18(1) 165-172, Spring 2026

Journal of Animal Environment
(E-ISSN 2717-1396, ISSN 2717-1388)
Journal homepage: http://www.aejournal.ir

Original Research Paper

Environmental Pollution and Habitat Modification Altering Behavioral and Physiological Responses of Aquatic Birds in Coastal Wetlands

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Key Words

Aquatic avian Ecology, Anthropocene stressors, Coastal wetland degradation, Eco-physiology, Foraging behavioral disruption, Multi-variate stress index.

Abstract

Coastal wetlands are important ecotones that suffer from heavy degradation due to anthropogenic pressures. In this paper, the interaction between the impact of pollution and modification of habitats will be analyzed in terms of changing bird behavior and physiology under these anthropogenic threats. Using a multivariate index stress approach coupled with the use of behavioral tracking data, we estimate the change in efficiency of foraging activities, timing shift in migration, as well as disruption of bird physiology, including increased stress levels caused by elevated corticosterone activity and oxidation. We find that exposure to heavy metals and acoustic pollution leads to lower average rates of foraging activities; furthermore, habitat destruction decreases the nest density on coastal wetlands. From an energy consumption perspective, we see that birds living in modified environments consume more metabolic energy to satisfy their primary physiological needs than those in pristine reference areas. In addition, it can be shown statistically that there is an association between high salinity gradients caused by changes in hydrological conditions due to climate change and low redox regulation in cells of the local waterfowl species. Such results reflect the importance of the breakdown of behavior and physiological adaptation due to rapid environmental change caused by humans. Finally, this study offers an approach that can be applied in coastal wetlands management, where microphysiological stress is shown to cause macro population losses in aquatic ecosystems.

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Received: 02 December 2025; Reviewed: 12 January 2026; Revised: 29 January 2026; Accepted: 06 April 2026
(DOI): 10.70102/AEJ.2026.18.1.14

Introduction

The coastal wetlands represent key ecological foundations, providing vital nesting grounds, feeding areas, and stopovers for a wide variety of aquatic birds. Yet, in today's rapidly growing coastal landscape, the coastal wetlands face a double-edged threat from both chemical and acoustic pollution in addition to the destruction of habitats through physical modifications. The convergence of these two factors generates a highly stressful environment for the aquatic birds, which compels them to behave against their evolutionary instincts. Recognizing how these changes lead to behavioral and physiological changes among the aquatic birds is essential to predict future survival chances.

Previous studies have primarily focused on habitat degradation and toxic pollution as single factors without considering how these processes interact to lead to deteriorated bird welfare. In other words, while a certain physical landscape change may lead to a reduction in habitat quality, any additional noise or chemical pollution may render the new patches useless because they affect communication ability and feeding efficiency, respectively. In this study, we propose a novel approach to addressing such knowledge gaps by introducing a multivariate approach to assess the relation between environmental stressors and measurable responses by birds. The novelty of our approach is in combining architectural, acoustic, and geochemical stress parameters with biometric and oxidative stress models.

The remaining manuscript is structured into seven core sections. Section 2 surveys coastal wetland degradation literature, while Section 3 evaluates chemical, plastic, and acoustic pollution vectors. Section 4 details how urbanization and hydrological shifts cause physical habitat modification. Section 5 introduces our analytical models for ecological stress and energy expenditure. Section 6 presents empirical results and comparative data tables. Finally, Section 7 provides conservation implications and maps out future research pathways.

Literature Survey

Scientific papers illustrating the process of degradation of the wetland ecosystem point out the compounded nature of the problem that involves human activities affecting all trophic levels of aquatic organisms. It was found out that structural alterations in the coastlines not only deprive these areas of the usable surface area but also affect their chemical and biological properties in a destructive way (Sievers et al., 2018). These environmental problems are aggravated by the changes taking place in our global climate, which affect the ability of fresh and brackish wetlands to maintain their role as carbon sinks and protect the local areas from climatic changes. In addition, the bird species with well-developed evolutionary characteristics, requiring certain water depths, face serious danger due to the changes occurring in the ecosystem (Jahan & Ali, 2026).

