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A Qualitative Assessment of Natural and Anthropogenic Drivers of Risk to Sustainable Livelihoods in the Indian Sundarban

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Abstract: In the Indian Sundarban, multiple attributes and interactions of natural hazards, exposure, and vulnerability pose severe threats to lives and livelihoods. Understanding the cause-and-effect relationships contributing to the risk of loss of sustainable livelihoods has become imperative but has not yet been holistically explored in a single study that provides a broader picture of all possible complex interactions. This study used the impact chain tool to holistically understand the risk that manifests as a result of interactions of hazards, exposure, and vulnerability. The secondary literature and authors' observations helped us structure the first draft of the impact chain, which was further developed and validated through fourteen gender-disaggregated interviews with key informants and delta dwellers. This validation process identified the complex interconnections contributing to risk as experienced by experts and delta dwellers, which is seldom reflected through exclusively quantitative data. A quantitative analysis of the qualitative data strongly indicated that tropical cyclones, rainfall variability, and storms are the dominant hazards that affect social–ecological vulnerability manifested through mangrove degradation, land loss due to erosion, and embankment breaching. Social vulnerability is caused by processes and factors that are either directly or indirectly influenced by natural hazards and social–ecological factors. Processes such as increasing seasonal male migration, uncertain agricultural income, and a lack of hazard-resistant housing exacerbates social vulnerability. Embankment breaching, the salinization of land and water, land loss due to erosion, mangrove degradation, land conversion, and groundwater abstraction were identified as the fundamental threats that can lead to a loss of sustainable livelihoods of the people if left unaddressed.

Keywords: natural hazard; exposure; vulnerability; risk; impact chain; Indian Sundarban

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1. Introduction

The confluence of the Ganga, Brahmaputra, and Meghna (GBM) rivers gives rise to the largest delta in the world and a unique geomorphic setting that is shared by India and Bangladesh [1]. The southern part of the delta shelters the largest contiguous mangrove forest on Earth (the Sundarban), which is also the only mangrove tiger habitat in the world [2]. Experiencing a typical hot and humid tropical climate all year round, the Sundarban mangrove forest hosts an array of floral and faunal biodiversity [3]. The felling (or deforestation) of dense and pristine mangrove trees began during the colonial era when the land was leased out to potential landlords to collect revenues through timber extraction [4,5]. Human encroachment has always accompanied the forest retreat in the Sundarban [6], and it is currently one of the most densely human-populated regions of Southeast Asia. The coastal human population has increased exponentially throughout the world [7], and the Indian Sundarban Biosphere Reserve (henceforth Indian Sundarban) is not an exception; it has had a recent decadal growth rate of >15% and shelters close to 1100 people per square kilometer [8]. As per the latest available Census data, the Indian Sundarban hosts a population of around 4.4 million people [8]. A large section of this population is marginalized and impoverished, and they directly or indirectly depend on the mangrove forest-derived products and services to meet their livelihoods [9–11].

The array of provisioning ecosystem services provided by the Sundarban mangrove stands includes fish resources [12], edible crustaceans [13], honey [14], timber [15], traditional medicine [16], and many more. The environmental aesthetics of the landscape composed of the Sundarban mangroves and the intricate mesh of estuaries attract tourism in this region, which comprises cultural ecosystem services [17]. This unique ecoregion also furnishes several regulating ecosystem services, which helps to absorb the effects of cyclones originating in the Bay of Bengal [18]. Recurrent tropical cyclones and coastal flooding in the Indian Sundarban have continually wreaked havoc [19,20]. Between November 2019 and May 2021, the region experienced three tropical cyclones followed by coastal flooding: Cyclone Bulbul (November 2019), Super Cyclone Amphan (May 2020), and Cyclone Yaas (May 2021). The Sundarban mangrove stands act as the frontline shield to these physical forcing events [21]. This habitat locks substantial blue carbon in several mangrove compartments [22]. The water bodies adjoining the mangrove stands and the sediment column act as filters to a variety of environmental pollutants [23,24] and furnish microhabitats for a range of microbial organisms [25,26]. Despite such immeasurable contributions to humans and biodiversity, the Sundarban ecosystem is under severe threat from natural and anthropogenic factors [27]. Owing to the prolonged loss of biodiversity and massive degradation of the overall environment, this region earned the tag of biodiversity hotspot two decades ago [28,29].

Climate change, natural hazards, and indiscriminate anthropogenic pressures have taken a heavy toll on the overall health of this ecosystem. Regional sea-level rise and coastal erosion have made the mangroves and the human settlements equally vulnerable [30,31]. Saline water intrusion due to these climatic hazard events that occur via embankment failure or overtopping deteriorates the soil fertility of the agricultural fields [32,33]. It directly impacts the livelihood of millions. The freshwater-scarcity-induced salinization of estuaries and mangrove habitats has lately emerged as a point of severe concern [34]. Besides these natural factors, unsustainable forest clearing and the spread of tourism and residential infrastructure have increased the pressure on resources in the last few decades [35]. The land use and land cover of the Indian Sundarban has witnessed drastic changes in the recent past [36]. Plenty of agricultural plots and aquaculture farms grew at the cost of severing mangrove stands [4,37]. Owing to such unplanned development and unsustainable mangrove resource management, the environment of the Indian Sundarban underwent rapid degradation [38]. Signatures of marine pollution such as coastal eutrophication, heavy metal contamination, persistent organic pollutants, and many other contaminants are found in every corner of this crucial ecosystem [39–41].

Exposure to extreme weather events and sensitivity to socioeconomic factors increase the vulnerability of the region [42]. With a dominantly rural population of 94.3% [8], 43.5% of the households live below the poverty line [43] and only 12.4% of households experience no shortage of food [44,45]. The lack of secure employment options in the Indian Sundarban acts as a push factor for migration from the area, and environmental factors are perceived by people to lead to more insecure livelihoods [46]. Judging by the interaction of these multiple physical, ecological, and social changes in this critical ecoregion, the scientific community as well as the delta communities predict a complete disruption of the social–ecological equilibrium of this region in the absence of positive human intervention and optimized management strategies.

With this background, the present study aims to develop a holistic understanding of the risk to sustainable livelihoods in the Indian Sundarban. The existing literature focuses on several issues faced in the Indian Sundarban, but there are limited examples showcasing the interlinkages between those issues and the processes contributing to the risk of loss of sustainable livelihoods. The IPCC and others conceptualize risk as a function of hazard, exposure, and vulnerability [47]. Thus, in this research, (i) natural hazards, (ii) ecological susceptibility, (iii) exposure, and (iv) coping capacities and adaptive strategies that either exacerbate the vulnerability or enhance the resilience of the social–ecological system (SES) of the Indian Sundarban are explored as interacting processes that lead to risks to sustainable livelihoods. This study used the impact chain analysis tool to help visualize the chain of processes that act as drivers of risk in the Indian Sundarban [48]. This tool was developed to allow us to consider ecosystem-based adaptation (or EbA) when conducting a risk assessment, with the latter being based on IPCC's formulation of risk. Therefore, central to the framework associated with the impact chain is the concept of social–ecological systems, which highlights the mutual interaction between social and ecological subsystems that are mediated by ecosystem services [48]; in our context, these include (i) regulating ecosystem services, which allows the impacts of natural hazards to be reduced, and (ii) provisioning and cultural ecosystem services, which allow the vulnerability of a system to be reduced [49–51]. This constitutes the theoretical and conceptual underpinnings of our research.

The present study explored the following research questions: (i) Which hazards increase the risk of loss of sustainable livelihoods in the region? (ii) How are exposure and vulnerability contributing to this risk? (iii) Which direct and indirect factors contribute to this increased vulnerability, exposure, and ultimately risk? Using these guiding questions and the key steps mentioned in Hagenlocher et. al. [48], we identified the hazards, hazard chains, and intermediate impacts and determined the social–ecological vulnerability through the interaction between the ecosystem susceptibility, the social–ecological susceptibility, the social susceptibility, the lack of coping and adaptive capacities, and exposure (Table 1). Natural, ecological, and social processes, which contribute to all these aforementioned factors as observed from the secondary literature, and ethnographic observations helped us develop the impact chain to determine the risk to sustainable livelihoods in the Indian Sundarban, which was then validated by experts and community members alike.

Table 1. Standard customary definitions of risk components considered in the present study.

Risk Component and Determining Factors	Definition
Risk	"The potential for consequences where something of value is at stake and where the outcome is uncertain (. . .). Risk results from the interaction of vulnerability, exposure, and hazard (. . .)." [52]
Hazard	"The potential occurrence of a natural or human-induced physical event or trend or physical impact that may cause loss of life, injury, or other health impacts, as well as damage and loss to property, infrastructure, livelihoods, service provision, ecosystems, and environmental resources. In the [IPCC] report, the term hazard usually refers to climate-related physical events or trends or their physical impacts." [52]
Exposure	"The presence of people, livelihoods, species or ecosystems, environmental functions, services, and resources, infrastructure, or economic, social, or cultural assets in places and settings that could be adversely affected." [52]
Vulnerability	"The propensity or predisposition to be adversely affected. Vulnerability encompasses a variety of concepts and elements including sensitivity or susceptibility to harm and lack of capacity to cope and adapt." [52]
Sensitivity or Susceptibility	"Sensitivity is the degree to which a system is affected, either adversely or beneficially, by climate-related stimuli. The effect may be direct (e.g., a change in crop yield in response to a change in the mean, range, or variability of temperature) or indirect (e.g., damages caused by an increase in the frequency of coastal flooding due to sea-level rise)." [52]
Adaptive Capacity	"The ability of systems, institutions, humans, and other organisms to adjust to potential damage, to take advantage of opportunities, or to respond to consequences." [52]

