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ARTICLE

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ASSESSING CLIMATE-INDUCED VULNERABILITY OF SMALL-SCALE FISHERIES IN THE LOWER GANGETIC DELTA, WEST BENGAL

LITON PAUL, SHREYA BHATTACHARYA, BASANTA KUMAR DAS*, YATEESH DC, ARUN PANDIT AND APARNA ROY

This study explores the vulnerability of fishing communities in four estuarine villages; Fraserganj, Kakdwip, Diamond Harbour, and Ganga Sagar, located in the South 24 Parganas district of West Bengal, India, within the Sundarbans mangrove region. Primary data were collected from 450 local fishers through interviews and focus group discussions in purposively selected villages between 2024 and 2025. A Livelihood Vulnerability Index (LVI) was calculated to assess climate-related impacts. The results show high environmental stress, with a Cyclone Exposure Index of 0.78 and a Water Salinity Impact score of 0.75, highlighting frequent storms and rising salinity. These risks emphasize the need for adaptive strategies and institutional support to strengthen community resilience.

Introduction

The coastal zone of the Gangetic delta, encompassing parts of West Bengal, India, represents one of the most ecologically diverse and socio-economically critical landscapes globally[1]. Situated within the estuarine Ganga basin, this region sustains the livelihoods of millions of small-scale fishing households whose socio-economic well-being is intricately linked to the dynamics of riverine and coastal ecosystems. These communities not only help provide food and nutrition for the local people but also play an important role in the culture and economy of the delta. However, this delicate ecological system is increasingly imperilled by the multifaceted impacts of climate change, including sea-level rise, intensified cyclonic activity, saline water intrusion, and altered precipitation patterns[2,3]. Small-scale fisheries (SSFs) in the Gangetic delta constitute an important of rural economies, playing a critical role in poverty reduction, employment generation, and nutritional sustenance, particularly among marginalized groups. In Bangladesh, more than 90% of fishers are engaged in artisanal or small-scale operations, a pattern mirrored in adjacent Indian coastal districts such as South and North 24 Parganas[4,5]. The Sundarbans, a UNESCO World Heritage Site and home to one of the world's largest mangrove ecosystems, exemplifies the intricate interdependence between ecological integrity and subsistence-based fishing practices[6,7]. Despite their importance, SSFs remain inherently vulnerable due to their reliance on natural resources, limited access to technology, inadequate infrastructure, and constrained adaptive capacities[8,9].

Climate-induced stressors are increasingly pronounced across the Gangetic delta. Sea-level rise and salinity intrusion are encroaching upon previously freshwater-dominated zones, altering fish species composition and degrading critical breeding habitats. Roy et al. (2023)[10] report that salinity has intruded nearly 100 kilometers inland, rendering numerous water bodies unsuitable for traditional freshwater aquaculture. Moreover, shifts in monsoon, irregular rainfall, and the intensification of cyclonic events—such as Cyclone Aila (2009), Amphan

ICAR-Central Inland Fisheries Research Institute, Barrackpore, Kolkata, West Bengal
* Corresponding author: basantakumard@gmail.com

(2020), and Yaas (2021), have inflicted substantial damage on fishing assets, including boats, nets, and storage infrastructure, often resulting in chronic indebtedness and forced migration[6,11]. The Intergovernmental Panel on Climate Change (IPCC) Sixth Assessment Report (2022)[12] identifies the Bay of Bengal as a climate hotspot, emphasizing its exposure to compound hazards arising from the convergence of oceanic, atmospheric, and fluvial extremes. These overlapping stressors contribute to both ecological degradation and heightened livelihood insecurity. Despite increased recognition of these challenges, existing vulnerability assessments in the region often remain fragmented, predominantly emphasizing environmental parameters while overlooking socio-economic and institutional dimensions[13]. For instance, Mandal et al. (2025)[1] developed a spatial vulnerability index for deltaic agricultural communities that incorporate environmental, socio-economic, and governance indicators. Nonetheless, such frameworks are rarely extended to fisheries-specific contexts. Given the socio-ecological importance of SSFs and their heightened exposure to climate risks, there is an urgent need for comprehensive vulnerability assessment frameworks. These frameworks must move beyond static indicators of exposure to encompass dimensions of adaptive capacity, institutional resilience, and livelihood diversification.

Accordingly, this paper synthesizes recent field-based insights to evaluate the vulnerability of small-scale fisheries in the Gangetic delta in the context of a changing climate. It aims to identify key drivers of vulnerability, analyze local coping strategies, and propose strategies to strengthen the resilience of coastal fishing communities.

