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Coastal Infrastructure and Climate Change adaptation in Bangladesh: Ecosystem services insights from an integrated SES-DAPSIR framework

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Summary

The escalating impacts of climate change on coastal regions stress the urgency for effective adaptation strategies, particularly for the case of high-risk countries such as Bangladesh. Nature-based solutions, grey and mixed coastal infrastructure offer promising solutions for addressing these challenges. Prior publications have utilized decision-making models such as the DPSIR framework to explore the link between coastal infrastructure and climate change. However, until now none of them have used it in combination with broader frameworks. Moreover, few works have analyzed the south central coast of Bangladesh by following an integrated approach. Hence, this working paper aims to bridge these gaps by employing an integrated SES-DAPSIR framework to evaluate the main benefits and challenges provided by different types of coastal infrastructure, with a particular emphasis on ecosystem services. Our methodology involves a two-step approach. Firstly, we consolidated a structured questionnaire and conducted surveys within three different locations to gather community's perspectives on coastal infrastructure. Secondly, we developed an integrated SES-DAPSIR conceptual model, engaging scientific and policymaking stakeholders through an international workshop co-organized with FEEM, Università Ca' Foscari and Murdoch University. The main results highlight the potential ecological impacts and costs associated with grey infrastructure, advocating for a balanced approach that combines green and grey solutions. Mixed solutions, integrating elements of both nature-based and grey infrastructure, show promise for optimizing adaptation efforts while minimizing ecological harm and cost. As part of this process, government leadership and international cooperation are deemed essential for driving public engagement and fostering societal resilience.

Keywords: Climate change adaptation, coastal infrastructure, nature-based solutions, ecosystem services, integrated frameworks

JEL classification: Q50, Q54, Q57, Q58

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This publication **has two first authors**, Sarker Md Monzer and Martinez-Hernandez Alberto Gabino.

Executive Summary

The escalating impacts of climate change on coastal regions stress the urgency for effective adaptation strategies, particularly for the case of high-risk countries such as Bangladesh. Nature-based solutions, grey and mixed coastal infrastructure offer promising solutions for addressing these challenges. Prior publications have utilized decision-making models such as the DPSIR framework to explore the link between coastal infrastructure and climate change. However, until now none of them have used it in combination with broader frameworks. Moreover, few works have analyzed the south central coast of Bangladesh by following an integrated approach. Hence, this working paper aims to bridge these gaps by employing an integrated SES-DAPSIR framework to evaluate the main benefits and challenges provided by different types of coastal infrastructure, with a particular emphasis on ecosystem services. Our methodology involves a two-step approach. Firstly, we consolidated a structured questionnaire and conducted surveys within three different locations to gather community's perspectives on coastal infrastructure. Secondly, we developed an integrated SES-DAPSIR conceptual model, engaging scientific and policymaking stakeholders through an international workshop co-organized with FEEM, Universita' Ca' Foscari, and Murdoch University. The main results highlight the potential ecological impacts and costs associated with grey infrastructure, advocating for a balanced approach that combines green and grey solutions. Mixed solutions, integrating elements of both nature-based and grey infrastructure, show promise for optimizing adaptation efforts while minimizing ecological harm and cost. As part of this process, government leadership and international cooperation are deemed essential for driving public engagement and fostering societal resilience.

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Introduction. Coastal adaptation in the face of climate change

Coastal and marine ecosystems are crucial for the global economy and human well-being, but they are increasingly vulnerable due to climate change risks. Nearly 37% of the world's population live within 100 kilometers of the coast and benefit from their ecosystem services (UN, 2007). These ecosystems have substantial monetary value, estimated at 28,917 USD/ha/yr for coastal systems, 193,845 USD/ha/yr for coastal wetlands, and 352,915 USD/ha/yr for coral reefs (Costanza et al., 2014; Mehvar et al., 2018; Davidson et al., 2019). Nevertheless, climate change, causing rising sea levels and more frequent extreme weather events currently impact an additional 14 million people annually, with projections suggesting this number could reach 73 million by 2100 (UNDP, 2023). Without taking adaptation measures, annual global damages from climate induced floods could surpass USD 3 trillion by 2080 (Tiggeloven et al., 2020). In Bangladesh, sea levels are projected to rise by 85 cm by 2050, potentially displacing 19.9 million people (MoEFCC, 2022). Additionally, the nation's current annual GDP loss due to climate-induced disasters may increase to 2% by 2050 and exceed 9% by 2100, with the southwest coastal region possibly seeing a 15.6% reduction in high-yielding-variety rice production by 2050 (The World Bank, 2015).

As part of the different responses to climate change, nature-based solutions (NbS) play a pivotal role in aiding communities to adapt to and mitigate their impacts, safeguarding biodiversity and supporting sustainable development. Defined by the United Nations Environment Assembly (UNEA-5) as actions that protect, conserve, and sustainably manage natural or modified ecosystems, NbS offers natural defenses against floods and erosion. Nature-based infrastructure (NBI) such as mangroves and wetlands provide essential ecosystem services, while hybrid infrastructure combining natural and engineered elements demonstrates significant protective capacity against coastal hazards. The concept of mixed approaches indicates potential for optimizing adaptation efforts and achieving sustainable outcomes amidst growing challenges.

In the urgency of climate change adaptation stakeholder engagement and public participation is crucial. This engagement involves active dialogue and communication between stakeholders, academia, and the general public to find compromise solutions supported by technical and scientific data. In this sense, the DPSIR framework has been developed, modified, and applied to different contexts to analyze coastal areas to define their ecological state and risks (Bruno et al., 2020; Delgado et al., 2021) and to provide and systematize information to support policy development and decision-making processes (Lewinson et al., 2016; Federigi, 2022; Kristiadi, 2022). However, for the case of the coastal regions in Bangladesh, most of the studies using DPSIR have focused on adaptation and mitigation (Roy et al., 2023; Hossain et al., 2013; Roy et al., 2017), coastal agriculture (Hossain et al., 2013), ecosystem services (Miah et al., 2021; Haque et al., 2019) but no studies have been found to address the SES for coastal adaptation through nature-based infrastructure. Furthermore, none of the existing studies have employed the DAPSIR framework, an updated version of the DPSIR one.

To fill these gaps we apply the SES-DAPSIR conceptual model (Cornacchia et al., 2023), which integrates the socio-ecological systems (SES) approach with the DAPSIR framework to the context of coastal adaptation in the south central coast of Bangladesh. This model provides a holistic methodology for analyzing complex socio-environmental challenges, particularly in coastal adaptation contexts, by considering the interdependence between human activities and the

environment. Unlike the traditional DAPSIR framework, the SES-DAPSIR acknowledges bidirectional interactions and incorporates feedback loops, capturing the dynamic nature of socio-ecological systems. Employing SES-DAPSIR facilitates the development of evidence-based adaptation strategies that address both social and ecological dimensions, promoting resilience in vulnerable coastal communities like Bangladesh.

