# Flood Vulnerability and Disaster Management in the Sundarbans Region

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**Abstract:** The Sundarbans, the world's largest contiguous mangrove ecosystem spanning India and Bangladesh, represents one of the most climate-vulnerable regions on Earth, facing intensifying flood hazards from tropical cyclones, storm surges, sea level rise and hydrological transformations. This research article provides a comprehensive analysis of flood vulnerability and disaster management frameworks in the Sundarbans region, synthesizing evidence from geospatial studies, community-based research and institutional assessments spanning the past two decades. The study reveals that the Indian Sundarbans Delta experiences significant physical flood susceptibility, with shoreline dynamics demonstrating gradual to severe changes due to fluctuating erosion and deposition patterns between 1990 and 2020. Multi-criteria decision-making analyses incorporating parameters including geomorphology, distance to water bodies, topographic wetness index and land use land cover identify Patharpratima's Surendranagar and Dhanchi as the most vulnerable areas, followed by moderately vulnerable Lothian. The frequency of cyclonic events has intensified markedly, with communities affected once every 17 months on average over the past 15 years, while 92% of households have experienced destruction of houses and crops, 88% have faced flood-related losses and 70% have lost homeland or farmland to riverbank erosion. Disaster management frameworks have evolved from reactive post-disaster responses toward more comprehensive approaches incorporating community-based disaster risk reduction, nature-based solutions including mangrove restoration achieving 95% survival rates in community-led initiatives and early warning system enhancements. However, significant gaps persist in institutional coordination, infrastructure adequacy and post-disaster trauma support. The study underscores the imperative for integrated, transboundary approaches combining scientific assessment, community knowledge and sustained investment to build resilience in this ecologically critical and culturally unique region.

**Keywords:** Flood vulnerability, disaster management, Sundarbans, cyclones, mangrove ecosystems, community-based adaptation, early warning systems, nature-based solutions.

## 1. Introduction

The interface between deltaic ecosystems and human habitation in the Anthropocene presents one of the most complex and urgent challenges confronting sustainable development. Nowhere is this challenge more vividly exemplified than in the Sundarbans, the world's largest contiguous mangrove forest, spanning approximately 10,000 square kilometers across the Ganges-Brahmaputra-Meghna delta system and shared between India (approximately 38 percent) and Bangladesh (approximately 62 percent). This

UNESCO World Heritage Site, recognized for its exceptional biodiversity including the iconic Bengal tiger and over 800 species of plants, fish, reptiles, birds and mammals, simultaneously serves as a natural fortress against rising seas and powerful storms while providing sustenance and identity to more than four million residents who inhabit its margins (Mitra, 2025). The intricate relationship between ecological integrity and human welfare in this region creates a vulnerability matrix of extraordinary complexity, where the degradation of natural buffers directly translates into heightened risk for coastal communities and where the imperatives of poverty alleviation must be reconciled with the conservation demands of a globally significant ecosystem.

The Sundarbans region occupies a distinctive bioclimatic and geographical setting along the Bay of Bengal coast, formed through the confluence of three great Himalayan rivers-the Ganges, the Brahmaputra and the Meghna. This deltaic landscape, characterized by low-lying topography, intricate networks of tidal creeks and dynamic estuarine islands, is inherently sensitive to hydrological variability and marine incursions. However, contemporary climate change is amplifying these inherent vulnerabilities to unprecedented levels, transforming the region into what many researchers characterize as a frontline of global climate impacts. Rising relative sea levels, documented at rates exceeding global averages, combine with increasing frequency and intensity of tropical cyclones to create conditions of chronic hazard that challenge both ecological resilience and human adaptive capacity (Acharyya et al., 2025). The statistical record reveals a trajectory of intensifying risk: over the last 40 years, the Bay of Bengal region has experienced 255 cyclonic storms ranging from low to severe categories, with cyclone intensity increasing over the last century. Between 2019 and 2020 alone, three cyclones impacted the Sundarbans, leading to hundreds of casualties and billions in economic damage. Cyclone Amphan in May 2020, reportedly the first category five cyclones to affect the region in two decades, caused 128 deaths and more than $13 billion in damage across India and Bangladesh (Mangrove Buffer Zone, 2025).

Flood vulnerability in the Sundarbans manifests through multiple, interacting pathways that complicate both assessment and response. Storm surges accompanying tropical cyclones inundate low-lying islands with saline water, destroying crops, contaminating freshwater sources and damaging infrastructure. Sea level rise progressively submerges land, with research indicating that approximately 210 square kilometers have been lost to encroaching seas since 1964 (Mitra, 2025). Riverine flooding, exacerbated by upstream hydrological modifications and sedimentation, combines with tidal flooding to create prolonged inundation events that stress both natural and human systems. Shoreline erosion, driven by the complex interplay of wave action, sediment supply and human interventions, consumes agricultural land and threatens settlements, with studies documenting that Patharpratima Block's thirteen estuarine islands have undergone shoreline changes ranging from gradual to significant between 1990 and 2020 (Acharyya et al., 2025). These physical processes interact with socio-economic vulnerability-poverty, marginalization, limited infrastructure access and livelihood precarity to produce outcomes that are not simply functions of hazard exposure but reflect the deeper structures of inequality and institutional capacity.