Table 1. *Cont.*

Risk Component and Determining Factors	Definition
Coping Capacity	"The ability of people, institutions, organizations, and systems, using available skills, values, beliefs, resources, and opportunities, to address, manage, and overcome adverse conditions in the short to medium term." [52]
Hazard chains	" ... hazard chain is essentially a phenomenon whereby one hazard follows another in consequence." [53]
Intermediate Impacts	" ... are not a risk component by themselves, but merely an auxiliary tool to fully grasp the cause-effect chain leading to the risk. By definition, they are a function of both hazard and vulnerability factors." [48]

2. Materials and Methods

2.1. Study Area

The Sundarban mangrove ecosystem acts as an abode to millions of humans and flora and fauna alike. Protecting the Royal Bengal Tiger, which is the unique keystone species of the region, was set as a priority by the Indian Government. In 1973, a substantial portion of the present Indian Sundarban was declared a Tiger Reserve under Project Tiger, which was taken up by the central government of India. The core area of the mangrove forest in the Indian Sundarban was inscribed by UNESCO as a world heritage site in 1987, primarily for being the abode of rich mangal species. The Indian Sundarban mangroves along with a predefined peripheral region were collectively declared a Biosphere Reserve under the Man and Biosphere Program (MAB) of UNESCO in 1989, and this region covers an area of 9630 km^2. In 2019, the Indian Sundarban earned the designation of a Ramsar site as well. All these accolades have been provided to the Indian Sundarban due to the conservation priority that this unique and biodiverse ecoregion deserves. The present Indian Sundarban comprises 19 administrative blocks covering two districts of West Bengal, namely North 24 Parganas and South 24 Parganas (Figure 1), and is broadly demarcated into three clusters (core, buffer, and transition areas) for effective forest management [54]. The transition, buffer, and core areas occupy 5300 km^2, 2500 km^2, and 1700 km^2, respectively. The transition area shelters the entire human population of the Indian Sundarban, whereas permitted activities (such as tourism, fishing, crab collection, honey collection, etc.) following some restrictions are allowed in the buffer region. However, the core which coincides with the Sundarban Tiger Reserve (STR), an area for tiger conservation designated by the State Forest Department, has stringent restrictions in terms of access or practicing any livelihood activities.

2.2. Impact Chain Development and Validation Methods

Characterizing risk is a challenging task as it involves a number of components and processes. In this regard, a visual documentation of the processes contributing to risk helps to simplify the complexities by elucidating the cause–effect interactions. The impact chain proposed by Hagenlocher at al. [48] provides such a framework, which helps with visualizing the complex interactions of the processes contributing to risk. The first version of the impact chain was developed to include processes that comprise (i) hazards, (ii) hazard chains, (iii) intermediate impacts, (iv) social–ecological vulnerability, (v) ecosystem susceptibility, (vi) social susceptibility, (vii) coping and adaptive capacities, and (viii) exposure following the basic outline of the impact chain proposed by Hagenlocher et al. [48] (Figure 2). Capacities were also included in the vulnerability assessment by inversing them because a lack of capacity results in increased vulnerability [56]. The impact chain was developed by using diagrams.net, which is an open-source diagramming software. It allowed us to easily share the diagrams among colleagues for feedback, and subsequent versions could be saved as layers without losing any data, which facilitated an easy comparison. Figure 3 shows the steps undertaken in this study to obtain the final version of the impact chain.

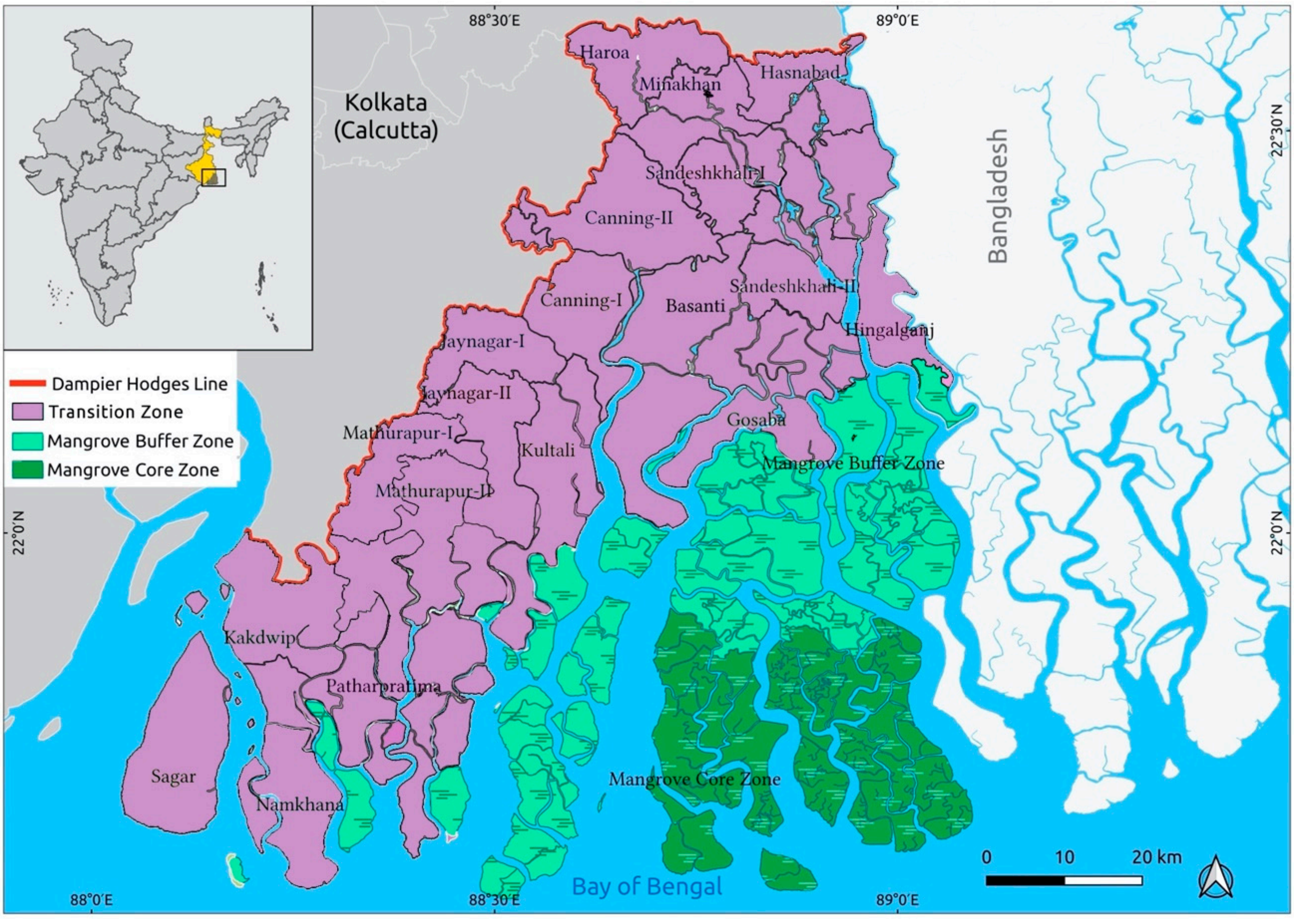

Figure 1. The study area map of the Indian Sundarban Biosphere Reserve showing the transition, buffer, and core zones (source: authors' elaboration based on Ghosh [55]).

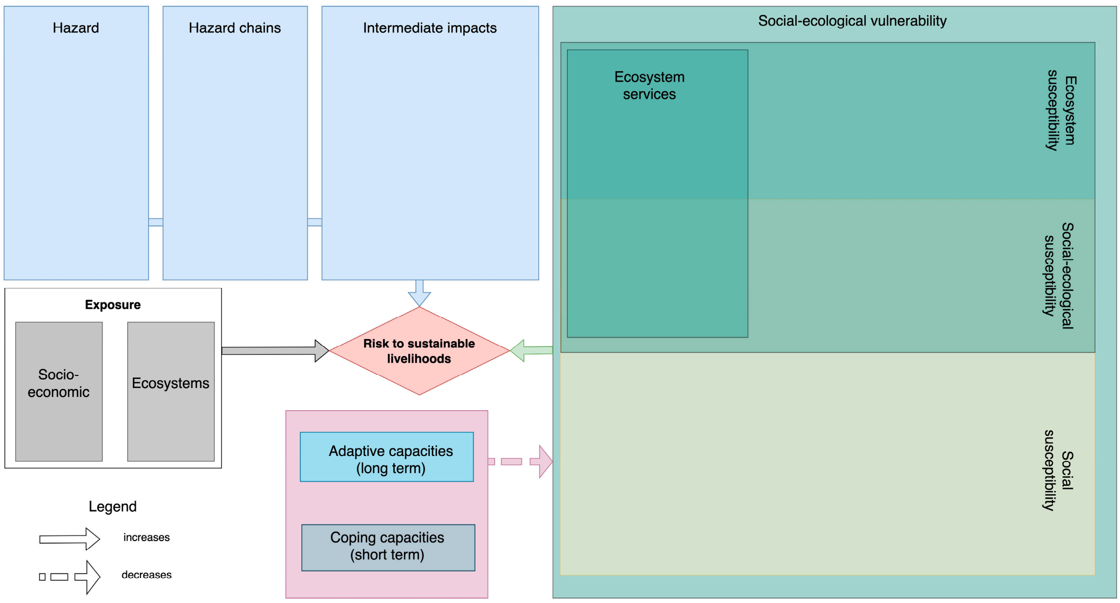

Figure 2. The basic outline of the impact chain used in the present study (source: modified after Hagenlocher et al. [48]).