Materials and Methods

This study was conducted between April, 2023 and March, 2024 to investigate the vulnerabilities of artisanal small-scale fisheries in the estuarine region of the Gangetic delta. Data collection was carried out in selected fishing villages, namely Fraserganj, Kakdwip, Diamond Harbour, and Gangasagar, located in the South 24 Parganas district of West Bengal, India (Fig. 1). These sites were purposively selected due to their ecological significance and dependence on estuarine fisheries. Primary data encompassed a wide range of variables, including livelihood patterns, exposure to environmental stressors, infrastructure availability, and socio-economic status of the fisher households. In addition, fishers' perceptions were systematically recorded to identify key threats and challenges facing the sector. This perception-based methodology allowed for the triangulation of experiential knowledge with empirical observations. Semi-structured personal interviews with 450 local fishers and focus group discussions FGDs, these two group-based and individual techniques from the participatory rural appraisal (PRA), were used for data collection. The data were collected across all four seasons throughout the year. Two FGDs conducted in each of the four study areas. Fishers with 10 to 15 years of experience were selected to participate in the FGDs. Each FGD lasted 45 to 50 minutes and included 5 to 8 participants. A semi-structured interview schedule was used to gather both qualitative and quantitative information related to socio-economic conditions, fishing practices, and perceived vulnerabilities. The questions asked during the SSIs examined the following themes, insights into fishing activities, species composition, socio-economic conditions, their learning from past experiences, how this knowledge had helped them cope and adapt, and factors that influenced them to translate their knowledge into action. The survey design adopted a community-participatory approach to ensure that local knowledge and lived experiences were integrated into the assessment of current challenges and potential adaptation strategies.

Secondary data were sourced from institutional repositories from ICAR-CIFRI annual reports[14] and included hydrological profiles of local river systems as well as climatic data such as temperature and rainfall trends (IMD)[15]. These environmental variables were used to contextualize the primary data within broader climate-induced changes in the region.

Vulnerability is the extent to which geophysical, biological, and socioeconomic systems are vulnerable to and unable to adapt to the negative effects of climate change, particularly climate variability and extremes, according to the IPCC's Fourth Assessment Report[21]. Vulnerability is determined by exposure, sensitivity, and adaptation capability, according to the IPCC's Annual Report[22,23]. The three factors determine overall vulnerability (V) of a particular ecosystem to climate change.

$$V = f(E + S - AC)$$

where E is the exposure, S is the Sensitivity, and the AC is the adaptive capacity.

The Livelihood Vulnerability Index (LVI) was employed to assess the vulnerability of four estuarine villages. The LVI framework was based on the IPCC model, utilizing a set of standardized indicators[16]. Key indicators included Cyclone Exposure Index, Income Diversification Score, Access to Credit and Subsidies, Awareness of Climate