The human dimensions of flood vulnerability in the Sundarbans are starkly illustrated by household-level data revealing the cumulative burdens borne by coastal communities. A comprehensive study conducted between July 2022 and September 2023 across 1,050 households documented that people in the region were affected by cyclones once every 17 months on average over the past 15 years, while instances of floods, drought, excessive untimely rain, river erosion, waterlogging and saltwater intrusion increased markedly (New Age, 2026). At least 92 percent of households have experienced destruction of their houses, crops and other assets by cyclones and storms; 88 percent have faced similar losses from floods; and 70 percent have lost homeland, farmland, or both due to riverbank erosion. The economic consequences cascade through household economies, with 81 percent of households compelled to take loans between 2007 and 2023 to cope with disaster-induced distress and 58 percent forced to borrow repeatedly, creating debt traps from which recovery becomes progressively difficult. Migration emerges as a survival strategy for 59 percent of households, with 86 percent migrating to different districts within Bangladesh and 14 percent moving abroad, often into conditions of exploitation and vulnerability.

Disaster management frameworks in the Sundarbans have evolved significantly over recent decades, moving from reactive, relief-oriented approaches toward more comprehensive paradigms incorporating prevention, mitigation, preparedness and recovery. The development of Flood Susceptibility Indices incorporating multiple parameters-geomorphology, distance to water bodies and coastline, topographic wetness index, modified normalized difference water index, soil texture, land use and land cover, arsenic concentration levels, population density and community perception-represents a methodological advance in identifying risk locations and targeting interventions (Yadav, Dey and Pan, 2024). Community-based disaster risk reduction initiatives, grounded in the recognition that "all disasters are local and first responders have an important role to manage the disaster," have demonstrated the potential of locally-led approaches that utilize indigenous knowledge and collective action (Bera, 2025). Nature-based solutions, particularly mangrove restoration efforts achieving 95 percent survival rates in community-led initiatives, offer pathways for strengthening natural buffers while generating livelihood benefits (Mangrove Buffer Zone, 2025).

Yet despite these advances, significant gaps persist between policy frameworks and ground-level implementation. The inadequacy of support programmes, the failure of existing rehabilitation efforts to address community needs and the lack of long-term initiatives for disaster-hit populations continue to undermine resilience building (New Age, 2026). Early warning systems, while improved since the devastating Cyclone Aila of 2009, still face challenges of last-mile connectivity, comprehension and trust, with many households relying on neighbors and family members rather than official channels for critical information (Sahana et al., 2023). Cyclone shelters remain inadequate in number and quality and post-disaster trauma support for affected populations remains largely absent despite recognized needs.

This research article aims to provide a comprehensive analysis of flood vulnerability and disaster management in the Sundarbans region, synthesizing evidence from geospatial studies, community-based research, institutional assessments and policy evaluations. By examining both the physical dimensions of

flood hazard and the social dimensions of vulnerability and response, the study seeks to characterize the nature and distribution of flood risk; evaluate the evolution and effectiveness of disaster management frameworks; assess the potential of community-based and nature-based approaches; identify persistent gaps and challenges; and generate recommendations for strengthening resilience in this ecologically critical and culturally unique region. The analysis pays particular attention to the transboundary dimensions of the Sundarbans, recognizing that effective management requires collaboration between India and Bangladesh and to the integration of scientific assessment with indigenous knowledge and community participation.

## 2. Materials and Methods

This research adopts a comprehensive review methodology synthesizing empirical evidence from peer-reviewed studies, technical reports and institutional documents examining flood vulnerability and disaster management in the Sundarbans region. The methodological framework integrates multiple data sources and analytical approaches drawn from geospatial science, hydrology, disaster studies and social science to construct a holistic understanding of flood risk dynamics and management responses across spatial and temporal scales.

*Data Sources:* The research draws upon secondary data from diverse sources including multi-temporal satellite imagery, field surveys, household questionnaires and institutional records. Satellite data utilized in the reviewed studies include Landsat Thematic Mapper imagery for historical periods, Landsat 8 Operational Land Imager and Thermal Infrared Sensor for contemporary assessments, Resourcesat LISS-III and AWiFS data for high-resolution analyses and Shuttle Radar Topographic Mission Digital Elevation Model data for topographic characterization. These datasets provide consistent time series spanning from 1990 to 2022, enabling systematic assessment of shoreline dynamics, flood susceptibility patterns and mangrove condition trajectories over three decades. Household-level data are gleaned from structured surveys conducted across multiple studies, including assessments of 1,050 households in the Bangladesh Sundarbans examining disaster impacts, coping strategies and migration patterns and field investigations in the Indian Sundarbans exploring early warning system effectiveness, community preparedness and economic losses.

*Flood Susceptibility Assessment:* The identification of flood-prone areas employs multi-criteria decision-making techniques integrated with geospatial analysis. Studies utilize parameters including geomorphology, distance to water bodies, distance to coastline, topographic wetness index, modified normalized difference water index, soil texture, land use and land cover, arsenic concentration levels, population density and community perception to construct comprehensive Flood Susceptibility Indices. The Analytical Hierarchical Process, a multi-criteria decision-making approach, assigns weights to each parameter through pairwise comparisons based on expert knowledge and literature review, enabling the integration of diverse factors into a unified vulnerability metric. Weighted overlay analysis performed

using Geographic Information System software classifies the study area into zones of varying flood susceptibility, identifying priority areas for intervention.