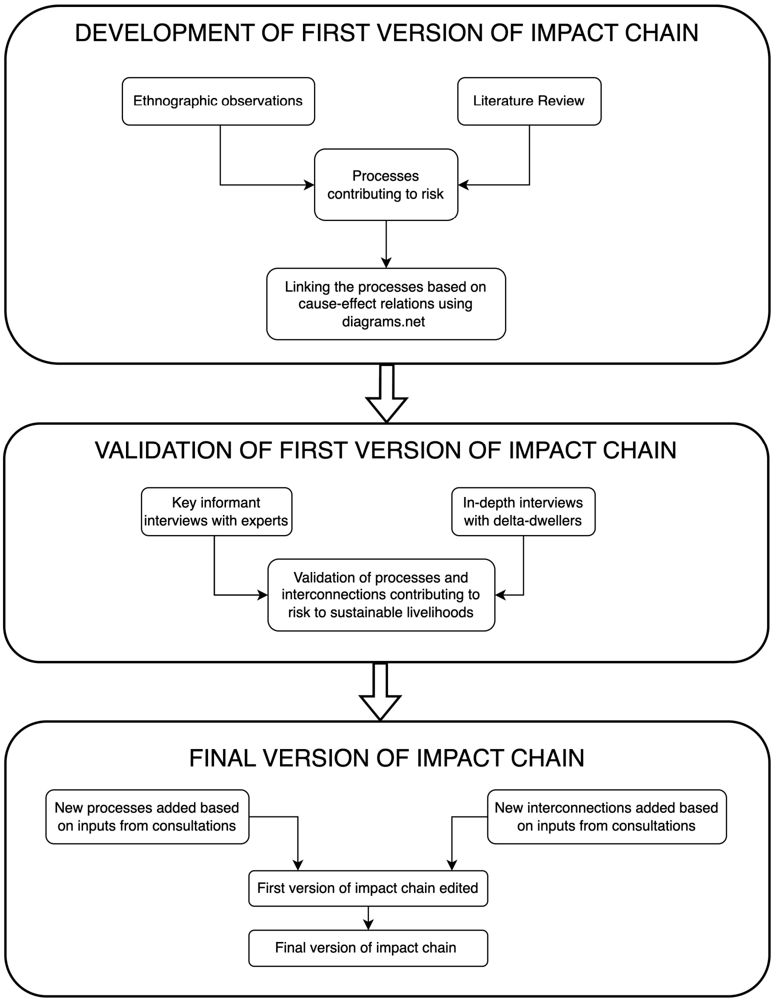

Figure 3. A flowchart diagram showing the steps undertaken in this study to obtain the final version of impact chain (source: authors).

We developed the first version of the impact chain based on our ethnographic observations of the Indian Sundarban spanning over two decades, which was then followed by a literature review to either support or contradict our observations. Once these events and processes were recorded, we started making connections between them using arrows to understand the cause–effect relations. This first version of the impact chain was then validated by experts through key informant interviews and in-depth interviews (Table 2). The process of validation was carried out by taking a dynamic approach that was tailored to suit the background of the expert; we kept to the ethical codes of participant anonymity and the participants' volition to withdraw from interviews, and we obtained their verbal consent to participate while being recorded. Additionally, adherence to the Living Deltas Hub's research integrity, ethical guidelines, and data collection protocols was maintained.

Key informant interviews (KIIs) with experts and in-depth interviews with the community, which were conducted simultaneously, helped us validate the impact chain for the Indian Sundarban (Table 2). Ground-level nongovernmental organizations (NGOs) spread across different Community Development (CD) Blocks of the region were considered to capture a holistic picture of the issues and processes that may contribute to risk because they have experience working in different sectors and designing programs to alleviate the issues affecting this region. Delta dwellers were consulted from the Sagar and Gosaba CD Blocks and relied on the authors' existing contacts as these interviews were conducted during a time when some of the COVID-19 restrictions were in place and only those who trusted the research team after following the necessary safety protocols (wearing masks, distancing, limiting the number of people during an interview/consultation) were approached. A total of 14 consultations (7 males and 7 females) were conducted.

Table 2. The details of the key informants and respondents and the rationale behind selecting them for the present study.

Method	Expert (Gender, Number)	Rationale
Key informant interviews	Representatives from ground-level NGO (male, 2)	Organization where both the experts were residents of the area and could share their lived experiences and a holistic view of the natural and social processes in the region.
	A representative from a ground-level NGO (male, 1)	Organization active for the past 47 years working in areas of health and nutrition; water, sanitation, and hygiene; environment and disaster response; education and protection; and livelihood and women empowerment. The expert was a resident as well.
	A representative from a ground-level NGO (male, 1)	Active in the region for the last 35 years; this organization works in areas of environment and disaster risk reduction, health, education, nutrition, livelihood, women empowerment, water, and sanitation. The expert was a resident as well.
	A representative from a ground-level NGO (female, 1)	Working in the region for around 20 years in areas of livelihood, education, rural health development, environment, water and sanitation, and women empowerment. The expert was a resident as well.
	Academic expert (male, 1)	With over a decade of experience in the region in biogeochemical studies of estuarine and lentic ecosystems covering aspects such as greenhouse gas dynamics and pollution characterization, this expert shared their overall observation on the recent changes and phenomena from across the entire study area.
	Ex government official (male, 1)	Hailing from the region itself and having the professional background of a government official, this expert shared their lived experience (>60 years) and holistic view of the processes from across the entire study area.
	Conservationist (male, 1)	Provided rich feedback on the natural and social processes active in the delta based on his lived experience (>50 years) and professional experience as a conservationist.
In-depth interviews	Delta dwellers (female, 6)	Since most of the KIIs had male perspectives, to ensure gender sensitivity in the research approach, women of different ages and livelihoods from the communities were consulted to understand their lived experiences.
TOTAL	Key informant interviews—8 (7 males, 1 female) In-depth interviews—6 (all females)	

The first consultation that was carried out with an academic expert revealed the challenge of concluding the consultation process within a stipulated period of time. The complexity of the diagram warranted the consultation to be broken down into two parts. While this was achievable for the academic expert owing to their academic training, the exercise of presenting a work in English depicted through a complex network to ground-level NGOs who are more comfortable with the Bengali language seemed like an unfair proposition. The impact chain was thus simplified in the form of a semistructured questionnaire. The experts shared their experiences, which helped us gather rich qualitative nuances in addition to helping us validate the processes. While this worked for most experts, some of the consultations were carried out to investigate the environmental, social, and economic issues in the region as experienced by the community, which naturally validated the processes and the cause–effect relations in the impact chain. The timing of these consultations was during July–August 2021, which was right after the region faced a third cyclone in a period of 18 months, and people's attention was naturally more focused on the aftermath of the disaster. Thus, when initiating the validation process with the communities, the entry point to the interviews was purposefully chosen as the natural hazards that they had recently experienced and their preparedness and response measures; during these interviews, we used open-ended questions. This too helped with validating different areas of the impact chain.

2.3. Data Analysis

The present study was carried out through semistructured interviews using open-ended questions that led to the generation of qualitative data. The data, which were recorded using an audio recorder, were mostly in the Bengali language and were then transcribed and translated into English before carrying out a framework analysis. The questions were developed by keeping the risk elements such as the hazards and social–ecological processes and their impacts on the social–ecological system in mind. Based on this and after familiarization with the data, the responses were categorized into subthemes to fit our impact chain figure.

The hazards were classified into subthemes of hazards, hazard chains, and intermediate impacts. The social–ecological vulnerability was categorized into ecosystem susceptibility, social–ecological susceptibility, and social susceptibility. Owing to the open-ended nature of the questions, the respondents organically shared the cause-and-effect nature of the processes without us having to ask follow-up questions, which thereby helped us validate the impact chain as these processes were connected with simple arrows. Dealing with qualitative data is always a tedious endeavor simply because the intrinsic nature of this information has no quantitative aspects. Hence, for this study, instead of ranking or indexing the responses in the standard quantitative framework, we adopted a summative protocol to collate all the relevant information acquired through the respondents' perceptions.

Based on the respondents' backgrounds and expertise, the responses were analyzed to clarify the priority areas of the region as experienced or perceived by each. In the final version of the impact chain, the drivers of risk that were discussed by at least one of the respondents were included. This helped us validate the first version of the impact chain and also add new drivers to it, which thereby helped us generate a holistic cause-and effect relation between the drivers, which culminated into risk to sustainable livelihoods.

3. Results

3.1. Hazards

The narratives from the interviews with the local stakeholders unequivocally pointed out that the Indian Sundarban is suffering from several manifestations of the ongoing climate change in the form of natural hazards (Figure 4). The recurrency and the enhanced intensities of the recent tropical cyclones (three cyclones in 18 months) left a catastrophic signature on the lives and livelihoods of the people. All of the respondents not only acknowledged this but shared experiences of facing and coping with the impacts of the cyclones, which are mentioned in the subsequent sections. In total, 93% of the respondents felt that rainfall variability led to other hazards (which are demonstrated under the hazard chains in the impact chain) and to intermediate impacts that finally culminated into a negative impact on their lives and livelihoods (Table 3). Furthermore, most respondents felt that the rainfall variability had increased in recent years. Storms were also potent hazards experienced by the respondents. The elevated ambient temperature throughout the Indian Sundarban was also felt by respondents beyond the age of 50 but was not reported by younger respondents. Sea level rise (36%) and land subsidence (14%) were also considered hazards that are relevant to the communities; however, there was a lack of unanimity among the respondents. While the academic experts mentioned sea-level rise occurring, the other experts who mentioned it stated that they heard of it occurring as a phenomenon being reported largely by the research community and that only scientific research can measure or corroborate it. As for land subsidence, only two experts who were residents of the region and in their late 50 s and 60 s reported it as occurring locally.