This working paper is structured in five sections. It begins with an exploration of Nature-based Solutions (NbS) and coastal infrastructure, offering insights into conceptual frameworks and strategic approaches currently in place in Bangladesh. The next section describes the methodological aspects of the research such as the selection of the area of study, the theoretical framework employed and the research design. Moving from theory to practice, the third section presents empirical findings coming from surveys with local communities on implemented strategies and the outcomes of the workshop carried out with scientific and policy stakeholders. The fourth section encompass the discussion and policy recommendations. Finally, the paper concludes with policy recommendations aimed at supporting coastal adaptation processes in Bangladesh and beyond, merging theoretical insights with practical implications to inform policy interventions.

1. An overview of conceptual and current climate adaptation strategies in Bangladesh

1.1. Nature based solution and Nature-based infrastructure

Nature-based solutions (NbS) are gaining international recognition for their pivotal role in aiding communities to adapt to and mitigate the impacts of climate change, all while safeguarding biodiversity and supporting sustainable development. In 2022, the United Nations Environment Assembly (UNEA-5) adopted formally the definition of NbS as “actions to protect, conserve, restore, sustainably use and manage natural or modified terrestrial, freshwater, coastal and marine ecosystems, which address social, economic and environmental challenges effectively and adaptively, while simultaneously providing human well-being, ecosystem services and resilience and biodiversity benefits'' (UNEP, 2022).

A crucial element of nature-based solutions (NbS) is nature-based infrastructure (NBI), which refers to areas or systems utilizing natural elements to provide infrastructure services for the benefit of people, the economy, and the environment (Bechauf et al., 2022). This encompasses not only naturally occurring ecosystems like forests, mangroves, wetlands, and grasslands but also hybrid infrastructure that combines engineered or grey structures, such as embankments, revetments and bulkheads, with nature-based solutions (Bechauf et al., 2022). Following this line, green infrastructure is “a strategically planned network of natural and semi-natural areas with other environmental features designed and managed to deliver a wide range of ecosystem services” (European Commission, 2013; see table 1a). Mangroves have a large protective capacity to cope with floods, providing flood protection benefits at the global level of more than USD 65 billion per year (Menéndez et al., 2020). Additionally, they have the capacity to reduce the rise in seawater levels between 4 and 16.5 centimeters and to bring down water inflow speed in between 29% and 92% (The World Bank, 2020).

In contrast, “grey infrastructure involves engineered assets that provide one or multiple services required by society, such as transportation or wastewater treatment” (IISD, 2024). Embankments, revetments and bulkheads, among others, have shown sudden positive impacts to protect human settlements, fisheries and agricultural production against flood, storms and high waves (Rahman et al., 2022). Moreover, these structures have increased productivity of existing economic activities, diversified the economy, and allowed population growth (see table 1b). Amidst these distinct approaches lies the concept of mix approaches or green-grey infrastructure that “combine conservation and restoration of ecosystems with the selective use of conventional engineering approaches” (Kuwae and Crooks, 2021). Examples include rain gardens, green roofs, sustainable urban drainage systems, and porous pavements. For the case of coastal adaptation, this perspective considers the benefits of natural assets that preserve natural cycles and sustain life, and of human-made materials that have sudden impacts to increase the welfare of a community. As the challenges diversify and grow, it is necessary to also consider among the adaptation strategies a hybrid approach that merges and optimizes functions of both infrastructure types.

Aspect	Vegetation-Only	Edging	Sills
Advantages	• Erosion control through root anchoring • Minimal impact to natural processes	• Erosion prevention • Habitat provision • Adaptability to different materials	• Wave reduction • Habitat provision
Disadvantages	• Limited storm surge and high water protection • Uncertainty in vegetation growth	• Limited storm surge and high water protection • Adjacent erosion	• Limited storm surge and high water protection • Seabed erosion • Sediment transport impacts
Costs	• Low initial construction costs • Low ongoing maintenance	• Medium initial construction costs • Low ongoing maintenance	• Medium initial construction costs • Low ongoing maintenance
Additional Information	• Ideal for enhancing biodiversity • Suitable for low-lying areas	• Various material options available	• Suitable for low-lying areas • Gapped approach enhances habitat connectivity

Table 1a. Green techniques for coastal adaptation
Source: adapted from Systems Approach to Geomorphic Engineering (SAGE). (2015). Natural and Structural Measures for Shoreline Stabilization. Developed with support and funding from SAGE, NOAA, and USACE.

Aspect	Revetment	Bulkhead	Seawall
Advantages	• Wave and erosion protection • Low maintenance	• Wave and erosion mitigation • Tide management	• Storm surge prevention • Wave resistance Shoreline stabilization
Disadvantages	• Limited flood protection • Seabed erosion • Adjacent erosion	• Limited flood protection • Seabed erosion • Sediment transport disruption	• Limited flood protection • Seabed erosion • Sediment transport disruption
Costs	• Very high initial construction costs • Medium ongoing maintenance	• Very high initial construction costs • Medium ongoing maintenance	• Very high initial construction costs • Medium ongoing maintenance
Additional Information	• Suitable for high-energy settings • Flexibility of material options	• Suitable for areas vulnerable to storm surge	• Suitable for areas vulnerable to storm surge

	(such as stone, concrete, steel)	• Flexibility of material options	• Flexibility of material options

Table 1b. Grey techniques for coastal adaptation
Source: adapted from Systems Approach to Geomorphic Engineering (SAGE). (2015). Natural and Structural Measures for Shoreline Stabilization. Developed with support and funding from SAGE, NOAA, and USACE.

1.2. Coastal adaptation strategies in Bangladesh

Adaptation is the way in which species change over time in response to the changing demand of their environment and institutional capacities (Reeve and Sherman, 1993). Through adaptation, people can develop certain physiological, behavioral, and structural traits to raise their survival chances in natural disasters events. Being the most disaster-prone country within South Asia, the government of Bangladesh has taken comprehensive initiatives of structural and nonstructural adaptation strategies to mitigate the risks of natural hazards on its coastal areas. Embankments, polderization, coastal afforestation, shelterbelts and construction of shelter-house are important structural adaptation strategies. Bangladesh became the first country created a separate Disaster Management Bureau (DMB) in 1993. In 2004 the Ministry of Food and Disaster Management (MoFDM) launched the Comprehensive Disaster Management Programme (CDMP), in order to facilitate the reform of the disaster management approach by expanding its focus from reactive emergency response to proactive risk reduction (MoFDM, 2005). The next section describes specific techniques and methods that have been put into action in Bangladesh. These measures reflect not only local efforts but also the global trend of finding effective ways to deal with climate related issues in coastal regions.

1.2.1. Structural strategies

Polders: enhancing coastal resilience through land reclamation

Since the 1960s, Bangladesh has constructed numerous embankments and 139 polders along its coastal belt to combat flooding and salinity intrusion, initially boosting agricultural productivity (Nath et al., 2019). Polders have helped to reclaim lands enclosed by dikes and drainage systems, protecting urban and agricultural areas from monsoon floods in Bangladesh (Beeftink, 1975). However, over time waterlogging and drainage congestion increased particularly in the south-western belt, leading to challenges in land use and management. For example, there has been an increased competition for resources between shrimp farming and traditional agriculture-based livelihoods, contributing to increasing poverty levels and threatening the long-term sustainability of coastal communities in Bangladesh (Nath et al., 2019). Additionally, the Government of Bangladesh has constructed approximately 4000 km long coastal embankment to protect coastal areas and inhabitants from inundation by tidal waves, storm surges and cyclones.