*Shoreline Change Analysis:* The assessment of coastal dynamics employs statistical models integrated with remote sensing within the Digital Shoreline Analysis System framework. Endpoint Rate and Shoreline Change Envelope methods are applied to multi-temporal shoreline data extracted from satellite imagery spanning 1990-2020. These techniques quantify rates of erosion and accretion, identify areas of shoreline instability and project future shoreline positions under scenarios of continued change. The analysis focuses on Patharpratima Block's thirteen estuarine islands, part of the delta formed by the confluence of the Ganges, Brahmaputra and Meghna rivers, providing detailed characterization of coastal vulnerability at local scales relevant to community planning.

*Cyclone-Induced Flood Vulnerability Mapping:* The assessment of post-cyclonic flood susceptibility utilizes remotely sensed data combined with multi-criteria decision-making techniques focused on major cyclonic events including Aila (2009), Amphan (2020) and Yaas (2021). Spectral indices including Normalized Difference Vegetation Index, Modified Normalized Difference Water Index, Normalized Difference Moisture Index, Normalized Difference Built-up Index, Bare Soil Index and Normalized Difference Turbidity Index are derived from satellite imagery to characterize land surface conditions before and after cyclonic events. The analysis identifies changes in flood vulnerability across the 19 community development blocks of Indian Sundarbans in the post-cyclonic timespans of 2009-2010, 2020-2021 and 2021-2022, revealing temporal dynamics in hazard exposure.

*Mangrove Damage Assessment:* The relationship between flood vulnerability and mangrove ecosystem condition is examined through correlation analysis linking physical flood susceptibility indicators with measures of mangrove damage. The Normalized Difference Fraction Index serves as a key metric for assessing mangrove health, with significant positive relationships observed between mangrove damage and flood susceptibility indicators. This analysis reveals the bidirectional relationship between ecosystem health and hazard exposure: mangrove damage increases with increasing flood index values, while degraded mangroves provide reduced protection against flood impacts, creating feedback loops that amplify vulnerability over time.

*Community-Based Research Methods:* Understanding the social dimensions of flood vulnerability and disaster response draws upon qualitative research methodologies including focus group discussions, in-depth interviews and participant observation. Studies examining community-based nature-based solutions employ naturalistic inquiry approaches, allowing themes to emerge from participant narratives rather than imposing predetermined categories. This methodology captures the lived experiences of flood-affected villagers, their coping strategies and their innovations in utilizing local resources for disaster risk reduction. The analysis reveals how communities reduce dependence on external supports and develop new strategies for living with risk, including formation of groups for alternative livelihood development,

house repair and construction, temporary shelter establishment, relief distribution, drinking water security and prevention of school dropout.

*Early Warning System Evaluation:* Assessment of early warning system effectiveness employs field surveys at household level combined with statistical modeling. The Poisson distribution model analyzes relationships between warning timing, household characteristics and loss outcomes, revealing correlations between early warning receipt and recovery capacity. The analysis examines multiple dimensions of warning system performance including timeliness of information, accessibility of communication channels, comprehension of messages, trust in sources and behavioral responses to warnings. Findings identify critical gaps in last-mile connectivity and the continued reliance on informal warning sources in many communities.

*Institutional and Policy Analysis:* Evaluation of disaster management frameworks draws upon government documents, policy statements and implementation reports. Analysis of the District Disaster Management Plan for South 24 Parganas, guidelines from the Sundarban Development Board and national disaster management frameworks reveals the institutional architecture for flood risk reduction. The assessment examines both policy content and implementation realities, identifying gaps between stated intentions and ground-level outcomes. Transboundary cooperation mechanisms between India and Bangladesh are evaluated based on joint initiatives, shared monitoring systems and coordinated disaster preparedness efforts.

## 3. Physical Dimensions of Flood Vulnerability

The physical landscape of the Sundarbans embodies a dynamic equilibrium between sedimentary accretion and erosive forces, shaped by the immense discharge of the Ganges-Brahmaputra-Meghna river system and the powerful tidal and storm surge energy of the Bay of Bengal. This equilibrium, however, is being progressively destabilized by climate change; sea level rise and anthropogenic modifications, creating conditions of accelerating physical vulnerability that threaten both ecosystem integrity and human habitation. The geomorphological template upon which flood dynamics play out is characterized by extremely low elevations, with most islands rising less than five meters above mean sea level. This low-lying topography renders the region inherently susceptible to inundation from even modest storm surges or tidal exceedances. The intricate network of tidal creeks and estuaries that dissect the landscape serves as conduits for flood waters, transmitting marine surges deep into the interior and prolonging inundation durations. Sediment characteristics, dominated by fine-grained silts and clays with low permeability, limit infiltration and encourage surface ponding, further extending flood impacts (Yadav, Dey and Pan, 2024).

