Effects of Climate Change on the Aquatic Ecosystem of the Sundarbans

Dr. Sanjib Saha

Climate change is increasingly altering the aquatic ecosystem of the Sundarbans, the world's largest contiguous mangrove delta, through sea-level rise, salinity intrusion, rising water temperatures, declining freshwater availability, ocean acidification, and more frequent cyclones and storm surges. These stressors modify hydrological regimes and water quality, leading to habitat loss, altered species distribution, reduced biodiversity, and disruption of fish breeding, recruitment, and migration patterns. Increased salinity particularly threatens freshwater-dependent and stenohaline aquatic species, while favoring euryhaline fishes, crustaceans, and brackish-water aquaculture species such as shrimp and mud crab. Cyclonic flooding and erosion further fragment aquatic habitats and damage fisheries-dependent livelihoods. Because the Sundarbans supports exceptional biodiversity and provides critical nursery grounds for commercially important fish stocks, climate-induced aquatic changes carry major ecological and socioeconomic consequences. This study emphasizes the need for integrated monitoring of salinity, temperature, pH, and species composition, alongside habitat restoration, sustainable fisheries management, and community-based adaptation strategies to preserve the resilience of the Sundarbans aquatic ecosystem.

Keywords: *Sundarbans, Climate change, Aquatic ecosystem, Salinity intrusion, Sea-level rise, Fisheries, Mangrove biodiversity*

Dr. Sanjib Saha[1,2]
[1]Aquatic Animal and Public Health Research Laboratory, Department of Zoology,Vidyasagar College for Women 39, Sankar Ghosh Lane, Kolkata – 700009, West Bengal, India.
[2]Department of Life Science and Biotechnology, Adamas University District-24 Parganas (North), Kolkata-700126, West Bengal, India.

[*]Email: wbdstbt25@gmail.com

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Introduction

The Sundarbans is a low-lying deltaic landscape of islands, tidal creeks, mudflats, channels, estuaries, and mangrove forests. It supports exceptionally rich aquatic biodiversity, including numerous fish, shrimp, crab, mollusk, and turtle species, and provides nursery habitat for many commercially important marine and brackish-water organisms (Saha and Munian, 2025; Saha et al., 2023). The ecosystem's health depends on

the regular exchange of freshwater and seawater. Freshwater inflow maintains lower salinity in upstream and inland areas, while tidal exchange delivers marine nutrients and sediments. Climate change alters both sides of this balance: sea-level rise pushes saline water inland, while reduced upstream freshwater flow weakens the dilution capacity of rivers and channels (Saha et al., 2024, Danda et al., 2024).

Major Climate Stressors

Sea-Level Rise

Sea-level rise is one of the most serious threats to the Sundarbans because much of the delta lies at or barely above sea level. Rising seas increase tidal inundation, push saltwater farther upstream, erode shorelines, and can permanently submerge low-lying islands and mudflats. Reported and projected rates of sea-level rise vary by location and time period, but the direction of change is clear: higher water levels increase the frequency and duration of flooding, especially during high tides and storm surges. This reduces the area of land available for mangrove establishment and alters the salinity of creeks, ponds, and estuarine habitats (Saha et al., 2024; Danda et al., 2024).

Salinity Intrusion

Salinity intrusion occurs when saline seawater moves into rivers, creeks, soils, and groundwater. In the Sundarbans, it is driven by sea-level rise, reduced freshwater discharge, tidal dynamics, and changes in rainfall and river flows. Salinity is not increasing uniformly across the entire Sundarbans. Some studies find that the central region has experienced a gradual increase in aquatic salinity, while parts of the western and eastern Indian Sundarbans have shown lower salinity, reflecting local differences in freshwater supply, tidal influence, and geomorphology. Nevertheless, salinization remains a dominant ecological stressor, particularly where upstream freshwater flows have declined (Saha et al., 2024; Danda et al., 2024).