Despite their effectiveness, erosion threatens the functions of polders, exacerbated by tidal surges and river tides. Hence, to enhance resilience it is crucial to consider integrated approaches that encompass natural features like mangroves (Saari and Rahman, 2003). Additionally, to prevent any social conflict of displacement of people and traditions, community involvement is key for effective management and maintenance. Investing in research for resilient polder designs is also critical for adapting to climate change and sea-level rise (Shariot-Ullah, 2024).

Cyclone shelters: safeguarding lives and livelihoods

Bangladesh's vulnerability to natural disasters has spurred the development of an extensive network of cyclone shelters and coastal defenses. Since the 1950s, various national, international agencies, and NGOs have collaborated to construct approximately 3000 cyclone shelters and 200 flood Shelters across Bangladesh (Faruk et al., 2018). These shelters, initiated as a response to the devastating Cyclone Bhola in 1970, have evolved into the Multi-purpose Cyclone Shelter Programme (MPCS) formalized in 1992 (Faruk et al., 2018). These shelters serve not only as vital havens during cyclones, but also as community healthcare centers or schools during regular weather, showcasing their multifaceted impact on local communities (Mallick, 2014; Faruk et al., 2018).

Multipurpose cyclone shelters serve as critical refuge centers during cyclonic events in coastal Bangladesh (Hossain & Saha, 2019). Equipped with essential amenities like tubewells, first aid rooms and sanitary facilities, these shelters play a crucial role in disaster preparedness and response. However, challenges such as improper maintenance and gender disparities in access highlight the need for inclusive and sustainable shelter management strategies (Ahmed et al., 2012). Effective management of cyclone shelters is essential to ensure they remain accessible and functional during emergencies, safeguarding lives and livelihoods in coastal communities. Current efforts are now underway to assess their inclusiveness and ensure they adhere to international standards for disaster risk reduction (Faruk et al., 2018).

Dyke cropping: integrating agriculture with flood management

Dyke cropping involves cultivating crops on embankments to mitigate waterlogging and enhance agricultural productivity in coastal areas (Hossain & Saha, 2019). The introduction of high value cropping on dykes in the southwestern coastal region of Bangladesh offers a promising intervention amidst challenges posed by salinity intrusion and sea-level rise (Akter et al., 2019). By utilizing dyke areas for vegetable cultivation, farmers can diversify their agricultural practices and enhance food security. Gher-based (enclosed ponds) integrated farming is characterized by low investment and it presents a viable option for rural entrepreneurs providing relatively high yields with minimal input costs (Akter et al., 2019).

Dyke Vegetable Production (DVP) is an indigenous knowledge-based practice, which demonstrates the potential of integrated farming to improve livelihoods and sustainability in coastal communities (Hossain & Saha, 2019). Despite facing various production related challenges, the exploration of dyke vegetable production highlights the importance of research initiatives in addressing evolving agricultural landscapes and ensuring food security in coastal Bangladesh (Akter et al., 2019). Initiatives like dyke cropping in Satkhira district show the advantages of integrating flood management with agricultural practices, contributing to livelihood diversification and food security (Harun-ur-Rashid & Islam, 2007). By utilizing available land and water resources more efficiently, dyke cropping offers a sustainable solution to the challenges of agricultural production in coastal regions prone to flooding.

1.2.2. Non-structural measures

Coastal green belt

Dense forests of certain plants can attenuate wave velocity (Mascarenhas, 2006). Mangrove plants act as natural shields to protect local, coastal and regional areas from storms, cyclones, tornadoes, tidal upsurges, shoreline changes and coastal erosion. Naturally grown halophytic plants such as

Sundri (*Heritiera fumes*), Geoa (*E. agallocha*), Goran (*Ceriops sp*.), Kankra (Bruguiera gymnorhiza), Khamo (Rhizophora mucronata), Baen (*Avicennia officinalis*), Keora (*Sonneratia apetala*) and Kulsi (*Aegiceros majus*) have the special adaptation for withstanding in the littoral zones with clayey alluvial soil, tides, strong salinity and winds (FAO Corporate Document Repository and Dutta, 1998). There are several palm species which have the soil-binding capacity and control erosion properties, such as Golpata (*Nipa fruticans*), Hital (*Phoenix paludosa*), coconut (*Cocos nucifera*), cane (*Calamus tenuis*), some swamp elephant grasses (*Typha angustata* and *Typha elephantiana*), *Alpinia allughas* and screw pine (*Pandanus facicularis)*. In the coastal areas, a total of 1,92,395 ha mangrove, 8,690 ha non-mangrove, 2,873 ha Nypa, and 12,127 km strip plantations were planted as of 2013 (Hasan, 2013).

Agricultural adaptation

Existing adaptation practices in coastal agriculture involve the selection of salt-tolerant crop varieties and alternative crops and the adaptation of different agricultural practices, such as planting time and cropping season duration, nutrient management, water management and rainwater harvesting in ponds (Kabir et al., 2018). These anticipatory adaptation practices, such as changing planting times, cropping patterns, salt-tolerant crop varieties, floating garden, poly culture, crab fattening, soil management, etc., not only reduce climate change impacts on coastal livelihoods but also result in potential economic benefits. Aquaculture based intervention showed highly promising followed agriculture-based adaptation measures as the coastal region is dominated by fisherman groups.

Integrated Coastal Zone Management in Bangladesh

While recognizing the limitations of conventional approaches, Bangladesh has embraced integrated coastal zone management (ICZM) strategies (Shariot-Ullah, 2024). ICZM takes a holistic approach to managing coastal resources, emphasizing the integration of environmental conservation with socioeconomic development (Jiménez-Illescas et al., 2019). Through stakeholder engagement, participatory decision-making and the use of ecosystem-based approaches, ICZM aims to build resilience to climate change and sea-level rise while fostering sustainable development along the coast. This approach recognizes the interconnectedness of social, economic, and environmental factors in coastal areas.

Integrated coastal zone management (ICZM) in Bangladesh requires a structured approach involving sequential procedures to address challenges. This begins by identifying issues like coastal erosion, sea-level rise, pollution, and socioeconomic factors. Effective implementation relies on tools like ecosystem-based and community-based management, supported by governmental policies (Shampa et al., 2023). Involving local communities, policymakers, and various stakeholders ensures holistic decision-making which is vital for effective ICZM.