Shoreline dynamics in the Sundarbans demonstrate the intense morphological instability that characterizes this deltaic frontier. Analysis of shoreline changes between 1990 and 2020 using Endpoint Rate and Shoreline Change Envelope methods reveal that the coastline undergoes gradual to significant changes due to fluctuating erosion and deposition patterns that directly impact local residents (Acharyya et al., 2025). Within Patharpratima Block's thirteen estuarine islands, Surendranagar and Dhanchi emerge as

the most vulnerable areas, experiencing the most severe erosion rates and associated land loss. Lothian Island ranks as moderately vulnerable, while other areas show variable patterns of stability and change. These shoreline dynamics reflect the complex interplay of relative sea level rise, sediment supply reductions due to upstream damming and the increasing frequency and intensity of cyclonic storm surges that mobilize sediment and reshape coastal landforms.

The population of the Sundarbans region has increased substantially over recent decades, while the total land area has simultaneously shrunk due to erosion (Acharyya et al., 2025). This demographic pressure on diminishing land resources concentrates population in areas of highest flood risk, as remaining habitable land becomes progressively more constrained. Communities find themselves pushed into ever more vulnerable locations, with limited options for retreat given the bounded nature of deltaic islands and the high population densities throughout the region. The resulting settlement patterns place households directly in the path of storm surges and erosion fronts, creating conditions where hazard exposure is not merely a matter of unfortunate location but a systemic outcome of demographic and environmental dynamics.

Sea level rise compounds these shoreline erosion processes by elevating baseline water levels against which storm surges propagate. Research indicates that relative sea level in the Sundarbans is rising at rates exceeding global averages, driven by a combination of eustatic sea level increase and local subsidence related to sediment compaction and tectonic setting (Mitra, 2025). This rising baseline means that storm surges of given magnitude reach farther inland and cause more extensive inundation than would have occurred under historical conditions. The cumulative effect of gradual sea level rise, when combined with the increasing intensity of cyclonic events, creates a non-linear amplification of flood risk that challenges conventional adaptation approaches based on historical experience.

Cyclone-induced flooding represents the most acute and destructive manifestation of flood vulnerability in the Sundarbans. Multi-criteria decision-making analyses incorporating spectral indices including Normalized Difference Vegetation Index, Modified Normalized Difference Water Index, Normalized Difference Moisture Index, Normalized Difference Built-up Index, Bare Soil Index and Normalized Difference Turbidity Index reveal that the coastline most impacted by tropical storms exhibits significant physical susceptibility to flooding (Sahana et al., 2024). The spatial pattern of susceptibility follows a clear gradient from the coastal front, where storm surge impacts are most severe, to interior areas where flooding is attenuated by distance and the buffering effect of mangrove vegetation. However, the progressive degradation of mangrove buffers due to both cyclone damage and anthropogenic pressures is reducing this natural protection, extending high susceptibility zones farther inland.

The temporal dynamics of flood vulnerability are illuminated by analyses spanning major cyclonic events between 2009 and 2022. Comparison of flood susceptibility patterns before and after Cyclones Aila (2009), Amphan (2020) and Yaas (2021) reveals that each major event leaves a legacy of altered vulnerability (Sahana et al., 2024). Cyclone damage to mangroves reduces vegetative buffering capacity,

while breaching of embankments creates new pathways for future inundation. Saltwater intrusion from storm surges degrades soil quality and vegetation health, reducing the landscape's capacity to recover and increasing susceptibility to subsequent events. These legacy effects mean that flood vulnerability is not a static property but a dynamic condition that evolves through the accumulation of impacts from successive disasters.

## 4. Social and Economic Dimensions of Vulnerability

The translation of physical flood hazards into human suffering and livelihood disruption is mediated by social, economic and institutional factors that determine differential vulnerability across households and communities. Understanding these social dimensions is essential for designing disaster management interventions that address root causes of vulnerability rather than merely treating symptoms of hazard exposure. The demographic profile of Sundarbans communities reveals patterns of marginalization that amplify flood impacts. The region is characterized by high population density, limited economic diversification and dependence on natural resource-based livelihoods including agriculture, fishing and forest product collection. These livelihood systems are directly vulnerable to flooding, storm surge and salinization, creating conditions where hazard events translate immediately into income loss and food insecurity. The limited asset base of most households-small landholdings, few livestock, minimal savings-means that recovery from even modest disaster impacts requires external assistance or distress strategies including high-interest borrowing and asset depletion (New Age, 2026).

The frequency of disaster impacts documented in household surveys reveals the cumulative burden borne by Sundarbans communities. People in the region were affected by cyclones once every 17 months on average over the past 15 years, while instances of floods, drought, excessive untimely rain, river erosion, waterlogging and saltwater intrusion all increased (New Age, 2026). This high-frequency exposure means that households rarely complete recovery from one disaster before the next arrives, creating conditions of chronic stress and eroding coping capacities over time. The psychological toll of repeated trauma, while difficult to quantify, manifests in mental health impacts, decision-making impairment and erosion of hope that compound material losses.