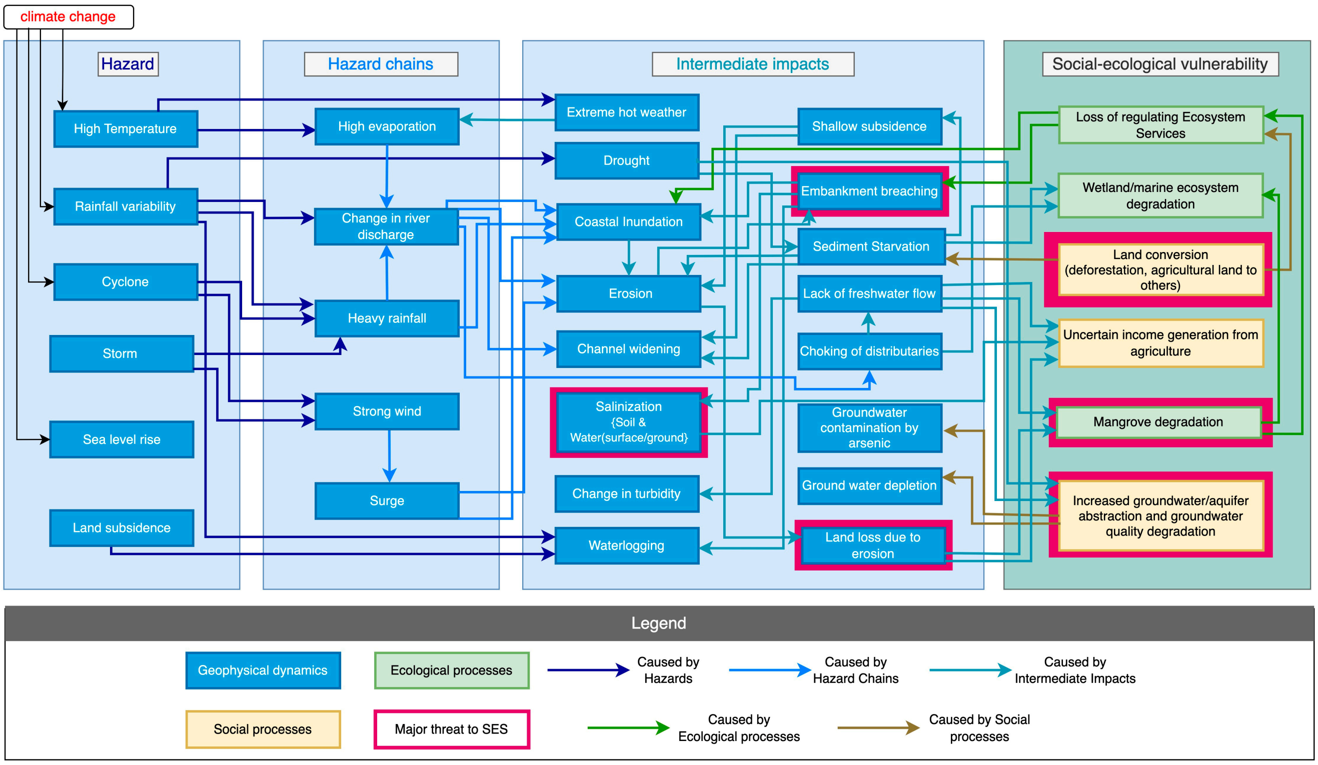

Figure 4. The cause–effect relations between hazards, hazard chains, intermediate impacts, and social–ecological vulnerability as validated in the study by experts (source: authors' elaboration based on framework proposed by Hagenlocher et al. [48]).

Table 3. Summary of responses from the respondents showing the relevance of the events and processes leading to risk in the context of the present study. The percentages in the responses column against each event/process were computed from the fraction of number of responses out of the total respondents consulted in this study.

Risk Element	Events/Processes	Responses
Hazard	Cyclone	100%
	Rainfall variability	93%
	Storm	57%
	Sea level rise	36%
	High ambient temperature	29%
	Land subsidence	14%
Hazard chains	Heavy rainfall	100%
	Surge	100%
	Strong wind	93%
	Change in river discharge	21%
	High evaporation	7%
Intermediate impact	Salinization (soil and water)	100%
	Coastal inundation	93%
	Embankment breaching	93%
	Erosion	79%
	Waterlogging	79%
	Land loss due to erosion	71%
	Ground water depletion	43%
	Choking of distributaries	43%
	Lack of freshwater flow	43%
	Channel widening	36%
	Sediment starvation	29%

Table 3. *Cont.*

Risk Element	Events/Processes	Responses
Intermediate impact	Drought	21%
	Groundwater contamination by arsenic	21%
	Extreme hot weather	14%
	Change in turbidity	14%
	Shallow subsidence	0%
Ecosystem susceptibility	Mangrove degradation	64%
	Loss of biodiversity	50%
	Wetland/marine ecosystem degradation	29%
	Change in species distribution	21%
	Loss of wildlife habitat	14%
	Weaker buffer zones	0%
Social–ecological susceptibility	Increasing pressure on natural resources (overexploitation)	64%
	Strong dependence on ecosystem-based livelihoods	64%
	Land conversion (deforestation, agricultural land to others)	50%
	Increased use of fertilizers, pesticides, etc.	43%
	Increased groundwater/aquifer abstraction and groundwater quality degradation	29%
	Lack of enforcement of restrictions/regulations (C)	29%
	Increasing human–animal conflict	21%
	Increasing cultural eutrophication	21%
	Increasing soil and surface water contamination by heavy metals, plastics, and other chemicals	21%
Social susceptibility	Increasing seasonal male migration	86%
	Lack of remittances (C)	79%
	Lack of hazard-resistant housing (C)	79%
	Uncertain income generation from agriculture	71%
	Damages to existing temporary housing	71%
	Lack of risk awareness (C)	64%
	Lack of financial resources (C)	64%
	Lack of access to basic services (C)	64%
	Increasing demand for irrigation	57%
	Lack of income diversification	57%
	Increasing workload of women	57%
	Lack of preparedness, mitigation, and risk-reduction plans (C)	57%
	Substituting traditional varieties of crop with high-yielding varieties	43%
	Decrease in availability of agricultural labor	43%
	Increasing reluctance in agricultural practices	36%
	Lack of social protection measures (C)	36%
	Absence of saline tolerant paddy	29%
	Lack of crop insurance (C)	29%
	Arbitrary locations of hazard protection structures (C)	21%
	Increasing industrial pollution	14%
Major Threat	Embankment breaching	93%
	Salinization {soil and water (surface and ground)}	86%
	Land loss due to erosion	57%
	Mangrove degradation	43%
	Land conversion	36%
	Increased groundwater/aquifer abstraction and groundwater quality degradation	14%

(C): capacity includes adaptive capacity (long term) and coping capacity (short-to-medium term)

3.2. Hazards Chains

The responses collated under this subtheme were gathered as effects of the hazards mentioned in Section 3.1. All the respondents mentioned that strong physical forcing events such as tropical cyclones have a follow-up hazard of torrential downpour, which also occurs as a result of rainfall variability and storms. Surge (100%) was also reported to have been experienced by all as a result of the strong wind (93%) that accompanies cyclones and storms. A follow-up hazard of rainfall variability and several other factors (anthropogenic encroachment and silting up in the upper catchments along with the natural eastward tilt of the delta) is the alteration in the riverine flow from the upper reaches (21%). This was reported by the academic expert and senior residents. The increase in ambient temperature led to high evaporation rates in the lentic (ponds) and lotic (estuaries) systems and the agricultural fields, which was reported by one senior expert.

3.3. Intermediate Impacts

The interviews enabled us to identify a series of intermediate impacts caused by the hazards and hazard chains that are further influenced by the vulnerability of the SES and thereby potentially hamper lives and livelihoods in the Indian Sundarban. Coastal inundation due to tropical cyclones and surges, rainfall variability, and change in river discharge often leads to embankment breaching and overtopping, which leads to waterlogging and the salinization of soil, surface water, and groundwater. These were reported as the most common occurrences by respondents.

Coastal erosion and the resultant land loss are a result of embankment breaching, storm surges, decreased sediment supply, and regional sea-level rise. Only one expert reported channel widening as resulting from the meander change in the channels and rivers; delta communities perceive channel widening as a consequence of riverbank erosion. Episodic events of waterlogging due to excessive rainfall and surges and temporary droughts due to a prolonged absence of rainfall are also considered as intermediate impacts. Groundwater depletion has been identified as another intermediate impact; however, it is largely due to the overexploitation of aquifers by humans in the absence of rainfall and freshwater flow, which contributes to increasing the social–ecological vulnerability and is also indirectly linked to hazards such as drought. Besides the depletion of groundwater, contamination by arsenic was mentioned by three of the experts. Overall extremely hot weather was reported by two experts, and this can be directly linked with the increase in the ambient temperature.

Sediment starvation, which was reported by an academic expert and three other senior experts, can occur as a result of rainfall variability and drought and can also be exacerbated by unplanned developmental and land-conversion activities undertaken by humans upstream of the delta. Shallow subsidence was not reported by any of the experts. Geophysical reasons and infrastructural interventions have led to reduced freshwater flow and the distributaries in the region being choked. One academic expert and one representative of a ground-level NGO mentioned the increase in turbidity levels in the estuarine water column that in turn compromised the primary productivity of these water bodies. Influenced by geophysical processes, land loss due to erosion was reported by most, which causes the degradation of mangroves and thereby increases ecosystem susceptibility and also exposes households to loss and homelessness, which thereby increases social susceptibility.

3.4. Social–Ecological Vulnerability

IPCC [47] highlights that the vulnerabilities of humans and the ecosystem are "interdependent". Thus, to understand the vulnerabilities of the social–ecological system of the Indian Sundarban, we divided social–ecological vulnerability into ecosystem susceptibility, social–ecological susceptibility, and social susceptibility before exploring their interdependence.