Several initiatives for the conceptualization of integrated coastal zone management (ICZM) have been taken by the government of Bangladesh (GoB) (Ahmad, 2019). The ICZM process was simplified by a program development office that was set up in 2001 under the 1999 policy directives. The following are key initiatives (Iftekhar, 2006):

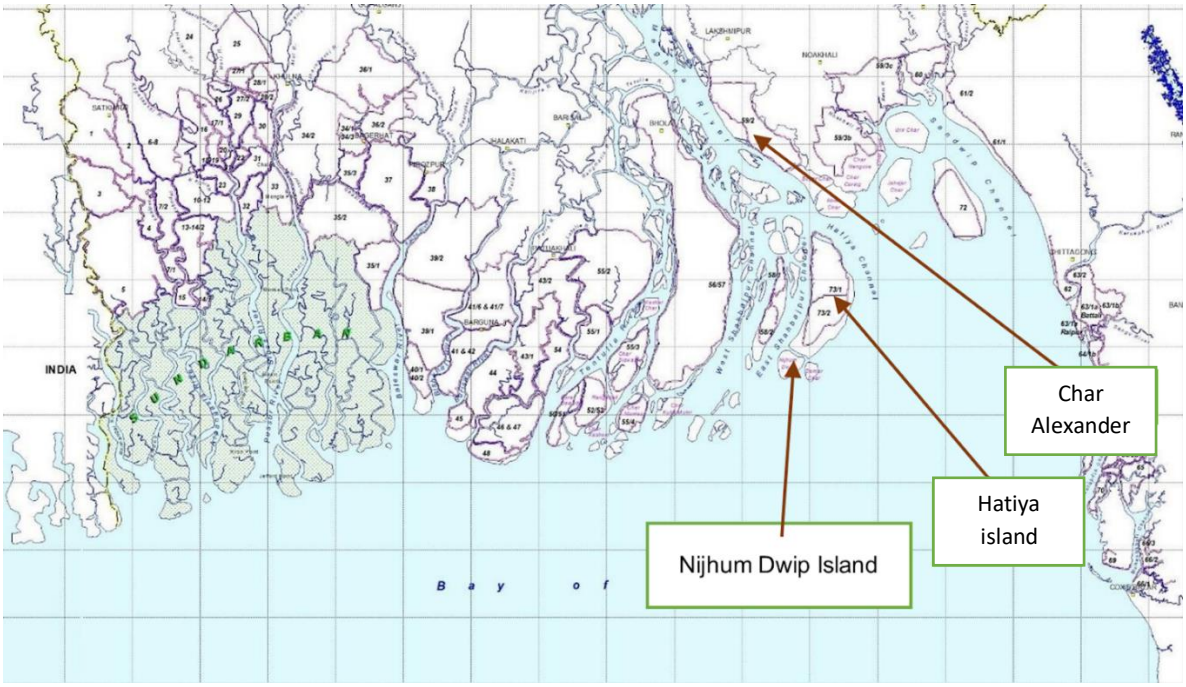
- Off-Shore Islands Development Board (1977–1982)
- Coastal Environment Management Plan for Bangladesh (1987)
- Special Parliamentary Committee on Coastal Area Development (1988–1990)
- Coastal Area Resources Development Plan (CARDMA) (1988)

- National capacity building approach the ICZM initiative (1997)
- Coastal Zone Policy (CZP) (2005)
- Coastal development strategy (CDS) (2006)
- The National Tourism Policy (2009)
- Char development and settlement project (CDSP)
- Bangladesh Delta Plan (BDP) 2100

2. Methodology

2.1. Study area

As indicated in Map 1, three areas were selected for the present study given their particular relevance to the different adaptation strategies described earlier. Firstly, Nijhum Dwip island was selected since it represents a remarkable of NbI and green techniques for coastal adaptation. Secondly, Char Alexender in Ramgati Upazlia was selected due to its importance in terms of grey adaptation measures, particularly revetments. Thirdly, Meghna estuaries in the island of Hatiya were also considered for this study as an example of mixed adaptation strategies (green and grey), such as earthen polders and mangroves. A brief description of each of the areas and its relation with coastal adaptation strategies it is presented in the next sub-sections.



Map 1. Map of the area of study area of coastal region of Bangladesh showing three Upazilas where the questionnaire survey were conducted.

2.1.1. Mangrove forests in Nijhum Dwip

Nijhum Dwip is a small island under Hatiya upazila with a population of over 25,000 and sustained in cultivation, fishing, livestock farming, and production of agricultural goods. The island is part of the Nijhum Dwip National Park (NDNP) which encompasses 163.5 km2 in Bangladesh's southern region, declared a protected area in 2001 under the Wildlife Conservation Act of 1974 (Islam et al., 2021). The Bangladesh Forest Department adopted a mangrove afforestation process in 1966 and accelerated it in the 1980s with the World Bank support in response to the increasing risk due to climate change (Islam et al., 2021). NDNP is considered a crucial ecosystem as it hosts migratory water birds and indigenous wildlife. Therefore, to maintain the ecosystem in NDNP, mangrove plantation efforts have focused on species like Keora, Gewa, and Baen due to their high adaptability capacity with the aim to restore and expand mangrove cover (Islam et al., 2021).

Despite afforestation efforts, human intervention remains the main cause of mangrove cover degradation with a non-linear trend observed. Between 1990 and 2001, forest cover decreased by 29.3%, attributed to coastal erosion and deforestation from activities like illegal logging (Hossain et al., 2016; Islam et al., 2021). From 2001 to 2011, a further decline of 28.7% occurred due to increased demand for timber and fuelwood, exacerbated by inadequate monitoring (Islam et al., 2021). However, between 2011 and 2020 a positive shift was noted, with over 310 ha of forest cover expanded through the Bangladesh Forest Department's coastal plantation program. Recognition of mangrove forests as crucial carbon sinks has highlighted the importance of forest carbon management for climate change mitigation and adaptation, particularly in initiatives like REDD+.

2.1.2. Revetment in Char Alexender

The Coastal Embankment Project (CEP) launched in 1961 aimed to boost coastal agricultural productivity by protecting against tidal floods and salinity intrusion (Gain et al., 2017; Crawford et al., 2020). Through the national strategies adopted, Bangladesh has undertaken the task to build:

- "5,816 km of coastal embankment in 139 polders,
- 2,728 km submersible embankment in haor areas and 7,984 km flood protection embankment in the country,
- to maintain a total of 16,528 km of embankments,
- to protect 1,457 km of riverbank and 31 districts from erosion,
- and to increase the navigability and water storage capacity through 4,375 km river dredging and excavation" (MoEFCC, 2022).

However, many polders are currently underperforming due to poor maintenance, suboptimal water management, and limited community involvement (Gain et al., 2017). To address these issues, the "Coastal Embankment Rehabilitation Project (CERP)" was launched during 1995–2003, focusing on effective embankment maintenance through afforestation (Gain et al., 2017). In this context, Char Alexender is situated under Ramgati Upazlia of Laxmipur Districts with a total land area of 52.54 km² and population of 40,978 (2011 census). In 2017, a centrally located revetment was completed in Char Alexender, with about 3.2 km in length completed to protect the area from storm surges and salinity intrusion from the Meghna Estuaries.