The material impacts of disasters documented in the Sundarbans are staggering in their cumulative scope. At least 92 percent of households have experienced destruction of their houses, crops and other assets by cyclones and storms; 88 percent have faced the same sort of losses from floods; and 70 percent have lost homeland, farmland, or both due to riverbank erosion (New Age, 2026). These losses extend beyond immediate consumption impacts to destroy productive assets-agricultural land, fishing equipment, livestock-that form the basis for future livelihood generation. The destruction of houses, often constructed from locally available materials with limited structural resilience, exposes households to post-disaster health risks and imposes reconstruction costs that strain already limited resources.

The economic coping strategies households employ in response to disaster-induced distress reveal both their agency and the constraints within which they operate. The study finds that 81 percent of households were compelled to take loans in 2007-2023 to deal with their distressing situation caused by climate change-induced disasters and 58 percent of households were compelled to take loans more than once (New Age, 2026). Loans, however, put them in a vicious circle, as most households cannot generate enough income to pay their loans and meet their daily needs. Microfinance institutions and local lenders provide credit at high interest rates, extracting significant portions of post-recovery income and perpetuating cycles of indebtedness that span generations. The debt trap phenomenon transforms temporary disaster impacts into permanent impoverishment, as households sell assets, reduce consumption and forego investments in human capital to service obligations incurred during crisis.

Migration emerges as a survival strategy for a majority of households confronting untenable conditions. The study finds that 59 percent of households have at least one member who has resorted to migration, with 86 percent migrating to different districts and 14 percent moving abroad (New Age, 2026). Migration flows from the Sundarbans are predominantly internal, with displaced populations moving to urban centers including Khulna, Satkhira and Dhaka in Bangladesh and to Kolkata and other West Bengal cities in India. These climate migrants often become prone to exploitation and trafficking, ending up working in vulnerable situations with limited legal protection and social support. The feminization of responsibility in sending areas, as men migrate in search of work, leaves women to manage households, children and remaining livelihood activities with reduced labor and support.

The social differentiation of vulnerability within Sundarbans communities reveals that marginalization operates along multiple axes including land ownership, caste, gender and age. Landless households, lacking productive assets and often residing on the most vulnerable land, face the most severe impacts and most limited recovery options. Women bear disproportionate burdens during and after disasters, responsible for childcare, food preparation and water collection under conditions of extreme stress, while having less access to resources and decision-making power. Elderly and disabled community members face mobility constraints that limit evacuation options and expose them to greater risk during flood events. These intersecting vulnerabilities require differentiated responses that recognize the diverse needs and capacities within affected populations.

## 5. Disaster Management Frameworks and Institutional Responses

The evolution of disaster management frameworks in the Sundarbans reflects broader shifts in global and national approaches to disaster risk reduction, moving from reactive, relief-focused paradigms toward comprehensive frameworks incorporating prevention, mitigation, preparedness and recovery. This evolution, while significant, has not fully closed the gap between policy intentions and ground-level implementation, leaving communities exposed to preventable losses. The institutional architecture for disaster management in the Indian Sundarbans centers on the District Disaster Management Plan for South 24 Parganas, developed within the framework of the National Disaster Management Act of 2005 and

guidelines from the National Disaster Management Authority. The plan establishes structures for early warning dissemination, evacuation coordination, emergency response and post-disaster recovery, assigning responsibilities to line departments and local government institutions (Yadav, Dey and Pan, 2024). The Sundarban Development Board, a specialized agency focused on the region, plays a coordinating role in infrastructure development, mangrove conservation and livelihood support programs that contribute to disaster risk reduction. Block-level committees with specialized functions have been established to improve coordination and response capacity at local scales.

The development of Flood Susceptibility Indices represents a methodological advance in targeting interventions to areas of greatest need. By integrating ten parameters-geomorphology, distance to water bodies, distance to coastline, topographic wetness index, modified normalized difference water index, soil texture, land use and land cover, arsenic concentration levels, population density and community perception-researchers have developed tools for identifying risk locations and prioritizing investments (Yadav, Dey and Pan, 2024). These spatial assessments reveal the heterogeneous distribution of flood vulnerability across the Sundarbans, enabling allocation of limited resources to areas where they can achieve greatest impact. The integration of community perception alongside physical parameters recognizes that vulnerability is not purely a technical matter but incorporates lived experience and local knowledge.

Early warning systems have undergone significant improvement since the devastating Cyclone Aila of 2009, which exposed critical gaps in warning dissemination and community preparedness. The establishment of block-level committees with specialized functions has enhanced coordination between meteorological agencies, civil administration and community structures (Sahana et al., 2023). Mobile-based warning systems, while still limited in coverage, offer potential for rapid dissemination of critical information. Digital platforms and social media increasingly supplement traditional communication channels, though challenges of last-mile connectivity and digital literacy persist. Comparison of casualties and damage between Cyclone Aila (2009) and Cyclone Amphan (2020) demonstrates that improvements in early warning systems and increased use of digital media have reduced harm, even as storm intensity has increased.

However, significant gaps remain in early warning effectiveness. Field surveys reveal that many households, particularly in remote and isolated communities, continue to rely heavily on informal sources-neighbors, relatives and acquaintances-for early warnings of cyclones (Sahana et al., 2023). The limited outreach of local Panchayats in warning entire villages perpetuates dependence on these informal networks, which are inherently variable in their reliability and timeliness. Many surveyed households receive warning information only 12 hours ahead of expected events, creating uncertainty regarding the most prudent response options and limiting the time available for asset protection and evacuation.

