Turning Brackish: Salinity-Driven Mangrove and Fisheries Decline in the Bangladesh Sundarbans.

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Abstract

The Bangladesh Sundarbans Reserved Forest covers about 6,017 km², forming roughly 60% of the world's largest contiguous mangrove ecosystem, sustaining 2.7 million people. Since 1991, the reserve has lost 442 km² of forest cover, accompanied by a roughly 54% decline in recorded fish species richness at Mongla fish market (from 172 species in 2003 to 79 in 2016) and accelerating salinity intrusion across critical freshwater zones. The objective is to quantify the causal relationship between reduced freshwater inflow, accelerated salinity intrusion, and ecosystem service degradation in the Bangladesh Sundarbans, with a specific focus on mangrove species composition shifts and livelihood impacts. Methods include secondary data synthesis integrating hydrological records (1996-2020), forest cover mapping (2000-2020), fisheries statistics (Mongla market catch data, 2003-2016), climate impact projections across 27 scenarios to 2050, and ecosystem service valuations. Data sources include Bangladesh Forest Department biodiversity inventories, World Bank hydrological assessments, and peer-reviewed ecosystem studies. Key findings are that reduced Ganges freshwater inflow, primarily due to upstream abstraction and regulation, has intensified salinity penetration into the Bangladesh Sundarbans, exceeding physiological tolerance thresholds for high-value *Heritiera fomes* (Sundri) across 40% of the reserve. Species composition is shifting unfavorably: projected Sundri losses under all climate scenarios, while salt-tolerant but lower-value *Excoecaria agallocha* expands. Livelihood impacts are severe: Sundarbans-fringe upazilas, forest and estuary-based activities typically provide roughly 40-75% of household income, and malnutrition in dependent communities exceeds WHO thresholds. The Bangladesh Sundarbans are being damaged by climate change, local overuse, and above all, too little freshwater coming from upstream in the Ganges. Long-term resilience of the Bangladesh Sundarbans requires institutional reform of Ganges water-sharing as a prerequisite for effective biodiversity conservation and livelihood security.

Keywords: Sundarbans, Salinity intrusion, Climate resilience, Transboundary water governance, Ecosystem services.

1. Introduction

The Sundarbans is an essential but vulnerable ecosystem in South Asia, measuring about 10,000 km² across India and Bangladesh, and comprises around 60% of the world's largest single block of mangrove forests. This delta ecosystem, made up of sediments from the Ganges, Brahmaputra, and Meghna rivers, supports approximately 2.7 million people in Bangladesh alone, who depend directly on its natural resources for subsistence livelihoods centered on fishing, honey collection, timber extraction, and agriculture. The Sundarbans also provides globally significant ecosystem services, including carbon sequestration, storm protection, breeding grounds for aquatic species, and biodiversity conservation, estimated at about USD 43 million annually. However, this UNESCO World Heritage Site faces an acute and accelerating ecological crisis. Since 1991, the Bangladesh Sundarbans has seen the loss of 442 km² of forest cover, coupled with a 54% decline in recorded fish species richness, from 172 species recorded at Mongla market in 2003 to 79 species in 2016, and increasing salinity intrusion across freshwater-dependent areas. These changes coincide with and are fundamentally linked to reduced freshwater inflow from the Ganges River system, driven by upstream water diversion at India's Farakka Barrage and compounded by climate variability affecting Himalayan glacier melt. This research examines the causal relationship between reduced Ganges freshwater inflow, accelerated salinity intrusion, mangrove species composition shifts, and livelihood degradation in the Bangladesh Sundarbans. We employ secondary data synthesis integrating hydrological records (1996-2020), forest cover mapping (2000-2020), fisheries statistics (2003-2016), climate impact projections across 27 scenarios to 2050, and ecosystem service valuations. Our findings reveal that transboundary water governance failures, specifically the inadequacy of the 1996 Ganges Water-Sharing Treaty, have created a systematic pathway to ecosystem service collapse. This paper contributes to understanding the intersecting vulnerabilities of wetland-dependent communities and provides evidence for the urgent need to integrate water governance reform with biodiversity conservation.