2.1.3. Earthen polder and mangroves in Hatiya Island

The National Adaptation Plan of Bangladesh (2030-2050) considers the maintenance, development and implementation of eco-engineering solutions to manage water resources in climate stress areas and protect human settlements, fisheries and land for agriculture (MoEFCC, 2022). Hatiya Island is an island in the northern Bay of Bengal at the mouth of the Meghna River. An earthen polder was constructed to protect the island from coastal erosion, storm surges and salinity intrusion from the Meghna Estuaries. The Meghna estuarine region, covering 5,278 km^2, hosts about 4.1 million people and constitutes 11% of Bangladesh's coastal zone and 3.5% of its landmass (Mahmood et al., 2019). It is fragile, low-lying condition makes it susceptible to natural hazards like shoreline erosion, salinity intrusion, and tropical storms. Strong seasonality in weather, calm during wet and dry seasons but punctuated by tropical storms in spring and fall, leads to river overflow and waterlogging.

Moreover, the Meghna estuary is confronted with significant challenges. Devastating cyclones, notably in 1970, 1991, and 1997, caused severe damages in the region. In addition to the former,

variations in water discharge and sediment load from upstream have contributed to salinity intrusion and shoreline erosion-accretion, exacerbating the region's vulnerabilities (Mahmood et al., 2019). In response to these challenges, mangroves act as natural shields against coastal processes and facilitate land extension through the acceleration of the accretion process.

Hatia Island is located in the Meghna estuary, in the southern part of Noakhali district. Within an area of 1,508 km^2, a total 346,853 people live on this island. Around 62% of the people are in the agricultural sector in some form, and 6% of the population belongs to the fishery sector, and the rest of the people are mostly day laborers and employees at water-related transportation systems businesses. Among the peasant population, 52% of them are landless. To prevent continual river bank erosion as well as to alleviate the energy of cyclones and storm surges from the Bay of Bengal, a mangrove afforestation program was started in the 1960s by the GoB in order to protect Hatiya Island. In addition, in order to lessen the damage caused by storm surges and seawater intrusion to the inner land, embankments were built to enclose entire Hatiya Island, except in the northern part of the island.

2.2. Theoretical framework

2.2.1 SES-DAPSIR model, participatory approach in decision-making processes

Throughout the process of decision-making in the context of climate change adaptation in coastal areas, the engagement of stakeholders with the local residents is key to include their perspectives and interests in the development and implementation of any project that benefits the community. The perception of individuals regarding projects that make significant contributions to the economy, social or environmental development is a result of an interaction “between personal experience and information from popular media, neighbors, authorities, and experts” (Wang et al., 2022). Active information gaining in a society results in a well-informed public that weighs the different advantages and disadvantages of adopting different responses to a social challenge (Wang et al., 2022; Li et al., 2019). In this sense, active dialogue and communication between stakeholders, academia and the general public lead to the best compromise solution that increases the welfare of the general society meeting its need and supported by technical and scientific data.

For this reason, to foster stakeholder engagement in climate change adaptation we decided to apply an integrated version of the socio-ecological systems (SES) approach with the DAPSIR[1] framework. The resulting SES-DAPSIR framework emphasizes the shared focus on understanding and addressing complex socio-environmental dynamics. Besides, both approaches recognize the interdependence between human activities and the environment, emphasizing the need for inclusive frameworks that consider feedback loops and dynamic interactions. Combining stakeholder engagement with the SES-DAPSIR framework facilitates the development of more effective and inclusive coastal adaptation strategies, promoting resilience in the face of climate change. In what follows it will be provided a brief description of each framework and its integration to study climate change adaptation in coastal areas.

2.2.2 Social-ecological systems framework

[1] Environmental management framework summarized as drivers, activities, pressures, states and impacts.

The social-ecological system framework (SES) depicted in Figure 1 captures the complex interdependence and coevolution of the fundamental natural and anthropic elements of a defined socio-ecosystem. It is made up of structural elements and functional interactions with positive and negative impacts, such as the supply of goods and services by natural ecosystems or the pressure of human activities on natural resources (Young et al., 2006; Giupponi et al., 2022; Cornacchia et al., 2023).

The framework considers a boundary that separates internal and external factors that affect the interaction of the elements and functions within the socio-ecosystem. For the case of internal factors, within the socio-ecosystem there are two main subgroups that assemble physical and biological elements. Regarding the physical elements, the SES considers the terrestrial and aquatic environmental elements defined as “natural capital”, as well as the elements of urbanized areas defined as “human capital”. For the biological elements the framework identifies two modules, “human population” and “other populations (plants and animals)”. The interconnections between natural and anthropic elements derive in ecosystem processes and functions (“ecosystem” module) and economic system dynamics (“economic system” module). The interaction and influence among these processes lead to a range of socio-ecosystem services or disservices, giving rise to unexpected emergent system properties that potentially enable the relation with other functional units (Cornacchia et al., 2023; Giupponi, 2022).

Concerning the external factors, three modules are pointed out to be considered for the effects of their components on the internal elements of the system. These modules are “adaptation policies and measures”, “socioeconomic drivers” and “environmental drivers”. These external forces include economic factors, such as macroeconomic trends; social processes or events, like political crises; and environmental variables, for example, extreme events and mean sea level rise. In conclusion, it's important to highlight that the SES framework suggests a reciprocal interaction between its modules, illustrating the possibility of creating feedback loops. These loops have the potential to either stabilize or destabilize the system, as discussed in the works of Cornacchia et al. (2023) and Giupponi (2022). This bidirectional dynamic underscores the complexity and interconnectedness of the system, emphasizing the critical role of feedback mechanisms in shaping the resilience and adaptability of socio-ecological systems.

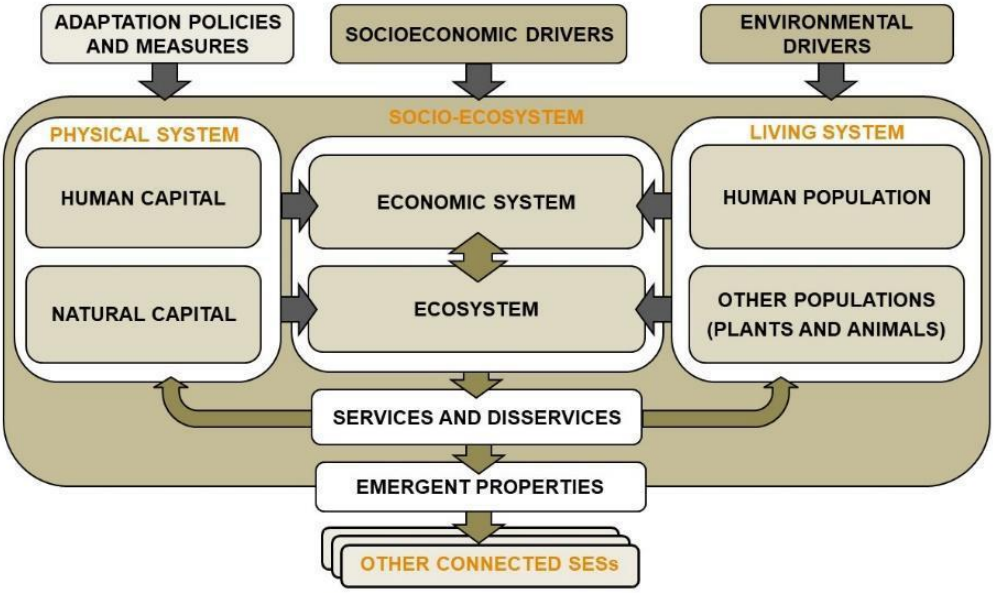


Figure 1: The socio-ecosystem (SES) and interactions among its main constituent modules (Source: Cornacchia, et al., 2023).