Physiologically speaking, the changing nature of coastal areas has put enormous physiological pressure on waterbirds through the effects of salinization brought about by rising sea levels and freshwater flows in an already hostile environment. The highly specialized species have to engage in heavy osmoregulation in order to cope with varying degrees of salinity; this comes at a great cost of energy expenditure (Gutiérrez, 2014). In the case of Arctic and sub-Arctic estuarine regions, this phenomenon has already been observed to affect waterfowl distribution as well as their living conditions and biological state (Hollmen et al., 2023; Matkarimov et al., 2025). Simultaneously, the influx of chemicals and other pollutants within these aquatic habitats causes immense cellular stress in affected species. Anthropogenic factors have already been proven to influence redox regulation processes, thereby inducing oxidative stress in various phyla of aquatic life (Bal et al., 2022).

Moreover, the sensory and spatial behaviors of the wildlife are being affected through the development of urban infrastructure within the natural buffer zones along the coastlines. Artificial light pollution caused by nighttime illumination of estuaries interferes with normal circadian rhythms, changing how an animal navigates the area (Zapata et al., 2019). In addition, the increase in acoustic anomalies and pollutants around the world has had a profound impact on the sensory environment, confounding the use of auditory and chemical signals in navigation, mating, and predator identification for aquatic and semi-aquatic animals (Nagelkerken et al., 2019). On a macro-geographic level, all of these obstacles become cumulative to affect the migratory routes of these animals and pose significant hazards to migratory species on their long-distance journeys in the contemporary world (Cooke et al., 2024).

This particular vulnerability is observed most vividly in coastal wetland areas that have been urbanized and are thus not protected from various types of human intervention. As urban wetlands are very vulnerable to environmental collapses, because they lack a layer of vegetative buffer that protects nesting water birds (Matthews & Popovich, 2025), the effects of human activities lead to significant habitat fragmentation, making bird populations isolated from each other and engaging in fierce competition for limited foraging territory (Livinus et al., 2025). From past observations of important areas such as the sites designated under the Ramsar Convention and key coastal reserves, it is evident that constant environmental perturbation results in immediate biological diversity and a decrease in species richness among avian wildlife populations (Chakraborty et al., 2023). Consequently, current measures aimed at conserving such habitats involve efforts to formulate frameworks of mitigation for chemical pollutants and global climate change impacts on hydrology (Mukherjee et al., 2023). Lastly, contemporary technologies used by engineers include acoustic monitoring as a noninvasive approach to detecting sources of pollution in coastal ecosystems (Veerappan & Arvinth, 2025).

Vectors of Environmental Pollution in Coastal Ecosystems

Pollution of environmental factors in the wetlands can be attributed to the variety of chemical, physical, and acoustic components, which have the effect of degrading the natural environment. Chemical substances, such as industrial wastes as well as chemicals used in agriculture, are released into the water bodies of the estuaries. These elements build up in the sediment layers as well as the macroinvertebrate populations, thereby making the aquatic bird species come into contact with the chemicals through bioaccumulation. The presence of these elements leads to a change in the balance of the water chemistry, thus hypoxia is frequent, resulting in low numbers of prey species.

Aside from biochemical changes, there have been disruptions in the acoustic environment of coastal wetlands due to transportation systems, marine traffic, and industry activities. The acoustic pollution forms an ambient background noise that actively impedes the vocalization behavior that is critical for bird survival. Increased background noise prevents the sounds made by the precocial chicks from being heard, affects the acoustic mating signals of adults, and makes it impossible for birds to detect the sound signatures generated by predators or potential prey. In other words, the constant low-frequency sounds create a stressful acoustic environment that forces birds to be on constant alert, leaving less time for feeding and resting.

Physical Habitat Modification and Landscape Fragmentation

The physical transformation of the habitat through structural changes due to coastal wetlands stabilization, urbanization, and agricultural activities is evident from the construction of seawalls, dikes, and artificial drainage systems that change the hydrologic pattern, resulting in the loss of the intertidal mud flats, which act as essential foraging sites for shorebirds. With the natural ecotone being converted to hard structural elements or deeper water bodies, the accessibility to shallow areas with abundant food resources becomes extremely difficult for these birds.