Reduced Freshwater Inflow

The Sundarbans depends on freshwater from the Ganges–Brahmaputra–Meghna River system and its distributaries. Climate change affects this inflow through changing monsoon patterns, glacier and snowmelt variability in the Himalayas, droughts, and upstream water abstraction. When freshwater inflow declines, the estuarine gradient shifts seaward: saline conditions extend inland, freshwater habitats shrink, and species adapted to low salinity lose suitable habitat. This affects fish migration, breeding, feeding, and the distribution of aquatic plants and invertebrates (Saha et al., 2021; Danda et al., 2024).

Ocean and Water Warming

Rising air and water temperatures influence metabolic rates, oxygen solubility, reproduction, growth, disease susceptibility, and species distributions in aquatic organisms. Warmer water holds less dissolved oxygen, which can stress fish, shrimp, and benthic animals, particularly during calm, hot periods or in poorly flushed water bodies. Temperature changes can also alter the timing of breeding, larval development, and migration. For species with narrow thermal or salinity tolerances, even modest environmental shifts can reduce survival and reproductive success (Saha et al., 2024; Danda et al., 2024).

Cyclones, Storm Surges, and Flooding

The Bay of Bengal is highly prone to tropical cyclones. Climate change is expected to intensify storm surges, flooding, and coastal erosion, increasing physical damage to mangroves, aquatic habitats, ponds, and aquaculture facilities. Cyclones can deposit saline water and sediment across islands, destroy embankments, uproot mangroves, alter creek morphology, and cause sudden salinity pulses. Although natural disturbances are part of deltaic ecosystems, more frequent and severe events can exceed the recovery capacity of both mangroves and aquatic communities (Saha et al., 2021; Danda et al., 2024).

Effects on Mangroves and Habitat Structure

Mangroves form the physical foundation of the Sundarbans aquatic ecosystem. Their roots trap sediment, stabilize shorelines, reduce wave energy, provide shelter for juvenile fish and invertebrates, and supply organic matter to tidal creeks. Increased salinity causes osmotic stress in mangrove plants, reducing their ability to absorb water and nutrients. This can lower growth and photosynthesis and, under severe conditions, cause mortality, especially in less salt-tolerant species. As salinity rises, salt-tolerant species may replace less tolerant ones. This shifts mangrove species composition and can reduce biodiversity. In particular, salinity-driven mangrove migration threatens high-value freshwater-loving species such as *Heritiera fomes*, with consequences for forest structure, habitat quality, and ecosystem services (Saha et al., 2023 and 24).

The loss or degradation of mangrove habitat has cascading effects on the aquatic ecosystem:

- ✓ Less shelter for juvenile fish and crustaceans.
- ✓ Reduced organic matter input to estuarine food webs.
- ✓ Greater shoreline erosion and sediment instability.
- ✓ Lower nursery capacity for commercially important species.
- ✓ Reduced protection from cyclones and storm surges.

Effects on Fish and Fisheries

Shifts in Species Distribution

Aquatic species respond to salinity according to their tolerance. Euryhaline species, which tolerate a wide salinity range, may expand into newly saline areas. These include some mullets, sea bass, shrimp, and mud crabs. In contrast, stenohaline species, which require narrow salinity ranges, may decline or disappear from increasingly saline waters. Salinity intrusion can therefore reorganize fish communities: marine and brackish-water species may move upstream, while freshwater-dependent species are pushed into shrinking low-salinity refuges (Saha et al., 2021; Saha and Munian, 2025).

Impacts on Reproduction and Migration

Many fish species depend on particular salinity and flow conditions for spawning, larval development, feeding, and migration. Increasing salinity can disrupt reproductive cycles, reduce suitable spawning areas, and interfere with longitudinal migration between freshwater and marine environments. Reduced freshwater discharge can also alter the timing and strength of estuarine circulation. This may affect the transport of eggs and larvae, the availability of planktonic food, and the connectivity between nursery grounds and adult habitats (Saha et al., 2021).