2.2.3 DAPSIR framework

Commonly, environmental and ecosystemic issues are analyzed through the lens of the Drivers, Pressures, State, Impacts, Response (DPSIR) framework, evaluating societal impacts on ecosystems and identifying various response strategies to address these challenges across multiple levels. Yet, a refined approach is provided by the DAPSIR framework (see table 2), as detailed by Elliott et al. (2017), Judd & Lonsdale (2021) and Cornacchia et al. (2023). This framework highlights that anthropogenic *Drivers* need fundamentally human *Activities* to be satisfied, therefore, humans have to be understood as part of the ecosystem and not as a system on its own. These activities generate *Pressures* on the ecosystem that modify the *State* of natural capital and elements, which have *Impacts* on the ecosystem services and human well-being. Finally, a set of *Responses* in terms of measures can be adopted to tackle the harm on the system. This helps to analyze the complex relationships between human activities and the environment to show the effects and come up with ways to respond.

Element	Definition
Drivers	Needs that define individual and social motivations for certain activities and shape an entire set of socio-economic factors. In addition to these, important environmental forces that affect socio economic activities can be identified.
Activities	Human activities pursued within the socio-ecosystem and undertaken as a consequence of the drivers in order to meet society's needs (Judd & Lonsdale, 2021).

Pressures	Pressures on the socio-ecosystem exerted by undertaken activities (Judd & Lonsdale, 2021).
State	State and/or condition (and related dynamics of change) of the elements belonging to the following SES modules: Natural Capital, Other Populations (Plants and Animals), Human Capital, Human Populations.
Impacts	Intended as the affections on socio-ecosystem services and economic features driven by changes in the state.
Responses	Policy or social responses, intended as planning and management measures (in place or potential) that are or can be implemented to prevent or minimize the causes of state changes or, where impacts have occurred, to mitigate their effects (Judd & Lonsdale, 2021).

Table 2. DAPSIR framework elements definition (Source: Cornacchia, et al. 2023).

2.2.4 SES-DAPSIR framework

Based on systems dynamics, Cornacchia et al. (2023) developed a general framework to analyze climate change adaptation issues in relation to policy-making processes. The proposed model allows to create a set of main macro-categories of elements framed in a combined SES-DAPSIR framework to capture specific categories and focus on the interest elements for modeling exercises that answer defined purposes in the realm of coastal adaptation. The SES-DAPSIR model, which integrates the social-ecological systems (SES) with the DAPSIR framework, provides a holistic methodology for examining complex socio-environmental challenges, especially within coastal adaptation context. It integrates insights from SES literature with the established DAPSIR framework, providing a nuanced understanding of the dynamic interactions between human activities and the environment.

The framework considers that anthropogenic and environmental drivers shape human activities, leading to pressures on socio-ecosystems. These pressures trigger changes in the state of natural and anthropogenic elements, ultimately impacting human well-being and necessitating responses or adaptive measures. Unlike the traditional DAPSIR framework, SES-DAPSIR acknowledges the bidirectional nature of these interactions and incorporates feedback loops, better capturing the interactive dynamics of socio-ecological systems. The SES-DAPSIR seems adequate to study coastal adaptation in Bangladesh, given the region's vulnerability to climate change and sea-level rise. A practical application of this framework, exemplified by an applied version of the conceptual model presented in Figure 2, aids in comprehending the causal connections between socio-environmental issues and management responses. This diagram serves as a valuable tool for guiding effective coastal adaptation strategies by synthesizing insights from scientific literature and elucidating key elements for decision-making processes.

By employing SES-DAPSIR in coastal adaptation planning for Bangladesh, stakeholders gain a systemic understanding of the intricate socio-ecological dynamics at play. This approach empowers decision-makers to develop evidence-based adaptation strategies that consider both social and ecological dimensions, thereby fostering sustainable and resilient coastal communities in Bangladesh.

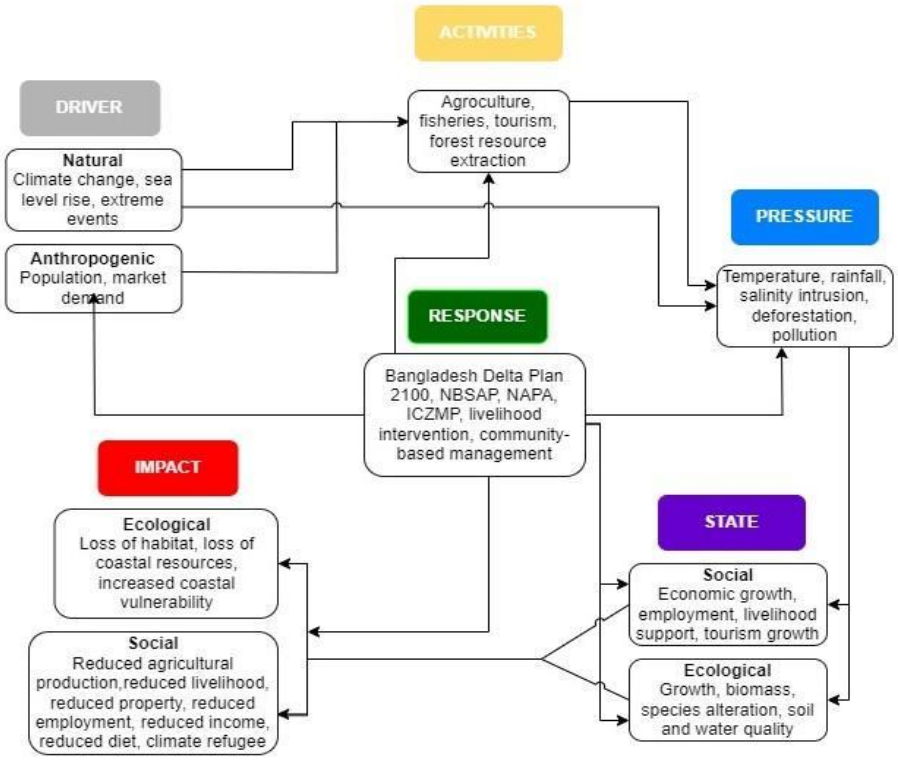


Figure 2. SES-DAPSIR conceptual model of a coastal SES (Model was developed following Cornacchia, et al., 2023).