3.4.1. Ecosystem Susceptibility

It was evident from the responses that a substantial section of the coastal community of the Indian Sundarban exclusively depends on forest-derived resources. The hazards, in one way or the other, led to a significant loss in biodiversity in the Indian Sundarban (Figure 4). The mangrove floral stands always bear the brunt of tropical cyclones, and land-conversion processes also negatively affect them. Residents pointed out that Cyclone Amphan caused damage to the mangroves in the region. They also mentioned how developmental activities have led to the clearing of mangroves in certain areas and pointed out the role of mangroves in coastal protection; thus, they highlighted that the areas devoid of mangroves faced worse impacts than the areas sheltered by them.

The changing rainfall pattern also takes a heavy toll on the species composition and the health of the mangroves. As a result, fish availability in the estuaries, crab abundance, and beehives are severely impacted, which is directly linked with the livelihoods of millions. The respondents indirectly indicated that these aforementioned processes accompanied by social processes such as a lack of enforcement of restrictions/regulations weaken the buffer zone, which in turn results in a greater risk of human–animal conflict (Figure 5). In summary, the respondents' responses on ecosystem susceptibility and social–ecological susceptibility could be categorized under the loss of provisioning, regulating, and cultural services. The conversion of mangrove cover to agriculture and aquaculture to maintain sustenance and for developmental activities was also pointed out by the respondents.

One expert who is a conservationist and resident of the region mentioned how they saw more Sundari (*Heritiera fomes*) and Hental (*Phoenix paludosa*) trees in their youth than they do now, which they attributed to the changing ecological conditions in the region rather than human intervention. Key informants who were residents of the region working with NGOs, senior experts, and academic experts mainly shared experiences on ecosystem susceptibility. Delta communities shared their experiences related to mangrove degradation and loss in biodiversity as a result of natural hazards and human activities.

3.4.2. Social–Ecological Susceptibility

Strong dependence on ecosystem-based livelihoods was validated by most of the experts, an aspect which we were able to capture well owing to the conceptual underpinning of the frameworks we used here. They opined that a loss in biodiversity and habitat degradation can play a significant role in the decline of nontimber forest products (NTFP), which thereby increases uncertainties around the livelihoods of segments of the population. This uncertainty is prominent in the capture fisheries and honey-collection sectors.

The monsoon variability has raised concerns for agriculture, the primary livelihood option in this region, and is a direct cause of the overexploitation of groundwater. One expert mentioned how the choking of distributaries leads to a lack of freshwater flow, which then leads to an increased abstraction of groundwater, mainly for irrigation purposes. The respondents indicated that a desperate drive to maintain the agricultural yield has led to the substitution of traditional crop varieties with high-yielding varieties, which demand the extensive use of fertilizers and irrigation.

While having the sound enforcement of restrictions/regulations from government authorities can increase the capacity of the social–ecological system, a lack of it can increase its susceptibility. Two of the senior experts and the academic expert opined that a lack in restrictions/regulations can increase the social–ecological vulnerability by causing an increase in incidences of human–animal conflict in the Indian Sundarban. Half of the experts talked about the repercussions of land conversion on the ecosystem.

Akin to ecosystem susceptibility, most of the responses were received from the KIIs, and according to the in-depth interviews, a few respondents focused on their strong dependence on ecosystem-based livelihoods, erosion, and the overexploitation of resources.

3.4.3. Social Susceptibility

The chain of hazards and the social–ecological susceptibility directly impacted the livelihood options of many people in this delta (Figure 5). Additionally, many social processes that are active in the region led to an increase in the social–ecological vulnerability. The erratic monsoon introduced considerable uncertainties in the productivity of the conventional agricultural sector of this region. When coupled with episodes of salinization, land loss due to erosion, and a lack of freshwater flow, this burdens the cultivators and leads to an uncertainty in income from this predominant livelihood option. While enhanced irrigation facilities can build the capacities of the cultivators by letting them scale up from the predominant monocropping agriculture, the lack of proper irrigation facilities can adversely affect their livelihood. A lack of adequate irrigation facilities makes Rabi crop cultivation difficult in many areas due to the acute water scarcity in the winter (dry) season.

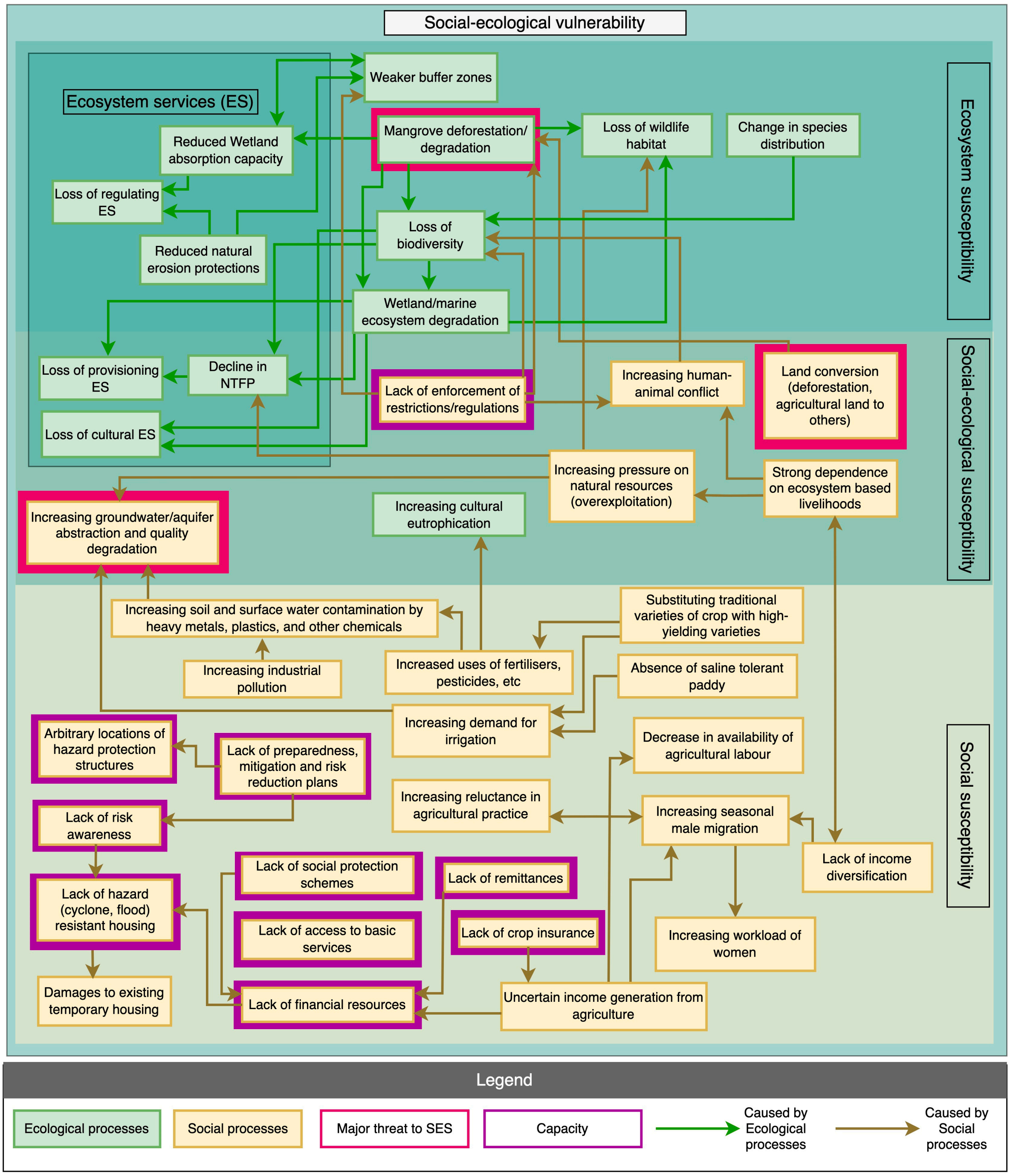

Figure 5. The cause–effect relations between processes contributing to social–ecological vulnerability as validated in the study by experts (source: authors' elaboration based on framework proposed by Hagenlocher et al. [48]).

Climatic variabilities have compelled segments of the population to shift from practicing agriculture to migrating to nearby cities or other states in India to work in the construction or garment sector. The shortage of agricultural laborers in the villages in recent years and an increasing reluctance to engage in agriculture, mostly among the younger generation, was also prominent in the responses. The trend of increasing seasonal male migration and the resulting receipt of remittances was validated by most respondents, and some mentioned how this leads to an increase in the workload of the women in rural areas.

Regarded as climate adaptations, the cultivation of high-yielding varieties of crops and salt-tolerant paddies, the use of fertilizers, access to crop insurance, and irrigation diversification can help people, but it was pointed out by the respondents that many of these have long-term costs which outweigh the temporary benefits. The increasing demand for high-yielding crop varieties has directly impacted the soil fertility of agricultural plots due to the overuse of fertilizers and pesticides and greater demand for irrigation. The latter has accentuated groundwater depletion, which has already started exhibiting serious consequences in terms of potable water availability in many places within the Indian Sundarban.

The strong dependence on ecosystem-based livelihoods has led to a lack of income diversification, and a lack of income diversification opportunities in the region has also increased the dependence on the available ecosystem-based livelihoods. However, the unplanned and indiscriminate urbanization outside of the study area is causing substantial marine pollution, which in turn might impact the tourism industry in the long run if the aesthetic beauty of the Indian Sundarban is compromised.

Focusing on disaster risk and people's experience of preparedness and response measures, we could create a list of adaptive and coping capacities which, when affected negatively, leads to an increase in social susceptibility. The respondents mentioned how risk awareness, evacuation plans, and early warning have helped prevent further loss and damage. This indicates that a lack of risk awareness, preparedness, and risk-reduction plans can adversely affect people when overcoming the impacts of recurrent tropical cyclones. Similarly, experts recounted how the presence of cyclone shelters has helped during evacuations in recent years, but the location of these infrastructures is critical to determine how conveniently people can access them. So, while cyclone and flood shelters can enhance the coping capacity of the people, their unplanned location can adversely affect it. Temporary housing is the most common in the region and most of the respondents mentioned how damage to existing temporary housing set them back by a few years. In this light, having hazard-resistant housing can build people's coping and adaptive capacities.