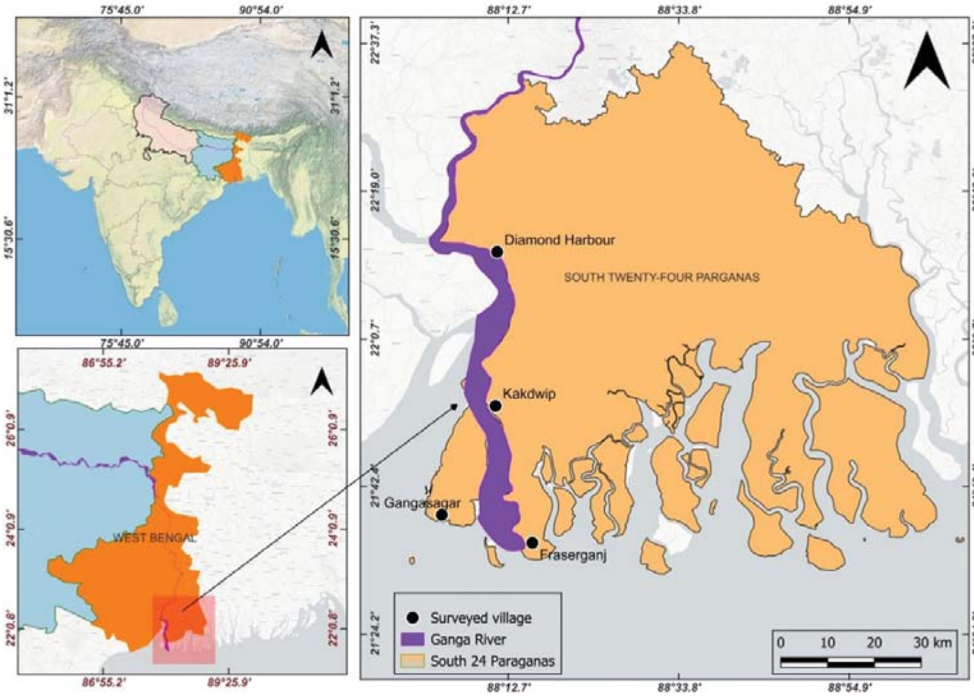

Fig. 1. Study area map of estuarine Gangetic zone

Information, Infrastructure Resilience, and Water Salinity Impact on Fishing. Each indicator was normalized using min-max scaling, grouped under relevant components, and averaged to calculate component scores. The overall LVI was computed as a weighted average of these components. The overall LVI was computed as a weighted average of these components using the following equation:

$$LVI = \sum_{n}^{i} Wi.Si$$

Where: LVI = Livelihood Vulnerability Index; Wi= Weight assigned to the component; Si = Standardized score of the i^{th} component; n = Total number of components

The findings informed the identification of locally embedded adaptation strategies and laid the groundwork for the development of a resilience-oriented framework for the sector.

Results and Discussion

The present findings highlight the socio-economic vulnerabilities and environmental challenges faced by small-scale fishers in the Sundarbans region. The majorities of the respondents were fishers (91%) and fish traders (9%). The age distribution showed a predominance of middle-aged fishers (45–55 years), reflecting an aging workforce and possibly a decline in youth participation in the sector (Fig. 2). Educational attainment among the respondents was low, with 80% not completing secondary education, which may limit access to alternative livelihood options and hinder adaptive capacity as also stated by (Allison & Horemans, 2006)[17]. Most of the respondents were dependent on fisheries and reported that the estuarine depth reduction in all the river areas in last 15 years. The average depth reduction during last 15 years in Fraserganj (mean= 4.52m), Kakdwip (mean=3.62m), Diamond Harbour (mean= 5.2m) and Ganga Sagar (mean= 2.53m). Several reasons are responsible for depth reduction, such as river connections being closed, siltation increasing, tidal flow alteration and climate change impacts. Overall, 98.5% of the fishers agreed on the change in fish reproduction in the surveyed area. This may change due to habitat loss, siltation, and closure of the link channel. The respondent opinion about the catch per unit effort (CPUE) of all fishes drastically decreased 15 years before