2.3. Research design and data sources

2.3.1. Surveys and fieldwork

In alignment with the adoption of the SES-DAPSIR framework, surveys serve as a key instrument clarifying local community perceptions concerning coastal defense measures. They hold a crucial importance in deepening the understanding of the effects and day-to-day experiences of those living in coastal areas, who are subject to a range of protection strategies. Consequently, surveys play an instrumental role in informing and giving a clearer overview to stakeholders in Bangladesh, facilitating the formulation of adaptation strategies along coastal areas that consider social and ecological aspects.

In this sense, it was decided to analyze local's people perceptions of green, grey and mixed infrastructure for coastal protection, drawing from surveys conducted in November 2023 across the three coastal communities described earlier in section 2.1. Specifically, structured questionnaire surveys were employed to investigate community perspectives on coastal protection measures, encompassing four types of ecosystem services (ES). Overall, 50 respondents were surveyed in the three study areas.

2.3.2 Science-policy workshop & questionnaire about ES

To grasp a holistic view of coastal adaptation strategies, the results of the surveys were complemented with the opinion of scientific and policymaking stakeholders in Bangladesh. Hence, an online workshop was jointly organized by Fondazione Eni Enrico Mattei's ADAPT@VE program, Murdoch University, and Universita Ca' Foscari Venezia. In total, 25 people attended the event mostly with a scientific or policy-related background. This event aimed to deliberate on two key

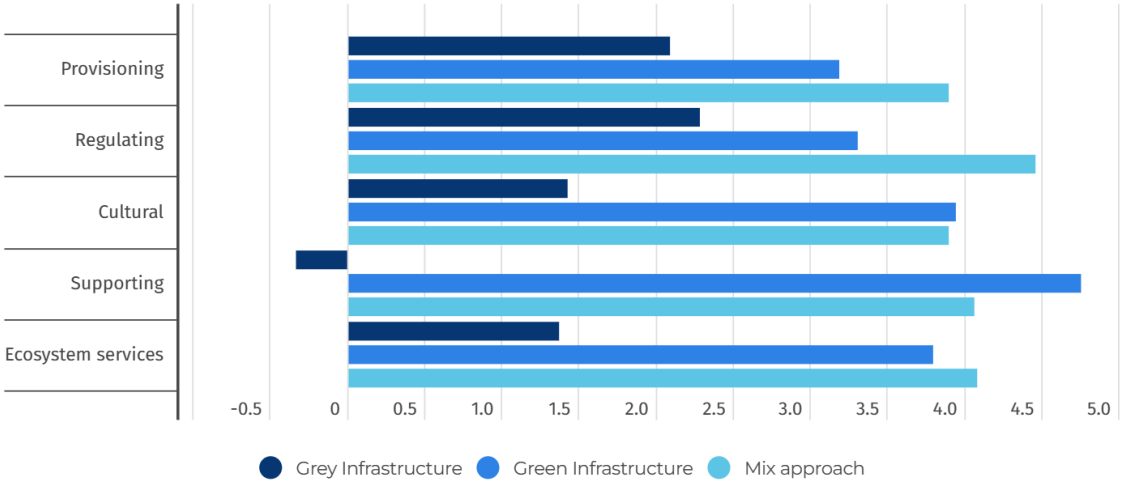
research activities: the results coming from the field surveys with local communities discussed before and the SES-DAPSIR model of Figure 2. Discussions revolved around assessing the effectiveness of grey, green, and hybrid infrastructure in providing socio-economic and environmental benefits to local communities, as well as consolidating the model to understand coastal socio-ecological systems functioning in the face of climate change. The participants also contributed to a survey in order to gather perspectives and priorities regarding the ecosystem services offered by coastal environments. Furthermore, the workshop aimed to derive policy implications and recommendations for coastal protection based on the insights gleaned during the sessions.

3. Results

3.1 Local communities' opinion about coastal infrastructure and ecosystem services

According to the residents of the Nijhum Dwip island, the implementation of green strategies is assessed to yield moderate to high levels of contribution across all ecosystem services, as depicted in Graph 1. Conversely, the utilization of grey infrastructure is perceived to offer lower to moderate levels of contribution to provisioning, regulatory, and cultural services, and is viewed as a detractor in terms of supporting performativity. Overall, the integration of green-grey infrastructure is perceived to confer a superior contribution across all ecosystem services.

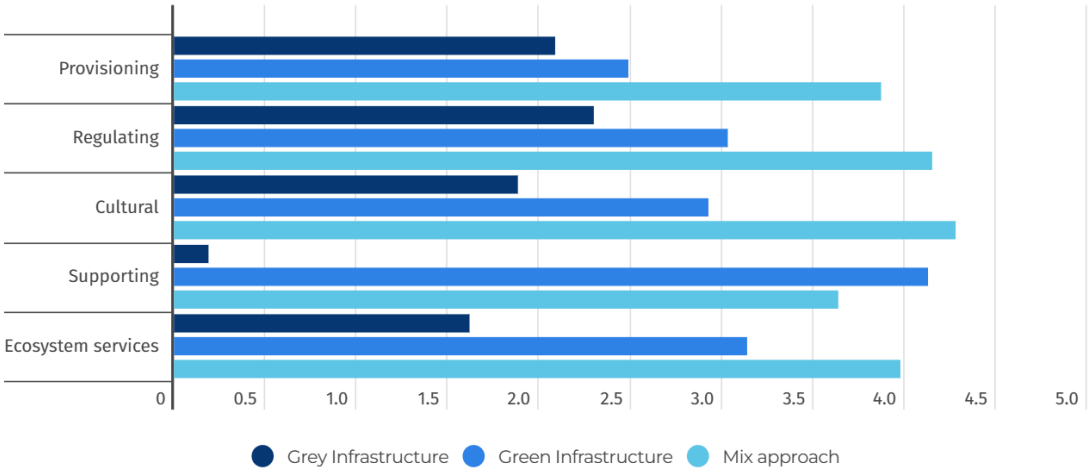
Graph 1. Evaluation of Nijhum Dwip residents on coastal adaptation approaches



The graph shows the evaluation of Nijhum Dwip residents on ecosystem services for each coastal adaptation approach (grey, green and mix). 0 represents the absence of a service while 5 is the highest score for the services, and negative numbers represent disservice. Source: Hossain M. S., Gain, A., Giupponi, C., *Questionnaire for Field Survey, Mangrove SES within the framework of NbS*, 2023.

From the point of view of local inhabitants of Char Alexander, grey infrastructure is perceived to have low to moderate contributions to ecosystem services (Graph 2). Conversely, residents attribute higher efficacy in ecosystem service provision to green and green-grey strategies. While residents acknowledge the advantages of revetment, the findings suggest that implementing mixed strategies to combat storms and salt intrusion would lead to an overall enhancement in ecosystem service levels.