Social protection measures have helped build people's adaptive capacities by improving access to subsidized rations, education, and subsidized housing, and also by preventing some social behaviors such as early marriage to name a few. As reported by most of the respondents, financial resources are instrumental in improving the standard of living and become of paramount importance in the disaster recovery phase; thus, a lack of financial resources can lead to social susceptibility. Additionally, a lack of access to basic services will contribute to an increase in poverty and thereby increase vulnerability.

3.5. Exposure

In this study, we divided the exposure of social–ecological systems into socioeconomic exposure and ecosystems exposure, whereby the concerned elements can be adversely affected by hazards only when vulnerable, which thereby leads to risk (Figure 6). Experts mentioned that people, livestock, infrastructure, forests, and crops were the most affected. They also highlighted the spatial dimension of exposure; i.e., those residing close to the river embankments are more exposed than those further inland. Based on these observations, people residing near the erosion-prone banks in the Indian Sundarban are more exposed and are therefore at higher risk.

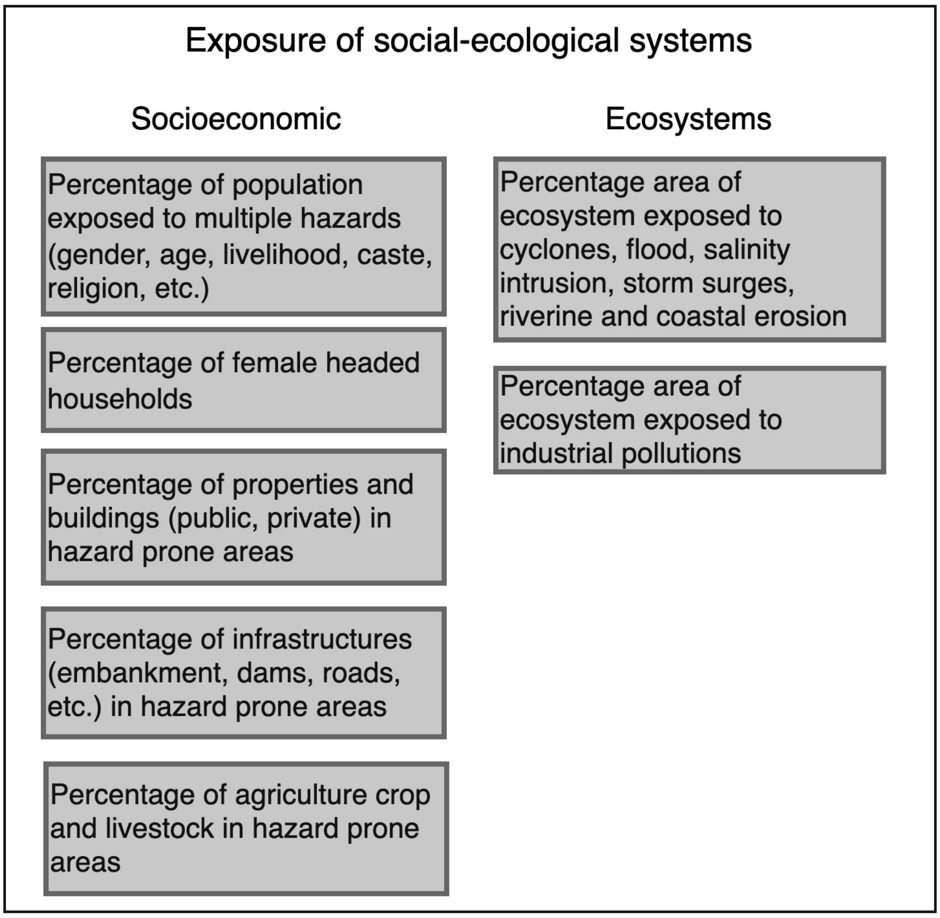

Figure 6. The elements contributing to socioeconomic exposure and ecosystems exposure as indicated in secondary literature and opined by the experts (source: authors' elaboration based on framework proposed by Hagenlocher et al. [48]).

For socioeconomic exposure, we listed components such as the population exposed to multiple hazards, infrastructures in hazard-prone areas, properties and buildings in hazard-prone areas, agricultural crops, and livestock. These factors have various degrees of vulnerability. With an increasing incidence of male migration and women left with additional workloads, it is natural for them to prioritize some actions over others, which can expose them to hazards. The respondents recounted how female-headed households with an absentee male struggled in the disaster preparedness and recovery phases as they juggled their household, livelihood, and repair work. Thus, female-headed households have higher levels of socioeconomic vulnerability and higher exposures to hazards.

Since the entire Indian Sundarban has critical interlinkages between several events and processes which contribute to the risk elements, experts felt that the entire ecosystem, which is exposed to hazards, industrial pollution, and over exploitation, should be accounted for when determining ecosystems exposure.

3.6. Risk

By analyzing the open-ended semistructured questions that led to the generation of qualitative data from the key informants and the respondents, we generated the final version of the impact chain (see Figure S1 in the Supplementary Materials), which demonstrates the elaborate and interconnected cause–effect relations that can lead to the risk of loss of sustainable livelihoods in the Indian Sundarban. As discussed in the earlier sections, hazards, hazard chains, and intermediate impacts can themselves be harmful for the region, but it is their interaction with the vulnerabilities and exposed elements of the system that leads to the risk. By understanding the inter-related processes and based on the views expressed by the respondents, the major threats could be identified; if left unattended, these threats can lead to detrimental impacts on the region, such as posing a risk to livelihoods (Figure 4). Embankment breaching (93%); the salinization of land, surface water, and ground water (86%); land loss due to erosion (57%); mangrove degradation (43%); and land conversion (36%) emerged as the major threats based on the responses. Reported only by experts who have experience working in the water sector, but particularly highlighted by them as a major threat for the region, was the increased groundwater/aquifer abstraction and groundwater-quality degradation.

4. Discussion

The Indian Sundarban is not a homogenous system, and this study aimed at providing a broad overview of the cause–effect relations between the risk elements that contribute to the risk of loss of sustainable livelihoods. Not all of these elements and processes can be quantified with data, but the merit of this cause–effect relation mapping helps highlight the complex nature of the interconnected parts of the system. While the risk maps generated from assessments that are primarily based on quantitative data offer spatially explicit visual references that are easily interpretable by relevant stakeholders, they often miss out on the richness of the lived experiences of communities. The nuances that the tailored qualitative approach undertaken in this study helped answer are why and how the multitude of events and processes occur to a greater extent than the quantifiable available datasets can offer. The first version of the impact chain developed by us was enriched by the lived experiences of the respondents, which not only validated the cause–effect relations but also helped in adding processes and connections. Additionally, the respondents' long-standing experience in the region helped us seek solutions for the persistent issues, which thereby aided in the co-production of recommendations to better manage the major threats for the region as emergent from this study.

4.1. Hazard

As evident from this study, tropical cyclones were the most dominant hazard for the region. Ali et al. [57] observed that more than nine administrative CD blocks of the Indian Sundarban are exposed to recurrent tropical cyclones. Rainfall variability was cited as a hazard that leads to other hazards through cascading effects and finally has negative impacts on the lives and livelihoods of people. The erratic nature of the monsoonal rainfall, its untimely appearance and withdrawal, the episodic occurrences of extreme precipitation, or no precipitation at all during a substantial time of the monsoon season are some of the potential hazards that affect the agricultural activities of this region. Ghosh and Mistri [58] analyzed the rainfall data over the Indian Sundarban from 2014 to 2018. They reported a steady decline in total rainfall during the monsoon and post-monsoon seasons; however, the intensity of rain per unit time increased substantially during the monsoon. Ghosh and Mistri [58] further mentioned that occasional torrential downpours during the initial stages of vegetation, when the crop height remains minimal, lead to waterlogging and an overall loss in agricultural productivity. This was further corroborated by experts and communities that experienced it in the month of June 2021 while they were still reeling from the blows meted out by Cyclone Yaas in May 2021. Besides cyclones, the respondents attributed storms as a potent hazard. This region experienced localized thunderstorms, especially during the months of April and May, which are locally known as *Kalbaishakhi* (Nor'westers) [59,60].

An elevated ambient temperature was reported by respondents who were above 50 years of age. Sahana et al. [61] analyzed the atmospheric temperature of the Indian Sundarban over 115 years (1901–2015) and observed a net increase of 0.5 °C in the last century. Regarding the sea-level rise and land subsidence, most of the respondents attributed their occurrences based on their own exposure to the news in the media and scientific literature [58,61–64]. Ghosh et al. [65] and Mondal et al. [66] quantified the degree of regional sea-level rise experienced by the Indian Sundarban in the past few decades. Mondal et al. [66] observed that the rate of regional sea-level rise varied between 1.7 and 3 mm yr^{-1} in the past three decades and is projected to increase up to 4 mm yr^{-1} by 2090. The scientific literature indicates a spatiotemporally varying rate of land subsidence in this delta from 5 mm yr^{-1} [62] to 15 mm yr^{-1} [67].

Hazard chains (also referred to as compound or cascading hazards) refer to the occurrence of one hazard following the other as a consequence [53]. Cyclones and storms can be accompanied by a surge. Using remote sensing and geographical information systems (GIS), Sahana and Sajjad [20] quantified the ground-level vulnerability of the Indian Sundarban from storm-induced surges and indicated that more than 50% of villages in the Indian Sundarban are in low-lying areas that frequently experience surges. The landfall timing of the recent Cyclone Yaas (2021) coincided with the peak in the flood tide, which resulted in surges of 7.5 m at Sagar Island [68]; this was evident in the unanimous experiential responses of the respondents, and all the respondents from Sagar Island in particular mentioned this emphatically.