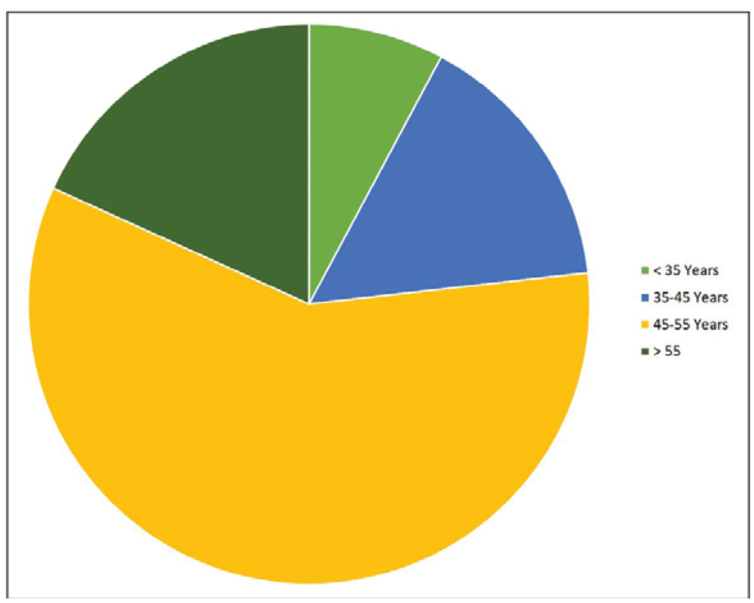

Fig. 2. Age distribution of the surveyed fishers in lower Gangetic zone

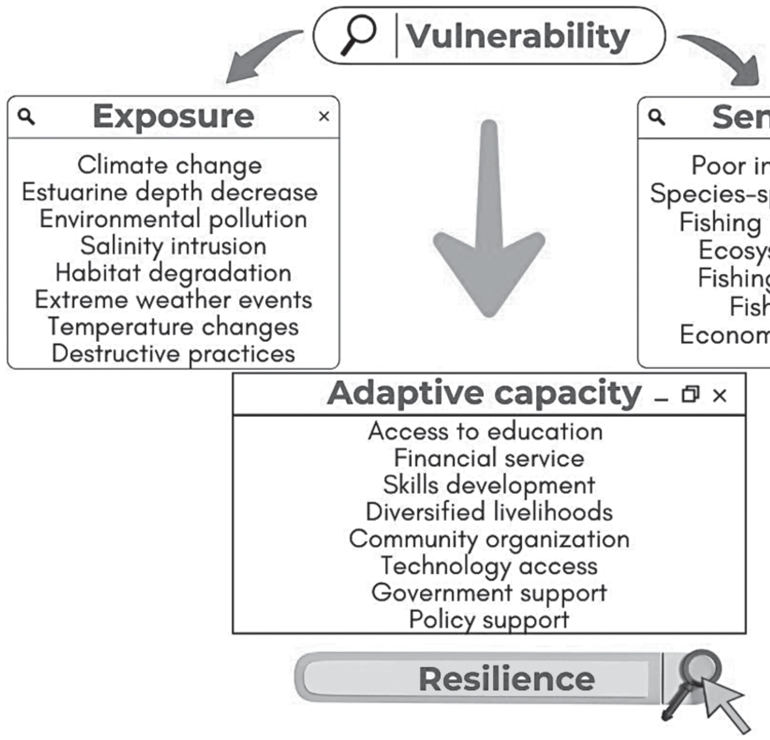

Fig. 3. Coastal Vulnerability Index Assessment Framework

80-900 kg/boat/day but only 24-200 kg/boat/day. Overall, it is observed that the number of species richness decreased by 14.33 % due to over exploitation. Fish such as *Setipinna taty, Trichiurus savala, Harpadon nehereus, Parapenaeopsis stylifera, Parapenaeopsis sculpilitis, Johinus sp, Coilia dussumieri, Parapenaeopsis hardwickii, Sardinella longiceps, Otolithoides pama*, small prawn and crabs were observed in regular catch. The majority of respondents observed that *Setipinna taty* are climate-resilient species.

Previous to the cyclonic events, at least 68.39% of the local community were dependent on the fisheries. However, this dependency on fishery is reduced. This area is important for fishing, but irregular weather patterns have disrupted traditional fishing times. With few alternative ways to earn a living, many fishers have been forced to migrate outside West Bengal in search of other jobs. As per the study, the migration of male workers leaving behind their families alone increased by 50.88% from the area.

Vulnerability in coastal small-scale fisheries is shaped by three major dimensions; exposure is increased cyclonic activity (e.g., Aila, Amphan), storm surges, hydrological changes, pollution and estuarine depth decrease. Sensitivities reflect the degree of dependence on the fishery, poor infrastructure, species dependency. Adaptive Capacity in terms of limited access to institutional support, credit, technology, or diversifies livelihood which are very similar with the report of previous researchers[18,19]. The indicators of exposure, sensitivity, and adaptive capacity, along with their relationship to vulnerability, are described in Fig. 3. Table 1, presents a synthesized LVI derived from field data and regional case studies. Each indicator is normalized on a 0–1 scale, where 0 indicates no vulnerability and 1 indicates maximum vulnerability. The cyclonic exposure and salinity impact indicates a high level of exposure, suggesting that the community is highly vulnerable to cyclonic events. This has direct implications for safety, livelihood disruption, and infrastructure damage.

Vulnerability arises from multiple factors such as

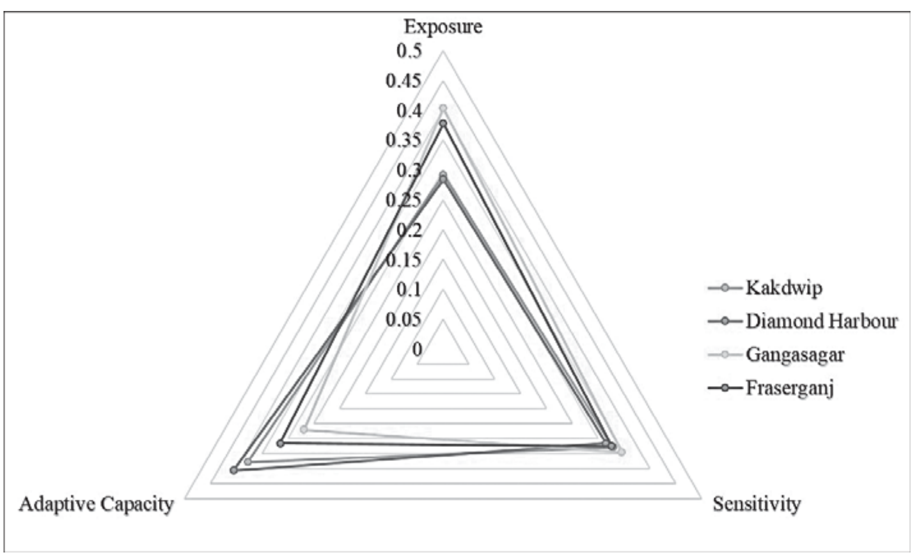

Fig. 4. Vulnerability index of each study area (0 indicate low contributing factor; 0.5 indicate high contributing factor)