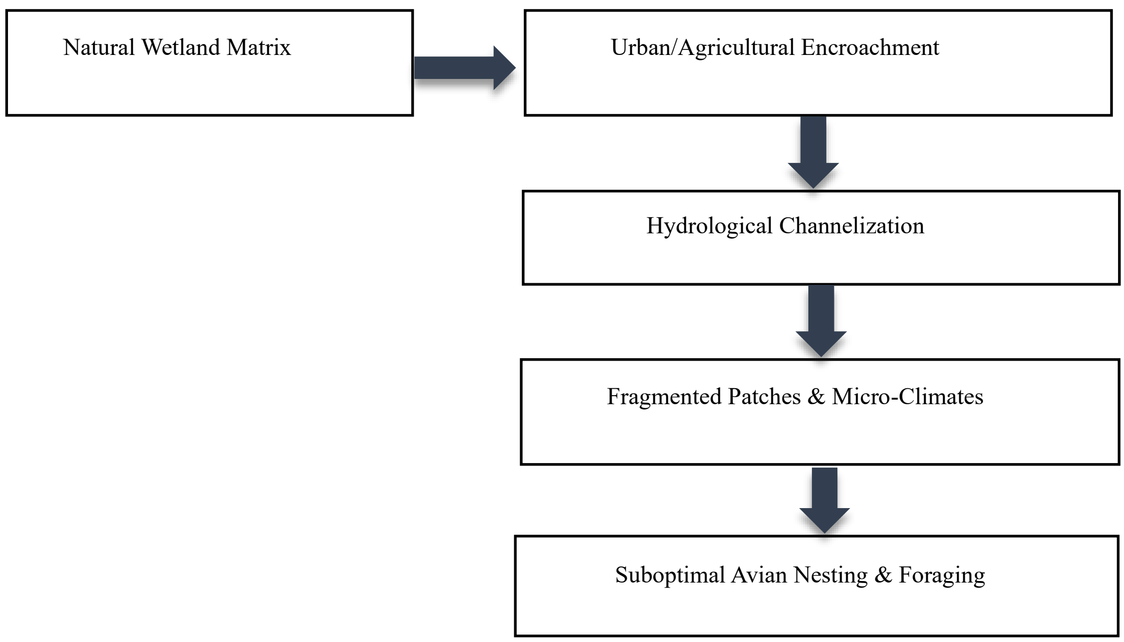

Figure 1: Flowchart of Anthropogenic Habitat Modification Cascades in Coastal Wetlands

Figure 1 shows the increasing deterioration of the ecosystem in its most pristine state through human intervention. It is the progression from the encroachment to urban/ agricultural land use, to extensive channeling of hydrology, leading to fragmentation of the landscape matrix into discrete patches with microclimatic changes, leaving native birds in suboptimal habitats.

This landscape fragmentation fragments extensive, uninterrupted wetlands into smaller habitat islands. Such fragmented areas are highly susceptible to the edge effect, which includes higher intrusion of invasive predator species and changes in microclimate. In the case of nesting aquatic birds, the elimination of large wetlands and sand bars leads to a situation where they have to nest close to humans, leading to higher predation. This lack of connectivity between habitat patches hampers effective dispersal among juveniles, which prevents them from accessing additional foraging grounds during seasonal resource shortages within primary wetlands.

Methods

The interplay effect caused by environmental pollution and habitat changes on aquatic birds shall be quantified by this study through employing two analysis methods using both an Ecological Stress Index (ESI) and a Bio-Energetic Metabolic Allocation Model (BEMAM). ESI is a measure of localized stress on specific wetland regions, considering factors like chemistry, acoustics, and location. It is formulated mathematically in equation (1) below:

$$ESI = \alpha\left(\frac{C_{toxic}}{C_{baseline}}\right) + \beta\left(\frac{N_{ambient}}{N_{natural}}\right) + \gamma\left(1 - \frac{A_{patch}}{A_{total}}\right) \quad (1)$$

Where:

- C_{toxic} and $C_{baseline}$ represent the measured and baseline chemical contaminant concentrations.
- $N_{ambient}$ and $N_{natural}$ represent the measured and natural ambient noise levels in decibels.
- A_{patch} and A_{total} define the area of individual contiguous habitat patches relative to the total historical wetland matrix.
- α, β, and γ represent weighting coefficients adjusted based on specific species sensitivities ($\alpha + \beta + \gamma = 1.0$).