The decision to evacuate or shelter in place involves complex calculations that early warning systems alone cannot resolve. Most surveyed households in the Indian Sundarbans decide to remain in

their current residences rather than transfer to safer locations, even after receiving early warning information (Sahana et al., 2023). For villages closer to Kolkata, where mangrove tracts provide buffering against storm impacts, this decision may be rational. However, in more vulnerable locations, households avoid cyclone shelters due to cramped conditions and their inability to bring belongings and livestock. These constraints reflect the inadequacy of shelter infrastructure and the failure to design facilities that accommodate the full range of community needs during disasters.

Cyclone shelter infrastructure, while expanded since Cyclone Aila, remains inadequate in coverage, quality and design. Many shelters lack sufficient capacity for affected populations, forcing difficult choices about who can access protection. Facilities are often located at distances that require significant travel time, reducing willingness to evacuate. Shelters rarely accommodate livestock, a critical livelihood asset, leading households to remain in hazardous locations to protect their animals. Post-cyclone water and sanitation facilities in shelters are frequently inadequate, creating health risks for displaced populations. The modernization and expansion of cyclone shelter infrastructure, incorporating community input on design and location, represents an urgent priority.

Post-disaster recovery support, while essential for rebuilding lives and livelihoods, remains limited in scope and duration. The study by the Ovibashi Karmi Unnayan Programme highlights the inadequacy of support programmes for people living in the Sundarbans region and the failure of existing support and rehabilitation programmes to address the needs of people affected by climate change-induced disasters (New Age, 2026). Recovery assistance tends to be short-term, focused on immediate relief rather than long-term rehabilitation and insufficient to cover actual losses. The absence of trauma support for affected populations leaves psychological wounds unaddressed, compromising mental health and community wellbeing long after physical reconstruction is complete.

**6. Community-Based Adaptation and Nature-Based Solutions**

The recognition that state-dependent disaster reduction mechanisms are not becoming adequate to meet local needs has catalyzed the emergence of community-based approaches that mobilize local knowledge, resources and collective action for disaster risk reduction. These initiatives, often operating below the radar of formal development programs, demonstrate the potential for locally-led adaptation that complements and extends government efforts. The fundamental premise of community-based disaster risk reduction in the Sundarbans is that "all disasters are local and first responders have an important role to manage the disaster" (Bera, 2025). Affected people work together to save lives and properties by utilizing local resources based on salt water, soil and collective activities. This recognition challenges top-down approaches that position communities as passive recipients of external assistance rather than active agents in their own protection. The utilization of local resources helps communities reduce floods and generate multiple alternative livelihood options, creating synergies between disaster risk reduction and sustainable development.

Qualitative research in villages of the Indian Sundarbans reveals that flood-affected villagers try to reduce their dependence on external supports and chalk out new strategies to live with the risk (Bera, 2025). These strategies become unique for managing disaster in frequently flood-affected hamlets, reflecting local conditions, resources and social structures. As there are inadequacies of local government to address all community needs, local people take efforts to form groups for multiple purposes: finding local resource-dependent alternative livelihoods, repairing or building houses, building temporary shelters, distributing relief materials, ensuring safe drinking water, stopping school dropout and managing disasters. Local initiatives are often supported by local government and work collaboratively, strengthening relationships and building confidence.

Mangrove restoration emerges from multiple studies as the most promising nature-based solution for flood risk reduction in the Sundarbans. Native species including Rhizophora and Bruguiera act as frontline defences against storm surges and coastal erosion, attenuating wave energy, trapping sediment and stabilizing shorelines (Mitra, 2025). The restoration of degraded mangrove areas enhances these protective functions while simultaneously providing habitat for biodiversity, carbon sequestration for climate mitigation and resources for sustainable livelihoods including honey collection, crab farming and eco-tourism.

The Tridibnagar community initiative in Jharkhali, a mid-estuarine island in West Bengal's South 24 Parganas district, stands as one of the few successful examples of mangrove restoration documented in the region. Determined women of Tridibnagar secured two kilometers of mud embankment while conserving 40 acres of pre-existing mangroves (Mangrove Buffer Zone, 2025). Nearly 200,000 saplings were planted over five acres, based on traditional wisdom to mimic the diverse mangrove ecosystem, achieving a 95 percent survival rate. The plantation evolved into a mass movement, with nearly every household today maintaining a mangrove nursery, ensuring a steady supply of saplings for future restoration. The project transformed into a community-led initiative-an example of effective application of restoration dynamics driven by deep understanding of local stakeholder needs and commitment to addressing their concerns while making it economical.

The challenges encountered in Tridibnagar reveal the social dimensions of successful restoration. Village policies were established to prevent cattle grazing, increasing population pressure and political interference (Mangrove Buffer Zone, 2025). These local governance innovations, emerging from community deliberation rather than external prescription, created conditions for restoration success that technical interventions alone could not achieve. The contrast with the broader track record of mangrove restoration-where data from the past 40 years indicate that 48.7 percent of restoration projects in South and Southeast Asian deltas have been unsuccessful due to social, governance and political constraints-highlights the critical importance of community engagement and local ownership.