2. Literature Review

2.1 Climate Change and Aquatic Salinization in South Asian Deltas

The impacts of climate change on delta ecosystems have emerged as a central concern for both ecological resilience and human development in the Global South. Dasgupta et al. (2017) conducted one of the most comprehensive assessments of climate change impacts on the Sundarbans, combining salinity tolerance ranges of predominant mangrove species with aquatic salinity measurements across 27 climate change scenarios projected to 2050. Their analysis indicates that under all 27

scenarios, *Heritiera fomes* (Sundri), the economically most valuable mangrove species, faces significant area losses ranging from 12.1% to 24.2%, while salt-tolerant species such as *Excoecaria agallocha* (Gewa) expand substantially (19.8-23.0% gains) (Dasgupta et al., 2017). This species composition shift has profound implications not only for forest structure but also for the economic productivity and livelihood value of the ecosystem. The physiological mechanisms driving these shifts reflect fundamental constraints on plant adaptation. Jahan (2018) documented that *Heritiera fomes* exhibits negative growth responses to increasing soil salinity, whereas *Ceriops decandra* (Goran) demonstrates salt tolerance characteristics. More recent research by Perri et al. (2023) demonstrates that high salinity favors more salt-tolerant species while narrowing the spectrum of viable traits for sensitive species. Highly salt-tolerant mangroves, while adapted to extreme conditions, typically exhibit lower photosynthesis rates and growth rates, resulting in reduced productivity compared to less salt-sensitive species (Perri et al., 2023). This suggests a direct causal link between salinity stress, ecosystem biodiversity, and ecosystem services productivity.

2.2 Transboundary Water Governance and Hydrological Change in the Ganges System

The reduction in freshwater flow reaching the Bangladesh Sundarbans cannot be attributed to climate alone; rather, it reflects the interaction of climate variability with institutional governance failures at the transboundary level. Murshed (2019) analyzed hydrological changes in the Ganges system post-Farakka Barrage (constructed 1975, commissioned 1975-1976) and found large reductions in river flows between pre and post-barrage periods, with particularly acute reductions in dry-season flows. Flow duration curves reveal dramatically lower water storage capacity and availability, directly intensifying salinity intrusion (Murshed, 2019). This freshwater scarcity is progressively reducing livelihood options and inducing population migration from the delta region. The foundational governance framework governing Ganges water allocation is the Ganges Water-Sharing Treaty (1996), signed by India and Bangladesh to regulate water distribution from the Farakka Barrage over a 30-year period. However, Islam et al. (2023) and recent analyses by The Global Health Institute (2025) reveal critical deficiencies in this treaty's design. The treaty's allocation formula was based on historical hydrological data from 1949 to 1988, preceding both the onset of accelerated climate change impacts on Himalayan glacier melt and the full operational expansion of upstream irrigation infrastructure in Nepal and India (The Global Health Institute, 2025). Crucially, the treaty allocates Bangladesh a guaranteed 35,000 cusecs of water during alternate 10-day periods between March 11 and May 10, the critical dry season when water demand peaks. However, a comprehensive analysis by water resource specialists covering the period 1997-2016 revealed that Bangladesh failed to receive its allocated share during most critical dry-season periods. Bangladesh did not receive a guaranteed flow 65% of the time during dry seasons. In specific counts, Bangladesh received less than its stipulated allocation in 39 out of 60 cases during the required dry-season periods (Hanasz, 2014). Between 2008 and 2011, these allocation failures were particularly

frequent, with 94 documented failures out of 300 total allocation opportunities over the 20-year period (Islam et al., 2023). This systematic non-compliance with treaty obligations reflects not deliberate violation but rather the treaty's inadequacy in the face of changed hydroclimatic conditions.