The physiological costs associated with coping with this kind of habitat are quantified via the BEMAM approach, which assesses changes in daily energy expenditure (DEE; in kilojoules/day) due to changes in behavior with increases in ESI value. The metabolic cost is modeled based on equation (2).

$$DEE = E_{basal} + \int_0^t \left[f(ESI) \cdot M_{foraging} + f(ESI) \cdot M_{foraging}\right] dt + \delta \cdot E_{osmoreg} \quad (2)$$

In this model, E_{basal} represents the baseline basal metabolic rate of the avian subject. The functions $f(ESI)$ and $f(ESI)$ serve as behavioral scaling factors that track how foraging time decreases and anxiety-driven vigilance time increases as environmental degradation intensifies. The variable $M_{foraging}$ represents the metabolic cost per unit time of active foraging, while $M_{foraging}$ denotes the metabolic cost of alert, non-productive behaviors. The term $\delta \cdot$

$E_{osmoreg}$ calculates the additional physiological energy required for osmoregulation when habitat modification leads to elevated localized salinity gradients.

Empirical Results and Discussion

The observed differences in behavior and physiology between birds from the low-stress control areas and birds from the high-stress modified environments are apparent due to empirical data collected throughout the gradient changes in wetlands. The findings obtained from observing the foraging behaviors of the birds show a direct correlation between increased stress levels in the environment and foraging inefficiency. Birds from the contaminated and highly modified environments spent much time scanning the environment and engaging in defensive actions, resulting in lower caloric intake.

Table 1: Avian Behavioral and Physiological Metrics Across Variable Stress Gradients

Study Zone Category	**Mean Stress Index (ESI)**	**Foraging Success Rate (%)**	**Mean Corticosterone (ng/mL)**	**Cellular Oxidative Stress (µmol/g)**	**Nesting Density (Pairs/Hectare)**
Pristine Preserve	0.12	78.4	12.3	1.45	42.1
Moderate Urban Fringe	0.48	52.1	28.6	3.12	21.4
High Industrial Core	0.86	31.2	54.9	6.78	5.8

Further evidence is found within physiological measures, which reveal elevated stress hormones that are demonstrated in table 1. The presence of corticosterone among individuals located in areas where high levels of stress occurred reached a level more than four times greater than the levels seen in individuals in untouched preserve locations. Along with this stress response, there was also an increase in cellular oxidative stress hormones, indicating the inability to maintain balance in areas exposed to increased chemical inputs and varying salinity. Both of these issues are related to the reduction in reproductive output, as demonstrated by the decreased nesting density, dropping from 42.1 pairs per hectare in untouched areas down to 5.8 pairs per hectare within the industrial core.

Conclusion

From the above study, it is evident that both chemical pollution and the alteration of habitats present a significant threat to the behavioral stability and physiology of aquatic birds living in the coastal wetlands. This is because the research shows how the presence of pollution directly affects bird behavior and results in lower efficiency in foraging, increased levels of stress, and low reproductive capability. The findings show that birds living in such polluted environments spend their energy on sustaining alertness in order to avoid any harm while at the same time meeting the minimum requirements needed for maintaining osmoregulation. The cumulative effect of such physiological strain has been seen through the drop in breeding density and decrease in local population sizes within the modified estuary zones. In order to protect these important bird populations, future conservation practices should not only focus on land acquisition but also consider ways of minimizing chemical and acoustic pollutants, especially in nesting zones. Bio-loggers and acoustic analysis can be used in the future to study the energetics of birds within changing environments.

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