The Bangladesh Environment and Development Society's community-managed disaster risk reduction initiatives in Satkhira district demonstrate parallel approaches in the Bangladesh Sundarbans.

Through interactive training sessions focused on climate risk identification, early warning systems and nature-based adaptation techniques such as mangrove restoration and rainwater harvesting, communities develop stronger understanding of their climate vulnerabilities and available response tools (Faruk, 2025). Local leaders and volunteers report increased confidence in their ability to respond to disasters, engage in proactive planning and effectively disseminate early warning information. Knowledge sharing meetings ensure that training benefits reach beyond direct participants, creating cascading effects through community networks.

The integration of traditional knowledge with scientific approaches emerges as a critical success factor in community-based adaptation. The belief systems centered on Bonbibi, the "Guardian of the Forest," and other deities including Dakshin Rai (the tiger god) and Kalu Ray (believed to protect against crocodiles) reflect the close connection between humans and the forest's wildlife (Mitra, 2025). These figures embody a deep respect for the region's ecological balance and their worship reinforces a code of sustainable interaction with the forest. Rituals, prayers and festivals that honor these deities play a significant role in maintaining social cohesion and environmental ethics, providing cultural foundations for conservation and sustainable resource use.

**7. Transboundary Dimensions and Future Pathways**

The Sundarbans' unique geography, spanning two nations and forming a single ecological unit, necessitates collaboration between India and Bangladesh for effective conservation and disaster risk reduction. The transboundary nature of the ecosystem means that actions in one country have implications for the other and that coordinated approaches can achieve outcomes beyond the reach of unilateral efforts. Joint conservation initiatives between India and Bangladesh have progressed through frameworks including bilateral consultations, shared monitoring systems and coordinated disaster preparedness exercises. Organizations including UNESCO, the Global Environment Facility and the World Bank have backed collaborative projects aimed at strengthening the resilience of this globally significant ecosystem (Mitra, 2025). However, translating these projects into lasting resilience for communities requires consistent, long-term commitment and shared goals that transcend political cycles and administrative boundaries.

The potential for coordinated early warning systems across the Sundarbans remains incompletely realized. Cyclones forming in the Bay of Bengal threaten both countries and timely information sharing can enhance preparedness on both sides of the border. Protocols for data exchange, joint training exercises and coordinated evacuation planning could strengthen disaster response across the ecosystem. However, technical coordination mechanisms must be complemented by attention to the different institutional contexts, communication infrastructures and community characteristics that shape warning effectiveness in each country.

Climate migration from the Sundarbans, documented extensively in research from both sides of the border, represents a transboundary issue requiring coordinated policy responses. As households lose land,

livelihoods and homes to erosion and flooding, displacement generates flows of migrants to urban centers throughout eastern India and Bangladesh (New Age, 2026). These climate migrants face vulnerabilities including exploitation, trafficking and insecure living conditions that transcend national boundaries. Developing protection frameworks for climate-displaced populations, ensuring their access to services and rights in destination areas and addressing root causes of migration through in-situ adaptation represent shared challenges requiring collaborative approaches.

The future of the Sundarbans under climate change scenarios presents sobering projections that underscore the urgency of ambitious action. Scientists warn that large parts of the forest may be submerged by the end of the century, jeopardizing both biodiversity and local livelihoods (Mitra, 2025). Sea level rise projections, combined with continuing subsidence and reduced sediment supply, suggest that substantial areas of the delta could transition from terrestrial to intertidal or subtidal regimes within decades. These changes would fundamentally alter the ecosystem upon which millions depend, triggering cascading impacts through biodiversity, fisheries and coastal protection.

Addressing this trajectory requires a multifaceted approach combining global climate mitigation, regional adaptation and local resilience building. Global efforts to reduce greenhouse gas emissions remain essential for limiting the ultimate magnitude of sea level rise and cyclone intensification. Regional cooperation on sediment management, water sharing and coastal protection can enhance the resilience of the delta system to unavoidable changes. Local investments in mangrove restoration, resilient livelihoods and disaster preparedness can strengthen community capacity to cope with changing conditions.

The integration of technological advances with community knowledge offers pathways for enhanced monitoring and response. Satellite imagery provides real-time data on deforestation, land loss and ecosystem health, enabling more effective conservation planning (Mitra, 2025). Geographic Information System mapping identifies vulnerable areas, helping authorities target mangrove replanting and allocate resources for disaster preparedness. Mobile-based early warning systems offer potential for timely alerts, though deployment faces infrastructure limitations requiring continued investment. The challenge lies in ensuring that these technological tools serve community needs rather than displacing local knowledge and decision-making.

Decision science approaches, integrating scientific and local knowledge with structured methodologies for participatory decision-making, offer frameworks for navigating the complex trade-offs inherent in Sundarbans management. Research advocates for deeper integration of diverse knowledge systems and enhanced public awareness to overcome social and governance barriers (Mangrove Buffer Zone, 2025). Decision support frameworks incorporating analysis of restoration manuals, spatial analysis, predictive modeling and stakeholder consultations can guide conservation and restoration efforts toward more sustainable outcomes.