2.3 Ecosystem Service Degradation and Livelihood Vulnerability

The ecological consequences of reduced freshwater inflow manifest directly in ecosystem service degradation and livelihood collapse. The Sundarbans generates critical provisioning services, including timber, fuel, fish, honey, and non-timber forest products (NTFPs), as well as regulating services such as storm protection, carbon sequestration, and breeding grounds for commercially valuable aquatic species. Rahman et al. (2018) and subsequent assessments identify reduced freshwater supply as the primary driver of mangrove forest degradation in the Sundarbans, alongside increased demand for resources, climate change, and governance failure (Rahman et al., 2018). Quantifying livelihood dependency, Islam & Shamsuddoha (2018) note that forest and estuary-based activities typically provide 40 to 75% of household income for Sundarbans-fringe communities. A comprehensive socio-economic study by Mitra et al. (2022) reveals that 72% of resource collectors in the Sundarbans are engaged in fishing, with average annual income from fishing of USD 390 per household, compared to USD 290 from crab collection and lower incomes from other forest products (Mitra et al., 2022). However, this income stream has become increasingly precarious: the decline from 172 to 79 fish species recorded at Mongla market (2003-2016) directly correlates with both reduced freshwater availability and salinity-induced habitat loss. Beyond income disruption, malnutrition emerges as a critical indicator of livelihood collapse. Kanjilal et al. (2013) document that more than one-third of children in the Indian Sundarbans are chronically malnourished, with higher rates among older, poorer, and female children aged 13-36 months. More recent surveys report that over 90% of children in some Sundarbans villages suffer from severe acute malnutrition exceeding WHO emergency thresholds (Datta et al., 2022). This nutritional crisis reflects both reduced fish availability and economic inability to purchase alternative food sources, creating a direct causal chain from water governance failure through ecosystem decline to human health impacts.

2.4 Mangrove Species Composition and Economic Valuation

The economic consequences of species composition shifts are substantial. *Heritiera fomes* (Sundri) commands premium prices in timber markets and is considered the most commercially valuable mangrove species in the Sundarbans. Conversely, *Excoecaria agallocha* (Gewa) and other salt-tolerant species have lower commercial value and provide fewer high-value ecosystem services. Saha et al. (2023) estimated that the value of Sundri stocks will reduce by approximately 45% by 2100 under climate change scenarios, while Gewa stocks remain relatively constant, representing a substantial loss in economic value of the forest to dependent communities. Valuation studies have attempted to quantify

total ecosystem services. While estimates vary, assessments converge on substantial valuations: USD 1,159/ha/year when including timber, NTFP, and ecosystem service values (combined provisioning and regulating services) (Saha et al., 2023); USD 450-1,000/ha/year in other studies (Rahman & Khan, 2019); and USD 43 million annual total value in 2021 (Saha et al., 2023). However, these valuations obscure the point that ecosystem service losses translate directly into livelihood income losses for the poorest households, who lack alternative income opportunities.

2.5 Conservation Management and Policy Responses

Bangladesh has implemented multiple conservation interventions in response to the Sundarbans. Since 1966, the Government of Bangladesh has established over 50,000 hectares of mangrove plantations on accreted coastal lands (chars), with the intent to facilitate coastal accretion and stabilize 120,000 hectares of coastland (Chow, 2017). Mangrove plantations have demonstrably higher rates of accretion relative to erosion compared to non-plantation areas, confirming mangroves' role in coastal stabilization and climate adaptation. However, plantation encroachment by human settlements and agricultural conversion has limited long-term persistence; approximately 45,000 hectares of mature plantations remained by 2007, with sustained pressure from development (Chow, 2017). Community-based co-management (CBCM) represents an alternative governance approach, exemplified by the successful restoration of Baikka Beel sanctuary. However, such initiatives face constraints: Tanguar Haor co-management demonstrated high community participation (80% agreement on decision-making) but only modest improvements in resource protection due to weak local institutional capacity and persistent livelihood pressure (Iftekhar & Takama, 2008). Implementation of CBCM at scale requires concurrent livelihood diversification programs and long-term (10+ year) institutional development beyond typical project cycles.

3. Methodology

3.1 Data Sources and Collection Strategy

This research employs secondary data synthesis. Data were compiled from five primary categories:

Hydrological Records (1996-2020): Flow data from the Bangladesh Water Development Board, Joint Rivers Commission, and World Bank hydrological assessments documenting Ganges discharge at Farakka Barrage. These records provide quantitative evidence of post-barrage flow reduction and seasonal variability.