The siltation and drying of the upper reaches of the major rivers in the region emerged as a cascading hazard due to rainfall variability. Bhadra et al. [69] helped corroborate this finding by pinpointing nine major blockages in the estuarine system of the Indian Sundarban caused primarily by natural siltation coupled with anthropogenic infrastructural obstructions in the riverbed. The climate-change-driven enhancement of ambient temperature accelerates evapotranspiration rates. Mondal et al. [70] indicated significantly high rates of evapotranspiration (ET) from the agricultural and forested lands of the Indian Sundarban. They mentioned that the high summer temperature range (32 °C to 42 °C) is fundamentally responsible for such high ET magnitudes, and it often leads to a depletion of water from the overall hydrological cycle of this region.

Intermediate impacts are a function of both hazard and vulnerability [48] and thus the processes or events of both hazards and vulnerabilities influence them. Embankment breaching leads to coastal inundation and subsequent salinization, which are the significant intermediate impacts that are caused by hazards such as cyclones, storm surges, and heavy rainfall. Dhara and Paul [60] indicated that such events led to severe damage to almost 280 km of the embankment length in the southwestern CD blocks of Kakdwip, Namkhana, Patharpratima, and Sagar. Chaudhuri et al. [32] examined several engineering faults in the embankment design and indicated that in most cases, the shear stress imparted by the adjacent estuarine water column on the wall of the embankments overwhelmed the critical shear stress, which makes these structures vulnerable to strong atmospheric forcing events. Such episodic events facilitate the saltwater to come in direct contact with the agricultural fields and render these fields unsuitable for agriculture for a few years to follow until the salinity is reduced through monsoon-induced precipitation. Spatially varying salinization throughout the Indian Sundarban has been comprehensively identified by several researchers [71,72], which leaves a longstanding effect on the agricultural plots of this region. Rani et al. [73] observed that the shallow aquifers of the Indian Sundarban are also equally vulnerable to saltwater intrusion, which leaves even fewer options for the local farmers to compensate for the saline water intrusion above the surface during such episodic events to sustain the agriculture.

Land loss due to erosion is another major intermediate impact identified in this study. Though erosion and accretion go hand in hand as a natural process in any deltaic regime, recent pieces of research exhibited that the Indian Sundarban is experiencing a net erosion that supersedes the accretion rate by a substantial margin [74]. Bera and Maiti [75] observed a stark difference in the net erosion rate between the mangrove islands and the human-inhabited ones. According to them, the net retreat of the shoreline is much higher in the human-occupied and embankment-guarded islands (6.1 m yr^{-1}) than the mangrove islands (4.8 m yr^{-1}). Channel widening has been identified as another intermediate impact. Bhattacharyya et al. [76] argued that the relative sea-level rise could substantially increase due to the ongoing channel widening.

Drought caused by rainfall variability and its resulting groundwater depletion are other intermediate impacts. Chakraborty and Mandai [77] mentioned that recurrent droughts occur in the post-monsoon months of December and January in the Indian Sundarban. This time of the year conventionally remains dry, and an inadequate monsoon often worsens the drought scenario. Das et al. [78] pointed out that overexploitation of groundwater is pushing the solutes of the estuarine water column to the deeper aquifers, which can pose an imminent threat to the potability of the aquifers of the Indian Sundarban in the near future. Besides the depletion of groundwater, contamination by arsenic has been reported in several studies [24,79].

A lack of freshwater flow along with the deprival of sediments has been reported in several pieces of research due to alterations in the riverine flow in the upper reaches of the Indian Sundarban [34,80]. Auerbach et al. [81] reported that the GBM deltaic plain continues to suffer from sediment starvation, which in turn amplifies the tidal inundation in the delta. Bomer et al. [82] inferred from their study that shallow subsidence is ongoing in the GBM delta principally due to clay mineral compaction and the lowering of groundwater tables. They further added that a loss in the sediment supply from the upper reaches would exacerbate the regional sea-level rise in this delta as the natural process of the deltaic elevation gain would not be able to cope with the rate of the sea-level rise. Recently, Jayaram et al. [83] reported that the shallow creeks and estuaries suffer from bottom churning, and a significant enhancement in turbidity takes place after cyclonic events primarily due to lack of freshwater flow.

4.2. Vulnerability

The vulnerability of the social–ecological system of the Indian Sundarban is influenced by ecosystem susceptibility, social–ecological susceptibility, and social susceptibility. This study indicated that a substantial section of the coastal community of the Indian Sundarban exclusively depends on forest-derived resources. This fact has been recognized by several scholarly works carried out in the Indian Sundarban [84,85]. To maintain these livelihoods, the mangroves of this region are of critical importance. Mishra et al. [21] quantified that the dense mangrove canopy cover of the Indian Sundarban reduced from 77% to 34% after super cyclone Amphan. Sievers et al. [27] documented that the mangrove clearing rate in the Indian Sundarban has declined when compared to that observed in the colonial era; however, the felling of mangrove trees is still practiced in the transition zone to meet agricultural, aquacultural, commercial and residential purposes. The deforestation, degradation, and fragmentation of mangroves have reduced the natural absorption capacity and erosion protection potential of this Ramsar site and has thereby led to a loss in biodiversity and wildlife habitats (Figure 5). A few pieces of research have strongly advocated that the Indian Sundarban is experiencing a rapid shift in mangrove floral species assemblage as highly salt-tolerant species are replacing the oligohaline mangroves [86,87].

The overexploitation of fishery resources affects both the ecology and livelihoods of the people in this region. Das et al. [88] quantified the ecotrophic efficiency of several pelagic fishes in the open bay waters adjoining the Sundarban and observed that overexploitation and unsustainable fishing practices are leading to considerable uncertainties in the fish catch. Livelihood processes of applying fertilizers and enhancing irrigation for agriculture takes a toll on the aquatic ecology of this region. Several scholarly studies indicated a deterioration in the ambient water quality in both lentic and lotic ecosystems due to the eutrophication caused by the nutrient-laden runoffs [89,90].

Human–animal conflict and indiscriminate land conversion occur as a result of a lack of proper law enforcement that increases the social–ecological susceptibility of this region. Sen [91] indicated that the loose ends and loopholes of the forest conservation protocol practiced in the Indian Sundarban indirectly enhance the probability of human–animal conflict. Acharyya et al. [92] discuss how land conversion from forested land to agricultural land, agricultural land to aquacultural land, and aquacultural land to brick kilns have taken a toll on the natural environment and demands sustainable adaptation options.

Social susceptibility is enhanced by a lack of returns from agricultural livelihood. To reap profits from agriculture, it has to shift from monocropping to dual cropping which can be facilitated through irrigation. Based on the 2011 Census data, Hazra et al. [93] found that more than 80% of the gross cropped area in the Indian Sundarban had no irrigation facility. Hajra and Ghosh [94] observed a statistically significant positive correlation between the decline in agricultural yield and the degree of out migration from the Indian Sundarban. An increasing trend of male migration from the region leaves females and female-headed households to experience disproportionately higher challenges when achieving their livelihoods and overcoming disasters as the females have to look after their families and at the same time remain underpaid in any occupation compared to males [95,96].

The deterioration in the estuarine water quality as a result of unsustainable agricultural and industrial practices enhances social susceptibility. Recently, Bhadra et al. [97] observed prominent signatures of saltwater intrusion in many shallow aquifers of the Indian Sundarban. They further noted that the water quality of deeper aquifers is gradually deteriorating and might not remain potable in the days to come. Research has indicated that the medium-to-large scale industrial hubs pour in substantial quantities of heavy metals such as arsenic, chromium, cadmium, cobalt, nickel, mercury, and a wide range of persistent organic pollutants [23,98].

The Indian Sundarban is a cyclone-prone region; to reduce disaster risk, cyclone and flood shelters are considered infrastructural adaptations. Padhy et al. [99] commented on the effective utility of multipurpose cyclone shelters by properly planning their location and infrastructure to enhance the coping capacities of those who are in dire need when cyclones or flooding affect an area.

The enhancement of the adaptive capacities of the population depends on the asset base, institutions and entitlements, knowledge and information, innovation, and flexible forward-looking decision making [100]. A lack of access to assets can reduce the adaptive capacity and increase vulnerability. This access to assets is often facilitated through institutions and entitlements [100], and studies from other parts of world have shown that institutional robustness helped groups perform well under environmental variabilities [101]. To reduce the vulnerability of a sensitive ecosystem such as the Indian Sundarban, the proper management of natural resources for both the ecosystem and the population dependent on the ecosystem is essential. In this regard, Zikos [102] notes that institutional performance is more important than institutional change, and the role of institutions should include facilitating interactions and putting together social rules; additionally, to reduce uncertainty by framing rights and duties with the purpose of avoiding conflicts. Finally, social protection measures can enhance the adaptive capacities in the region as observed by Marcinko et al. [103]; however, there are still ample scopes to improve and look for other avenues to achieve better results.

4.3. Exposure

Recent disasters and hazards have impacted people, livestock, infrastructure, forests, and crops in and around the Indian Sundarban [104]. These elements were impacted because they were vulnerable and exposed to the hazard. Based on the observations from this study and Ghosh [105], it is evident that people residing near the erosion-prone banks in the Indian Sundarban are more exposed and therefore at a higher risk. The infrastructure in hazard-prone areas determines exposure. For example, when a concrete house and a temporary house are exposed to cyclones, the temporary house is more at risk and likely to be damaged as it is more vulnerable (it is made of less robust building material). Females and female-headed households can also become more exposed to natural hazards. With the increasing incidence of male migration and women being left with additional workloads, it is natural for them to prioritize some actions over others, which can expose them to hazards, as observed by Banerjee and Vincent [106].

