Ramsar site of international importance, offers a compelling example of a wetland ecosystem facing intense pressures from both global climate shifts and pervasive local anthropogenic activities. This case study will critically examine how these stressors interact to impact faunal diversity and ecosystem integrity within the lake, thereby contributing to broader conservation discourse and informing targeted management strategies. This comprehensive analysis will synthesize existing literature to identify critical research gaps and propose future directions for wetland conservation and management in similar ecologically sensitive regions.

Geographic and Ecological Significance

Kolleru Lake, a designated Ramsar site, is a shallow freshwater lake nestled between the Krishna and Godavari deltaic plains, serving as a critical habitat for numerous resident and migratory avian species and supporting diverse aquatic biodiversity. Its strategic location within the Central Asian Flyway underscores its global ecological importance as a stopover and breeding ground for waterfowl and waders (Harfoot et al., 2021, p. 1512).

Ramsar Status and Biodiversity Importance

The lake's Ramsar designation underscores its international significance as a wetland of critical importance, recognizing its role in maintaining regional biodiversity, especially its support for vulnerable and endangered species of flora and fauna. However, despite this recognition, Kolleru Lake faces considerable ecological degradation stemming from an intricate interplay of anthropogenic activities and climatic shifts (Gaini & Syeda, 2024, p. 32).

Quantitative Data on Habitat Loss and Faunal Decline

The spatial extent of habitat loss, particularly the conversion of natural marshes and open water into aquaculture ponds, can be quantified through remote sensing and GIS analysis, revealing a direct correlation with observed declines in waterbird populations and native fish species. This quantitative assessment provides empirical evidence of the severe ecological impact of human activities, necessitating urgent conservation interventions to mitigate further faunal decline and habitat degradation within this vital wetland ecosystem. Such data-driven insights are crucial for developing effective management strategies and informing policy decisions aimed at restoring Kolleru Lake's ecological integrity and sustaining its unique biodiversity (Shivakrishna et al., 2021, p. 110).

Impact of Aquaculture and Policy Interventions

The historical proliferation of aquaculture, notably shrimp farming, within the Kolleru Lake basin has significantly altered the lake's hydrogeomorphology and ecological processes, leading to widespread habitat loss and water quality degradation (Poikāne et al., 2023, p. 111340). Despite various policy interventions aimed at regulating aquaculture and promoting restoration, the legacy of intensive farming practices continues to pose substantial challenges to the lake's ecological recovery and the conservation of its faunal communities, underscoring the complexities of balancing socioeconomic development with environmental protection in Ramsar sites (Rahaman et al., 2023;)

Interaction Between Climate Change and Anthropogenic Activities

This section will critically analyze how these two major drivers interact synergistically, often amplifying their individual detrimental effects on wetland faunal communities in Kolleru Lake and other similar ecosystems (Han et al., 2024, p. 1). This synergistic interaction can manifest as increased vulnerability of species to climate-induced stressors due to habitat degradation from anthropogenic activities, thereby accelerating biodiversity loss and ecosystem collapse (Li et al., 2024).

Synergistic Effects and Feedback Mechanisms

For instance, habitat fragmentation by human land use amplifies the negative impacts of climate-induced hydrological shifts on aquatic biodiversity, as isolated populations are less resilient to environmental perturbations (Xie et al., 2024). Conversely, climate change can exacerbate human-wildlife conflicts by altering resource availability and species distributions, further stressing already vulnerable populations (Abrahms et al., 2023).

Limitations of Climate Change as a Sole Driver of Biodiversity Loss

While climate change undoubtedly exerts profound ecological pressures, it is crucial to recognize that anthropogenic factors frequently constitute more immediate and substantial drivers of biodiversity loss, particularly in heavily impacted wetland systems such as Kolleru Lake (Luedtke et al., 2023). For example, land-use change, often driven by agricultural expansion, is currently a greater driver of biodiversity change than climate change, although climate impacts are projected to intensify (Boakes et al., 2024).