Consequences for Fisheries Livelihoods

The Sundarbans supports fishing and aquaculture communities that depend on fish, shrimp, crabs, and other aquatic resources. Changes in species availability, catch composition, and habitat quality can reduce income and food security. Some euryhaline species and coastal aquaculture species, such as shrimp, sea bass, mullet, and mud crab, may benefit from more saline conditions. However, these potential gains are uneven and may not compensate for losses of freshwater and brackish-water species, damage from cyclones, and risks to aquaculture infrastructure (Das, S. 2025; Saha and Munian, 2025).

Effects on Invertebrates, Plankton, and Food Webs

Shrimp, Crabs, and Mollusks

The Sundarbans supports diverse crustaceans and mollusks, including shrimp, crabs, gastropods, and bivalves. These organisms are important both ecologically and economically. Salinity, temperature, sedimentation, and pollution influence their survival, growth, reproduction, and distribution. While some brackish-water species may tolerate or benefit from higher salinity, extreme salinity, habitat loss, and cyclone damage can reduce populations and disrupt nursery functions (Saha et al., 2022).

Plankton and Primary Production

Phytoplankton and zooplankton form the base of many aquatic food webs. Changes in salinity, turbidity, nutrient supply, temperature, and freshwater discharge can alter plankton abundance and composition. Increased turbidity from erosion and storm runoff can reduce light penetration, limiting photosynthesis. Conversely, nutrient enrichment from floodwaters or human activities may stimulate algal growth, sometimes leading to oxygen depletion when algae decompose. These shifts affect zooplankton, fish larvae, filter-feeding invertebrates, and higher predators.

Food-Web Restructuring

As species composition changes, energy pathways through the ecosystem change as well. A shift from freshwater-dependent species to euryhaline or marine species can alter predator–prey relationships, competition, and the availability of food for humans and wildlife. For example, declines in freshwater fish may affect piscivorous wildlife, including birds and aquatic mammals, while increases in salt-tolerant crustaceans may favor species able to exploit new prey resources. Such changes can reduce food-web stability and make the ecosystem more vulnerable to further disturbances.

Effects on Aquatic Mammals and Charismatic Species

The Sundarbans is home to aquatic and semi-aquatic wildlife, including the Ganges River dolphin, Irrawaddy dolphin, estuarine crocodile, and numerous waterbirds. These species depend on healthy fish populations, clean water, undisturbed channels, and suitable salinity conditions.

Salinity intrusion and declining freshwater availability threaten freshwater aquatic life, including fish and giant prawns, and can force freshwater-dependent organisms into the last remaining low-salinity habitats. Reduced prey availability, habitat degradation, increased vessel traffic, and cyclone-related disturbance can further threaten top predators and protected species.

Effects on Water Quality and Sediment Dynamics

Oxygen and Water Quality

Higher temperatures reduce dissolved oxygen, while organic pollution, decomposition, and stagnant conditions can worsen oxygen stress. Salinity changes can also affect the chemical behavior of nutrients and pollutants, altering their availability and toxicity.

Poor water quality affects fish health, shrimp survival, mollusk reproduction, and the suitability of water for domestic and agricultural use. In the Sundarbans, climate-driven salinization also reduces the availability of freshwater for drinking and irrigation.

Sediment Supply and Land Building

Deltas survive when sediment input keeps pace with sea-level rise and subsidence. Mangroves trap sediment and help land accrete, but reduced riverine sediment supply, altered flows, and increased erosion can weaken this process.

If sediment delivery is insufficient, islands may erode or subside relative to rising seas. This increases flooding, salinization, and mangrove loss, creating a feedback loop in which habitat degradation further reduces sediment trapping and shoreline protection.

Social and Economic Consequences

The aquatic ecosystem of the Sundarbans is closely linked to human well-being. Millions of people in the surrounding coastal region depend on fisheries, aquaculture, agriculture, forest products, and protection from storms.