## 8. Conclusion

The comprehensive analysis of flood vulnerability and disaster management in the Sundarbans region reveals a system under accelerating stress, where physical hazards intensify while social and institutional responses struggle to keep pace. The evidence synthesized from geospatial studies, community-based research, household surveys and policy evaluations converges on several robust conclusions that carry implications for policy, practice and future research in this globally significant ecosystem.

First, the physical vulnerability of the Sundarbans to flooding is profound and increasing. Shoreline dynamics demonstrate gradual to severe changes due to fluctuating erosion and deposition patterns, with Surendranagar and Dhanchi emerging as the most vulnerable areas within Patharpratima Block. Sea level rise, cyclone intensification and sediment supply reductions combine to elevate baseline risk levels, while each major cyclonic event leaves a legacy of altered vulnerability through mangrove damage and embankment breaching. The spatial pattern of flood susceptibility, concentrated along coastlines most impacted by tropical storms, reflects the fundamental exposure of this deltaic landscape to marine hazards. Approximately 210 square kilometers of land have been lost to encroaching seas since 1964 and this trajectory shows no sign of abating without transformative intervention.

Second, the social and economic dimensions of vulnerability translate physical hazards into human suffering through complex pathways mediated by poverty, marginalization and limited adaptive capacity. Households in the Sundarbans face cyclones once every 17 months on average, with 92 percent experiencing destruction of houses and crops, 88 percent suffering flood-related losses and 70 percent losing land to erosion. The economic consequences cascade through indebtedness, with 81 percent of households compelled to take loans and 58 percent borrowing repeatedly, creating debt traps from which recovery becomes progressively difficult. Migration emerges as a survival strategy for 59 percent of households, often leading to exploitation and vulnerability in destination areas. These patterns reveal that flood vulnerability is not merely a function of hazard exposure but reflects deeper structures of inequality and institutional failure.

Third, disaster management frameworks have evolved significantly but remain inadequate to address the scale and complexity of challenges. The development of Flood Susceptibility Indices incorporating multiple parameters enables identification of risk locations and targeting of interventions. Early warning systems have improved since Cyclone Aila, with block-level committees and digital media reducing casualties even as storm intensity increases. However, significant gaps persist in warning dissemination, with many households relying on informal sources and receiving information too late for effective response. Cyclone shelter infrastructure remains inadequate in coverage, quality and design, failing to accommodate the full range of community needs. Post-disaster recovery support remains limited in scope and duration, with trauma support almost entirely absent.

Fourth, community-based adaptation and nature-based solutions demonstrate significant potential for strengthening resilience in culturally appropriate and sustainable ways. The Tridibnagar mangrove

restoration initiative, achieving 95 percent survival rates through community leadership and local governance innovations, stands as a model of effective restoration that contrasts sharply with the high failure rates characterizing top-down approaches. Community-managed disaster risk reduction initiatives in Bangladesh demonstrate how local groups can mobilize resources, share knowledge and coordinate response in ways that complement government efforts. The integration of traditional knowledge and belief systems, including reverence for Bonbibi and other forest deities, provides cultural foundations for conservation and sustainable resource use that external interventions cannot replicate.

Fifth, the transboundary nature of the Sundarbans ecosystem necessitates collaborative approaches between India and Bangladesh that transcend political boundaries. Joint conservation initiatives, shared monitoring systems and coordinated disaster preparedness exercises have progressed through bilateral frameworks and international support. However, the full potential of transboundary cooperation remains unrealized, particularly in early warning coordination, climate migration management and sediment sharing. The future of the Sundarbans depends on sustained collaboration that recognizes the ecosystem as an indivisible whole deserving of joint stewardship.

The policy implications of these findings extend across multiple domains. Investment in mangrove restoration must prioritize community-led approaches that address social and governance dimensions alongside biotechnical considerations, learning from successes like Tridibnagar and avoiding the high failure rates documented across South and Southeast Asian deltas. Early warning systems require strengthening of last-mile connectivity, ensuring that warnings reach remote communities through accessible channels and that recipients understand and trust the information they receive. Cyclone shelter infrastructure needs expansion and redesign to accommodate livestock, belongings and diverse community needs, reducing barriers to evacuation. Post-disaster support must extend beyond immediate relief to address long-term rehabilitation, including trauma recovery and livelihood reconstruction. Climate migration requires policy frameworks that protect displaced populations, ensure access to services and rights and address root causes through in-situ adaptation.

The imperative for action is urgent. With large parts of the forest projected to be submerged by century's end, with cyclone intensity increasing and with communities already pushed to the limits of coping capacity, the window for effective intervention is narrowing. The Sundarbans represent not only a unique ecosystem of global significance but also a test case for humanity's capacity to respond to climate change in ways that protect both nature and culture. The resilience demonstrated by communities in the face of repeated disasters, the innovations emerging from grassroots initiatives and the growing recognition of the region's importance at national and international levels all provide grounds for hope. Translating this hope into reality requires sustained commitment, adequate resources and collaborative approaches that honor the complexity of this extraordinary place and the dignity of its people.

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