Forest Cover Mapping (2000-2020): Bangladesh Forest Department biodiversity inventories (field surveys, forest inventory plots) were integrated to establish baseline forest composition and quantify area losses over 20 years.

Fisheries Statistics (2003-2016): Catch records from Mongla fish market, maintained by local fishing communities and documented in academic studies, provide species richness data and market supply trends.

Climate Impact Projections (27 scenarios to 2050): The foundational study by Dasgupta et al. (2017) combined multiple general circulation models (GCMs) with different greenhouse gas emission pathways (AR4 scenarios: A1B, A2, B1) and coastal subsidence assumptions (2, 5, 9 mm/year), generating 27 discrete scenarios for salinity and species distribution projections to 2050.

Ecosystem Service Valuations: Multiple valuation studies employing direct valuation methods (timber market prices), contingent valuation, and benefit transfer approaches to estimate the monetary value of provisioning and regulating ecosystem services.

3.2 Data Quality Assessment and Limitations

All sources employed in this study were vetted for credibility: peer-reviewed publications, official government agency datasets, and international development organization reports (World Bank, UNDP, FAO). Data age was assessed; older studies (e.g., 1991 baseline for forest cover loss) were retained when necessary for establishing historical trends, while recent studies (2021-2025) were prioritized for contemporary conditions.

Methodological transparency was evaluated for each data source. However, limitations merit acknowledgment:

(1) Fisheries data from Mongla market represent only one measurement location and may not reflect system-wide trends.

(2) Climate projections contain inherent uncertainty regarding future greenhouse gas emissions and local climate response.

(3) Ecosystem service valuations employ varying methodologies, limiting direct comparison.

(4) Community-level livelihood data were often collected at different temporal periods, complicating temporal alignment.

4. Results

4.1 Forest Cover Loss and Species Composition Shifts

Secondary data analysis has shown that mangrove forest cover loss is considerable in the Bangladesh Sundarbans. From 1991 to 2019, forest cover loss amounted to 442 km², equivalent to 4.4% of the total reserved forest area. The area of forest loss is not uniform. Forest loss is mainly reported in Sundri-dominated regions where the intrusion of salinity has gone the farthest. Critically, forest degradation is accompanied by detrimental changes in co-occurring species composition. Climate model projections for 27 different scenarios have indicated that, by 2050, there will be a reduction of *Heritiera fomes* (Sundri) forest cover by 12.1-24.2 percent over different geographic zones and subsidence rates. On the other hand, *Excoecaria agallocha* (Gewa) forest cover will increase by 19.8-23.0 percent between the same period, implying a forced substitution of more valuable forest species with those of lower value. This shift reflects the increasing salinity penetration into zones historically characterized as oligohaline (low-salinity) freshwater or mesohaline (moderate-salinity) environments where Sundri thrives (0-8 dS/m). As salinity exceeds these tolerance thresholds, Sundri mortality increases and salt-tolerant Gewa expands.

4.2 Fisheries Decline and Economic Consequences

At the market of Mongla, the richness of fish was reduced from 172 recorded fish species in 2003 to 79 recorded fish species in 2016. As a result, there were 93 fewer fish species recorded, an 54% decline over the 13 years. At the same time that there was a decline in the recorded fish species, there was an increase in measured salinity levels of estuarine zones of the river system and a decline in the dry-season freshwater inflow of the Ganges as registered by hydrological data. While the fish data accessed from the market of Mongla is site-specific, the marketplace data are an indicator of the basin-scale representation of fish populations. The average income generated per household from fishing in the Sundarbans region was estimated to be worth $390 per annum, which is amongst the highest income-generating activities from the forests and accounts for 40 to 75 percent of the income generated in the region for fishing communities. The decline in the marketable fish species from the region by 54 percent indicates the income loss to fishing communities in the region, particularly for the poorer segments of the population.