4.4. Risk

This study strongly indicated that tropical cyclones and rainfall variability are the most serious natural hazards. Heavy rainfall, cyclone-induced surges, and strong winds are the most prominent in the hazard chain. These have immediate and longer-lasting impacts on lives and livelihoods and can lead to risk when interacting with the vulnerable and exposed elements of the system. Two of the topmost major threats identified by the respondents, namely embankment breaching and the salinization of land and surface water, which are a part of the intermediate impact, occur as an effect of two natural hazards such as tropical cyclones and cyclone-induced surges. Embankments are the "lifeline of the delta" as pointed out by an expert, and these structures are critical in protecting lives and preserving livelihoods. Embankment breaching is a major threat for the communities, and this has been recognized in the secondary literature, observed first hand by the authors, and unequivocally shared by all the respondents that echoed how they have been affected by it. Delta dwellers emotionally recounted that their existence in Sundarban is determined by the embankments. Embankments breach because of natural reasons such as riverbank erosion, undercutting, and the consequent collapse of the base of the embankment, which is often heightened during a cyclone and cyclone-induced surges. Manmade reasons for embankment breaching include cutting canals in the embankments for aquaculture and also to push newly made boats from the land to the water through the wider cut channels. Also, while constructing the embankments, the mud used to build it is extracted from the soil of the riverbed. With cyclones and cyclone-induced surges, the vulnerable embankments breach, which pave the path for the saline water to enter the habitable lands, which affects the cultivable lands and surface water; therefore, it poses substantial risk to livelihoods such as agriculture and freshwater fisheries, which in turn affects the wellbeing of the people, such as by affecting their food security. The salinization of the soil, groundwater, and surface water was thus identified as a major threat for the study area. Since the habitable areas in most of the region are below the high-tide line and protected by these embankments, livelihood assets and other infrastructure are at risk when these events occur.

Land loss due to erosion is another major threat that can act as a driver of risk when people lose their habitable and cultivable lands. Originating from geophysical causes but also affected by anthropogenic factors, erosion is a major threat for the people as it leads to land loss. Homestead lands, cultivable lands, and water bodies often succumb to an eroding bank, which exposes the populations to hazards. Ghosh [105] pointed out that progressive land loss and a stark absence of infrastructural ability and financial aid to combat the phenomenon have led to considerable risk, especially to the households near the erosion-prone banks in the Indian Sundarban. Experts mentioned that it is often the marginalized populations who reside along the river banks, and their inherent socioeconomic vulnerabilities are exacerbated by the erosion and subsequent loss of land, which leads to forced displacements and a loss of livelihood assets such as cultivable lands and ponds (freshwater and brackish water), which thereby poses a significant risk to their lives and livelihoods.

The fourth major threat was mangrove degradation, which is caused by both geophysical and social processes such as a lack of freshwater flow and land conversion, respectively. Also, a lack of enforcement or regulations can lead to illegal activities such as the felling of mangroves, which results in deforestation. Some respondents recalled how some areas were cleared of mangroves in the past for developmental reasons and the impacts of such actions can be felt by residents in present days, in particular the loss of regulating ecosystem services. Mangroves provide a nurturing habitat for different marine faunal species, and the degradation of these can lead to a change in species distribution, which can pose a risk to livelihoods based on fish and crab cultivation. The degradation of mangroves also poses a risk to the livelihoods of honey collectors as the mangrove floral stands act as the natural platforms where beehives thrive. Bera and Maiti [107] inferred that almost 46% of the households in the forest fringe islands earn half of their total income from forest-derived resources, and the deterioration in both the quality and quantity of crabs and fish has severely affected their livelihood in the recent past. The region is a UNESCO world heritage site and around 2600 km^2 of the region is designated as the STR with the principal aim to protect the last refuge of the endangered Royal Bengal Tigers [4]. The degradation of mangroves can lead to a deterioration in the aesthetic values of this unique landscape by affecting the natural heritage and the lives of the endangered species in the region, and it can thus lead to a loss of cultural ecosystem services and put the livelihood of those engaged in tourism at risk. Ghosh and Ghosh [54] further indicated that the marginal communities of the Indian Sundarban receive only a nominal share of the tourism-based profit, and the capital investors who are mostly situated outside the Indian Sundarban enjoy substantially higher returns from this sector. Thus, a decline in tourism makes the scenario even worse for the delta dwellers who are directly engaged in the tourism industry.

As stated above, experts shared how land conversion happened as a result of social processes, and this included the conversion from mangroves to agricultural land, and agricultural land to land for fishery and ultimately to habitation or in some cases to brick kilns. Such conversion poses a risk for the loss of all the nature-based livelihoods practiced in the region and was thus identified as the fifth major threat.

Groundwater/aquifer abstraction and groundwater quality degradation was the other threat that is caused by geophysical processes such as responses to droughts, a lack of freshwater flow, social processes such as increasing demand for irrigation, and surface water contamination by heavy metals, plastics, and other chemicals. This poses a risk for agriculture as increasing groundwater abstraction leads to groundwater depletion; under a changing climate with rainfall variability, this can lead to a dearth of sources for irrigation and can thereby affect agricultural livelihoods.

5. Conclusions

Ethnographic observations of over 20 years ascertain that residents of the Indian Sundarban report a lack of economic opportunities in the region; thus, reliance is more on ecosystem-based livelihoods, which are increasingly at risk from natural hazards owing to the interaction of hazards, vulnerability, and exposure as discussed in this paper. Since the wellbeing of both the humans and ecosystems in this region are dependent on the sustainable management of livelihoods, it was imperative to understand the events and processes that can contribute to risks to sustainable livelihoods. The use of impact chains conceptually underpinned by the inclusion of social–ecological concepts integrated in a risk assessment framework allowed us to capture the relevant interactions between social and ecological systems and the sustainable livelihoods of the communities living in the delta.

As observed from this study, tropical cyclones, rainfall variability, and storms are the dominant hazards. Natural hazards also directly or indirectly influence the processes that impact vulnerability which, when exposed, lead to the risk of loss of sustainable livelihoods. Social vulnerability is aggravated by processes such as increasing seasonal male migration, uncertain agricultural income, and a lack of hazard-resistant housing. As identified in this study, the complex interconnections between the elements of risk give rise to some threats that can pose risk to sustainable livelihoods. The major threats are embankment breaching; the salinization of land, surface water, and ground water; land loss due to erosion; mangrove degradation; land conversion; and increased groundwater abstraction and quality degradation, which need to be addressed to prevent future risks to sustainable livelihoods.

This study indicated that the embankments of the Indian Sundarban and their management require immediate attention to reduce the exposure and vulnerability of the social–ecological system. The breaching of embankments is a persistent issue for the Sundarban and for the protection of lives and the long-term sustainability of livelihoods in the region; thus, it is imperative that adaptive decisions be proposed and implemented as a priority. Proper embankment management can not only help reduce future disaster risk but also alleviate the erosion rate and degradation of the mangrove and wildlife habitats. Saline water intrusion into cultivable lands has also been recognized as a persistent problem that often has a cascading impact on embankment breaching. In this regard, the enhancement of the feasibility to practice salt-tolerant paddy cultivation can improve the adaptive capacity by sustaining the principal source of income for many. Traditional varieties of paddy are not only salt tolerant but also have lesser demand for irrigation than the high-yielding varieties. Thus, promoting a salt-tolerant paddy can not only allow the effects of saline water intrusion to be withstood, but it can also alleviate the demand for groundwater. Government initiatives have recently stressed rainwater harvesting for irrigation, and only when these efforts have equitable access can these increase the capacity of the cultivators and the ecosystem alike. Land conversion needs to be planned and longer-term benefits should be prioritized instead of quick gains. Sacrificing green for gray infrastructure needs to be reconsidered by introducing ecosystem-based adaptation options and, where possible, by including a mix of gray–green infrastructure. One of the principally recognized functions of mangroves in recent years has been their ability to withstand storms and cyclones. Government initiatives have accelerated mangrove plantation efforts to strengthen the ecosystem, but attention must be paid to make these sustainable adaptation options and not failed adaptations. Since the mangroves are the backbone of this ecosystem, their health and spatial extent should not be compromised. Exploring the suggestion for a mix of gray–green infrastructure seems to allow a number of these major threats to be addressed, even though they will not solve all the issues. If embankments are engineered with stretches of mangroves planted in parallel, this can promote mangrove cover and prevent riverine erosion, which would thereby reduce land loss and embankment breaching; additionally, as a result salinization, this would contribute to provisioning ecosystem services that directly support local livelihoods.

This holistic understanding of the inter-relations of the processes contributing to the risk of loss of sustainable livelihoods will be useful for research, policy, and practitioner communities. For research, this transdisciplinary approach can help shed light on the intricacies of relevant processes outside the research area of single disciplines. The interconnections can help to better visualize issues and design robust policies with cross-departmental collaboration amongst policymakers. The practitioner community can also benefit from understanding these interconnections to better design future risk-reduction interventions.

Supplementary Materials: The following supporting information can be downloaded at https://www.mdpi.com/article/10.3390/su15076146/s1: Figure S1: The cause–effect relations between hazards, hazard chains, intermediate impacts, social–ecological vulnerability, and exposure leading to risk of loss of sustainable livelihoods in the Indian Sundarban as validated in the study by experts and demonstrated through an impact chain diagram.

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Informed Consent Statement: Informed consent was obtained from all subjects involved in this study by adhering to the ethical codes of participant anonymity and participants' volition to withdraw from interviews; we obtained their verbal consent to participate while being recorded.

Data Availability Statement: The data used in this study are mostly qualitative in nature. The quantitative data derived by analyzing the interviewee responses are furnished in the main manuscript.

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