Table 1. Livelihood Vulnerability Index of Gangetic Coastal Fishing Villages of West Bengal

Indicator	Index	Vulnerability	Impact Type
Cyclone Exposure Index	0.78	High	Ecological risk
Income Diversification Score	0.32	Low	Low resilience
Access to Credit & Subsidies	0.28	Low	Institutional Gap
Awareness of Climate Information	0.45	Medium	Medium Adaptability
Infrastructure Resilience	0.40	Medium	Physical Vulnerability
Water Salinity Impact on Fishing	0.75	High	Environmental risk

Table 2. Main drivers of vulnerabilities of small-scale fisheries

Types of drivers	Drivers of vulnerability	Description	Impact
Ecological	Sedimentation	Water depth reduction Thick layer of bottom sediment accumulation of bio-waste	High BOD Bio gas formation Reduce production Flood occurrence
	Reduce Inflow	Modification of natural water channels	Biodiversity loss Water depth reduction
	Climate change	Flood Drought High temperature Late monsoon	Breeding problems Loss of fish stock Water quality changes
	Eutrophication	Aquatic weed and algal proliferation	DO decrease Bio-waste creation Less access to fishing grounds Human skin disease
Anthropogenic	Pollution	Plastic Agricultural waste/pesticide Industrial waste	Water quality degradation Drinking water degradation Bio-diversity decline
	Habitat destruction	Changes in land use pattern	Loss of breeding ground Reduce production
	Marginalization	Prioritising other activities than SSF	Governance issues Conflict over resources Management issues
Social and economical	High dependence on fisheries	Fishing is the main source of nutrition and employment	Over-exploitation Loss of bio-diversity Low income
	Lack of fund	No proper funding support	Obstructions on modern practices Lack of infrastructure development
	Increase seasonal fishers	Migrant fishers for a particular season	Lower income Increase in fishing pressure
	Property rights	Fishers remain underrepresented	Conflict over the natural asset
Technological	Policy and regulations	No proper breeding ground conservation rules	Management issues
	Poor infrastructure	Poor access to technology, less transfer of traditional knowledge to the upcoming generation.	Less production Decreasing biodiversity

ecological degradation, socio-economic disparities, and climate change[20]. The communities dependent on small-scale fisheries for their livelihood are highly vulnerable to these stressors. A decline in fish catches, marginalization, and environmental changes are the most common drivers of vulnerability (Table 2). The table organizes these drivers according to their specific causes, provides a description, and notes their impacts on both the environment and the people dependent on these systems. The cumulative impact of these drivers is ecosystem degradation, loss of livelihood, social conflict, and reduced resilience of communities that rely on aquatic resources.

According to the IPCC framework[24], natural disasters and climate variability are major contributors to exposure, while factors such as health, food security, and access to water are critical in determining sensitivity. Adaptive capacity is assessed through indicators such as the socio-demographic profile, livelihood strategies, and strength of social networks. These components collectively inform the vulnerability index, which has been calculated for each study area and is presented in Fig. 4. The analysis reveals that Gangasagar exhibits highest climate exposure whereas and relatively low adaptive capacity. In contrast, Diamond Harbour shows a significantly lower sensitivity and exposure, reflecting stronger resilience and more robust adaptive mechanisms. Similar patterns have been observed in other coastal vulnerability assessments in coastal Sundarbans[25,26], where adaptive capacity played a crucial role in mitigating climate-related vulnerabilities.

Conclusion

This study highlights the increasing vulnerability of small-scale fisheries in the lower Gangetic delta, driven by ecological degradation, hydrological changes, and climate variability. A sharp decline in CPUE and river depth, points to a declining fishery resource base. The majority of fishers are elderly, poorly educated, and highly dependent on fisheries, with limited adaptive capacity and access to institutional support. The Livelihood Vulnerability Index reveals high exposure to cyclones, low income diversification, and significant environmental risks such as salinity intrusion. Migration and reduced fishing opportunities further reflect the socioeconomic strain on these communities. To enhance resilience, there is an urgent need for integrated strategies; livelihood diversification, improved institutional access, effective policy implementation, capacity building programs, and the scientific utilization of underused impounded water bodies like backward ponds, to reduce over-dependence on government support and marine capture fisheries.

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