4.3 Hydrological Failure and Transboundary Water Governance

Analysis of the Ganges Water-Sharing Treaty of 1996 shows consistent non-delivery of the apportioned water during critical dry-season periods. During 1997-2016, 19 years of treaty implementation, Bangladesh received the guaranteed 35,000 cusecs allocation during the critical period from March 11 to May 10 in only 6 out of 20 dry seasons-a non-compliance rate of 65%. This was despite formal treaty

provisions and reflects the design inadequacy of the treaty within the changed hydroclimatic conditions, caused by reduced glacier melt and increased irrigation in the upstream subregion, and a lack of environmental flow provisions. Concurrently, the Gorai River, a main Ganges distributary that has been supplying freshwater to the southwestern coast, was subject to extreme siltation post-barrage. Sediment deposition and channel morphology change are multifactorial, involving supply and flow regime variables; however, hydrological studies demonstrate that post-barrage reduced discharge velocity and flow momentum reduced Gorai's carrying capacity and resulted in progressive siltation, further reducing freshwater penetration southward.

4.4 Salinity Intrusion and Ecosystem Threshold Exceedance

Reduced freshwater input, along with sea-level rise due to climate change and local subsidence, enhances saltwater intrusion into the Sundarbans. *Heritiera fomes* manifests optimal growth in oligohaline conditions (salinity 0-8 dS/m or 0-5 ppt). However, secondary data of salinity measurements showed that mesohaline conditions (8-15 dS/m) characterize 40% of the former Sundri-dominated reserve, already beyond the physiological tolerance threshold for continued productivity of the species. In the polyhaline zones (>15 dS/m), the survival rate of Sundri drastically declines, despite being the iconic species of the Sundarbans. This physiological constraint is expressed in forest demographic change: Sundri regeneration failure in high-salinity zones, reduced growth rates in transitional zones, and gradual replacement by salt-tolerant species. Secondary data from forest inventory plots document an increase in basal area of Gewa, coupled with a decline in basal area of Sundri in historically Sundri-dominated zones.

4.5 Livelihood Vulnerability and Nutritional Impacts

The linkages between hydrological failure, ecosystem change, and livelihoods degradation are measurable by using various indicators. For instance, the poverty levels of Sundarbans-adjacent upazilas exceed 40% in some areas. Low livelihood diversification opportunities exist beyond forest-dependent activities. The reduction of marketable fish species by 54% is equivalent to the reduction of income for fishing-dependent households. More people are pushed into poverty. Nutritional indicators show the acute human health impacts. In Sundarbans-dependent populations, the prevalence of malnutrition far exceeds emergency thresholds set by the World Health Organization. In village populations from Sundarbans-dependent communities studied, severe acute malnutrition prevalence was found to be greater than 90% among children. This is because of reduced fish availability (reduced source of proteins and micronutrients) and the economic inability to source other foodstuffs.

5. Discussion

5.1 Systemic Failure of Transboundary Water Governance

The results synthesized in the secondary data synthesis indicate that the conclusion is inclined towards an unexpected outcome, as the cause of the failure of ecosystem services in the Bangladesh Sundarbans is not climate change but the failure of the transboundary water management regime to incorporate the effects of climate variability. Although it is undeniable that climate change is altering the salinity tolerance limits of mangrove forest species and the risks of increasing coastal flooding due to sea-level rise, it is diminished by the reduced flow due to water diversion. The Ganges Water-Sharing Treaty, while being a landmark in nature as the first water-sharing treaty in the subcontinent, was arrived at from a hydrologic perspective that presumed hydrologic flows to be stable. The treaty distribution method, derived from 40-year historical averages between 1949 and 1988, presumes that future flows will behave in the same way as past flows. Yet this presumption has been negated by climate change impacting precipitation as well as consumptive use from upstream development. The 65% failure rate to deliver one's share to Bangladesh in the dry season has been due to institutional incapacity, not non-compliance. This failure of governance has significant consequences, in part, for the Sundarbans ecosystem because, here, fresh water input is not just one of many variables, but the very key factor controlling salinity levels in an environment where sea levels and land subsidence continually press against seawater. In other words, without adequate fresh water flow from upstream, the delta would become increasingly brackish: fresh water, salt water, and then fresh water-dominated, salt water-dominated ecosystems, and so on.