Climate-driven changes affect communities through:

- ✓ Reduced availability of preferred fish species.
- ✓ Increased damage to fish ponds, shrimp farms, and crab-fattening operations.
- ✓ Loss of agricultural land and drinking-water quality due to salinization.
- ✓ Greater vulnerability to cyclones and storm surges.
- ✓ Increased pressure to migrate or adopt alternative livelihoods.

Research on projected salinization suggests that areas where poor households lose fish species are much more widespread than areas where they gain species, highlighting the equity dimensions of climate impacts.

Interactions Among Climate and Human Stressors

Climate change interacts with local human pressures, including embankments, shrimp aquaculture, pollution, overfishing, oil transport, tourism, and changes in upstream river management. These stressors can reduce the ecosystem's natural resilience (Danda et al., 2024). For example, embankments may protect settlements in the short term but can block sediment exchange and alter tidal flushing. Unsustainable shrimp aquaculture can convert mangrove or agricultural land, increase salinity in surrounding soils and water, and reduce habitat diversity. Overfishing can weaken fish populations already stressed by warming and salinity changes.

Adaptation and Conservation Strategies

Restore Freshwater Flows

Maintaining environmental flows from upstream rivers is essential for limiting salinity intrusion and preserving estuarine gradients. Coordinated basin-scale water management should consider the needs of the Sundarbans alongside agriculture, cities, and industry.

Protect and Restore Mangroves

Mangrove restoration should use appropriate native species and site-specific hydrological conditions. Restoration should prioritize areas where sediment supply, tidal exchange, and freshwater availability can support long-term survival.

Build Climate-Resilient Fisheries

Fisheries management should protect breeding grounds, regulate destructive fishing, maintain migration corridors, and support diversified livelihoods. Aquaculture planning should avoid conversion of natural mangrove habitat and incorporate salinity-tolerant, low-impact practices.

Strengthen Cyclone and Flood Protection

Nature-based protection–healthy mangrove belts, mudflats, and sediment management– should be combined with well-designed embankments, early-warning systems, and evacuation planning. This approach reduces disaster risk while preserving ecological functions.

Monitor Salinity, Biodiversity, and Livelihoods

Long-term monitoring of salinity, water temperature, dissolved oxygen, sedimentation, fish catches, mangrove cover, and community livelihoods is essential for adaptive management. Monitoring should include both ecological indicators and social indicators, such as income, nutrition, and displacement.

Conclusion

The Sundarbans, spanning coastal Bangladesh and India, is the world's largest contiguous mangrove forest and one of the most productive and biologically important estuarine ecosystems on Earth. Its aquatic environment is shaped by a dynamic mixture of freshwater from Himalayan rivers, saline water from the Bay of Bengal, tides, sediments, cyclones, and monsoonal rainfall. Climate change is disrupting this balance through sea-level rise, salinity intrusion, altered freshwater flows, warming waters, intensified cyclones, and changing sediment dynamics (Hoque et al. 2023). These changes affect mangroves, fish, shrimp, crabs, mollusks, plankton, dolphins, and the people whose food security and livelihoods depend on the Sundarbans (Mitra and Zaman, S. 2019). This chapter examines the major climate-related pressures on the aquatic ecosystem, their ecological consequences, and possible adaptation strategies (Rahman et al., 2025). Without strong mitigation and adaptation, sea-level rise, salinization, warming, and extreme events are likely to continue reshaping the Sundarbans aquatic ecosystem. The likely outcomes include mangrove compositional change, reduced freshwater habitat, altered fish communities, declining biodiversity, and increased risks to fisheries-dependent communities. The future of the Sundarbans depends on maintaining the delicate balance between riverine freshwater and marine influence. Protecting freshwater flows, restoring mangroves,

reducing local stressors, and supporting climate-resilient livelihoods can help preserve the ecological integrity of this globally significant delta.

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Conflict of Interest

The authors have no conflict of interest.

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