Conservation Strategies and Management Approaches

Addressing these complex, interwoven threats necessitates a comprehensive and adaptive management framework that integrates ecological restoration with socio-economic considerations and robust policy enforcement. Such frameworks must incorporate adaptive environmental management recognizing conservation and restoration objectives as dynamic targets capable of modification to align with global change and optimize biodiversity protection (Haase et al., 2023, p. 586).

Restoration of Hydrological Regimes

Restoring the natural hydrological connectivity and flow regimes is paramount for rejuvenating Kolleru Lake's ecological functions, as altered water levels and flow patterns directly impact wetland fauna through habitat desiccation, salinity intrusion, and disrupted breeding cycles. This requires integrated watershed management strategies that account for upstream land use and water abstraction practices to ensure adequate water availability and quality for the wetland ecosystem.

Regulation and Sustainable Aquaculture Practices

Implementing stringent regulations and promoting sustainable aquaculture practices, including polyculture and eco-certification, are critical to mitigating the adverse environmental impacts of shrimp farming and fostering a more harmonious coexistence between aquaculture and wetland conservation.

Climate-Resilient Wetland Management

Developing and implementing climate-resilient management strategies is essential for buffering wetland ecosystems against the impacts of changing climatic conditions, including altered precipitation patterns and increased temperatures (Tigchelaar et al., 2021, p. 678). These strategies should encompass investments in conservation planning and adaptive management to create climate-resilient wetland networks, which not only benefit waterbird conservation but also support other dependent species and human communities (Breiner et al., 2021, p. 748).

Lack of Long-Term Ecological Monitoring Data

A significant impediment to robust ecological understanding and effective adaptive management within Kolleru Lake is the paucity of continuous, high-resolution datasets concerning key environmental parameters and faunal population dynamics. This data deficit hinders the accurate assessment of trends, the prediction of future impacts, and the evaluation of conservation intervention effectiveness. Therefore, establishing comprehensive, long-term monitoring programs is imperative for tracking ecosystem health, discerning subtle ecological shifts, and informing evidence-based conservation strategies (Kuang et al., 2024).

Need for Integrated Climate-Biodiversity Models

Developing integrated models that couple climate projections with biodiversity responses at fine spatial and temporal scales is crucial for understanding complex interactions and predicting future vulnerabilities of wetland fauna under various anthropogenic and climatic scenarios. These models should incorporate parameters beyond generic templates, considering specific hydro-morphological and ecological requirements of diverse wetland taxa (Nisi et al., 2024).

Policy Implementation Gaps and Challenges

Despite the existence of various environmental protection laws and international agreements, significant challenges persist in the effective implementation and enforcement of policies designed to safeguard wetland ecosystems such as Kolleru Lake. These gaps often stem from institutional weaknesses, insufficient resources, and conflicting developmental priorities, necessitating a critical analysis of policy-science interfaces to identify actionable improvements.

Conclusion

This review has systematically analyzed the multifaceted drivers of faunal decline in wetland ecosystems, specifically focusing on Kolleru Lake, highlighting the intricate interplay between climate change and diverse anthropogenic pressures. The synthesis underscores that while climate change acts as a pervasive modifier, direct anthropogenic impacts often represent more immediate and localized threats requiring urgent mitigation. Therefore, effective conservation strategies necessitate a holistic approach that simultaneously addresses both global climate change mitigation and localized reduction of human-induced stressors to ensure the long-term ecological integrity and biodiversity persistence of such vital wetland habitats. A sustained commitment to interdisciplinary research, robust monitoring frameworks, and adaptive management, underpinned by strong policy implementation and community engagement, will be crucial for reversing current decline trends and fostering resilience in these critical ecosystems (D'Agata & Maina, 2022, p. 1235; Guo et al., 2023, p. 11; Haase et al., 2023, p. 586; Pörtner et al., 2023). Furthermore, future policy frameworks must integrate climate-informed coastal development strategies with conservation and planning initiatives to avert irreversible degradation of sensitive aquatic systems (Schoeman et al., 2023, p. 10). This integrated approach is paramount for safeguarding not only the unique biodiversity of Kolleru Lake but also the myriad ecosystem serv ices it provides to surrounding human populations.

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Conflicts of interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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