5.2 Ecological Tipping Points and Economic Implications

The changes in species composition revealed by modeling changes to the climate are not slow changes, but rather possible abrupt changes in an ecological system. With increases in salinity beyond certain limits of plant species tolerance levels, there may be increased stress levels (ionic toxicity, osmotic water stress, reduced rate of photosynthesis) for individual trees, eventually leading to death and subsequent replacement by salt-tolerant plant species. Since plant reproduction for *Heritiera fomes* (Sundri) occurs by establishing their seedlings in low-salinity microhabitats, gradual increases in salinity may eventually eliminate plant recruitment even when trees individually manage to survive. The economic implications, however, are tremendous as a decrease in Sundri stock value by 45% is expected to be realized by 2100. A more concerning issue is that, as a result of changes to an increasing Gewa population or that of any salt-resistant species, an increase in ecosystem service productivity is not achieved. Gewa offers some timber and non-timber products, yet it does not replace Sundri in a significant manner in terms of monetary, carbon, or socio-cultural values linked to Sundarbans, as Sundri has been considered a local marker for Sundarbans.

5.3 Livelihood Vulnerability and Climate Justice

The proportionate livelihood consequences identified from secondary data, such as the 54% reduction in marketable fish species, income reduction, and increased rates of malnutrition exceeding the WHO threshold, necessarily create essential questions regarding climate justice and international obligation. Bangladesh contributes just less than 0.6 percent to overall worldwide greenhouse gases but sustains a disproportionate climate regime as a least-developed country exposed to transboundary hydrological variability and climate change. However, the dimension of governance failure adds a second dimension to the issue of equity. This is because the vulnerability created by climate change in Bangladesh is not just a function of the effects of climate change, but is aggravated by India's unilaterally directed water diversion at the Farakka Barrage. While the treaty was a step forward in terms of cooperation between the two countries, its design failure has ensured a disproportionate impact of scarcity in the region as a result of climate change on the downstream country, Bangladesh.

5.4 Policy Implications and Adaptation Pathways

The evidence suggests that adaptation strategies focused solely on ecosystem-level conservation (mangrove plantation, community-based co-management) are insufficient without addressing underlying governance constraints. Mangrove plantations provide valuable coastal stabilization and carbon sequestration, but cannot substitute for ecosystem service provision if freshwater inflow remains inadequate to prevent progressive salinization. Similarly, community-based co-management initiatives, while important for local resource governance, operate within a larger hydrological context that they cannot control.

Effective adaptation thus requires institutional innovation at the transboundary scale. Potential pathways include:

1. Treaty renewal incorporating environmental flow requirements based on species salinity tolerance thresholds.
2. Multilateral basin cooperation involving Nepal, Bhutan, and China to address upstream uses affecting the Ganges flow.
3. Climate-informed water allocation mechanisms adjusting for projected decreases in dry-season flow.
4. Joint ecosystem monitoring systems providing shared data on salinity, freshwater flow, and species status.

6. Conclusion

The Bangladesh Sundarbans faces an acute ecological crisis that is at the heart of the interaction between climate change, hydrological governance failure, and ecosystem service degradation. Synthesis of secondary data showed that while climate variability indeed changes the species' salinity tolerance range, the main proximate driver of ecosystem changes is the reduced freshwater inflow from the Ganges due to upstream water diversion and not well-managed through the 1996 Ganges Water-Sharing Treaty. The loss of 442 km² of forest cover since 1991, along with a 54% decline in marketable fish species between 2003 and 2016, signals ecosystem service collapse that cascades directly into livelihood degradation and malnutrition in forest-dependent communities. The projected replacement of high-value *Heritiera fomes* with lower-value *Excoecaria agallocha* represents not merely species turnover but economic loss and reduced provision of critical ecosystem services. The evidence indicates that institutional reform of transboundary water governance, specifically, the incorporation of environmental flow requirements into renewed water-sharing arrangements and expansion of basin cooperation beyond bilateral India-Bangladesh mechanisms, is a necessary condition (though not sufficient) for the Sundarbans ecosystem resilience. Without such reform, domestic conservation efforts will fail against the hydrological constraints imposed by inadequate freshwater inflow. Urgent policy action is needed to align transboundary water governance with climate adaptation imperatives and ecosystem conservation objectives.

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