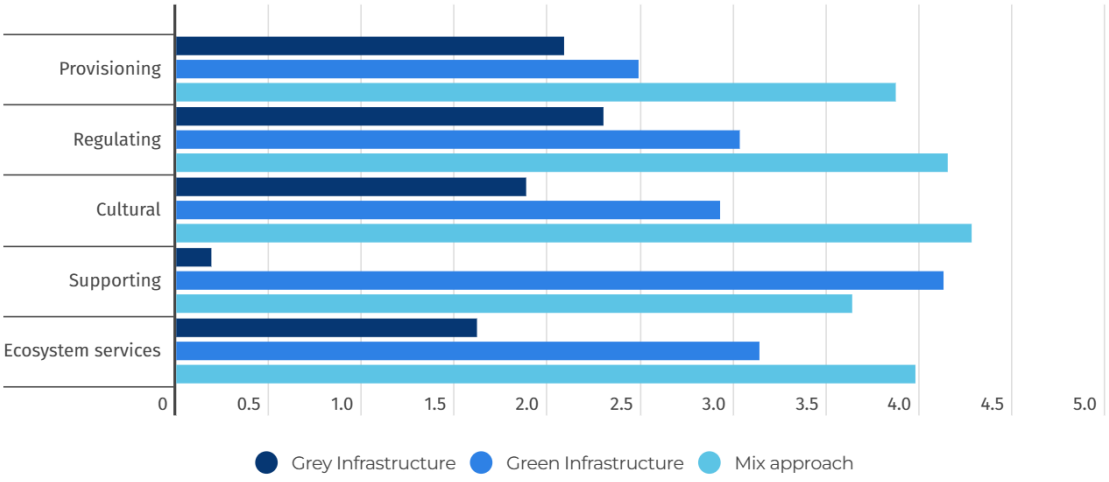
Graph 2. Evaluation of Char Alexender residents on coastal adaptation approaches



The graph shows the evaluation of Char Alexender residents on ecosystem services for each coastal adaptation approach (grey, green and mix). 0 represents the absence of a service while 5 is the highest score for the services, and negative numbers represent disservice. Source: Fondazione Eni Enrico Matei, Questionnaire for Field Survey, Mangrove SES within the framework of NbS, 2023.

Lastly, residents of Hatiya perceive the contribution of green-grey infrastructure to ecosystem services as above medium and high. Graph 3 illustrates that respondents evaluated the other two approaches, green and grey, as falling under the performativity level of the mix approach. However, for supporting services, respondents indicated that green infrastructure would enhance the level of contribution.

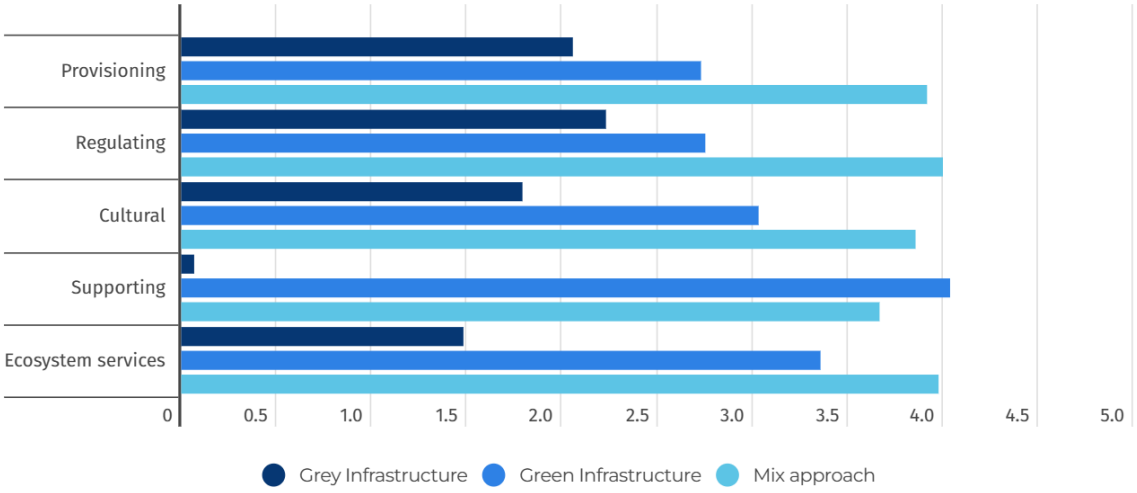
Graph 3. Evaluation of Hatiya residents on coastal adaptation approaches



The graph shows the evaluation of Hatiya residents on ecosystem services for each coastal adaptation approach (grey, green and mix). 0 represents the absence of a service while 5 is the highest score for the services, and negative numbers represent disservice. Source: Hossain M. S., Gain, A., Giupponi, C., Questionnaire for Field Survey, Mangrove SES within the framework of NbS, 2023.

Across the surveyed communities, perceptions regarding the impacts and benefits of the three approaches for coastal change adaptation show similar preferences. Inhabitants generally perceive green infrastructure as yielding medium to high contributions across all ecosystem services, contrasting with the perceived low to medium contributions of grey infrastructure. The combination of green and grey approaches, however, is perceived to achieve higher levels of ecosystem services overall. Furthermore, residents recognize the benefits of mixed strategies, particularly in enhancing the level of ecosystem services, such as supporting services, while providing more protection against extreme events such as floods or cyclones. This indicates a generalized preference among communities, favoring hybrid approaches that embrace the strengths of both green and grey infrastructure for coastal protection and adaptation.

Graph 4. General evaluation of residents on coastal adaptation approaches



The graph shows the general evaluation of residents on ecosystem services for each coastal adaptation approach (grey, green and mix). 0 represents the absence of a service while 5 is the highest score for the services, and negative numbers represent disservice. Source: Hossain M. S., Gain, A., Giupponi, C., Questionnaire for Field Survey, Mangrove SES within the framework of NbS, 2023.

3.2 Connecting science and policy through a participative workshop

3.2.1 Discussion of communities' perception of NbI

Recognizing the importance of green, grey, and mixed solutions

Understanding the significance of nature-based, grey, and mixed solutions is key in coastal protection efforts in Bangladesh. Given its vulnerability to climate change and rising sea levels, Bangladesh relies heavily on effective coastal management strategies. Nature-based solutions, such as mangrove restoration and wetland preservation, play a crucial role in shielding against coastal erosion, storm surges among other challenges. Conversely, the implementation of grey infrastructure, including concrete seawalls and embankments, has been common practice to mitigate immediate threats. However, there is growing recognition of the need for mixed approaches that amplify the strengths of both nature-based and grey solutions to achieve sustainable coastal resilience.

Preferences for green, grey, and mixed solutions

Stakeholders in Bangladesh express preferences for nature-based, grey, or mixed solutions based on various factors distinctive to the region. Given the country's extensive network of rivers and coastal areas, there is a strong emphasis on finding nature-based solutions to address erosion and flooding issues. However, the cost-effectiveness and long-term viability of nature-based solutions are emphasized, especially in comparison to traditional grey infrastructure like cement concrete blocks, which may be less suitable for the country's environmental conditions.

Challenges in green, grey, and mixed solutions

Implementing nature-based, grey, and mixed solutions in Bangladesh presents both challenges and opportunities. While nature-based solutions offer ecological benefits and align with the country's environmental priorities, there are challenges in quantifying their impacts and integrating them effectively into coastal management plans. Grey solutions, on the other hand, often face issues related to high construction costs and potential ecological harm. To address these challenges, there is a need for collaborative efforts between government agencies, researchers, and local communities to develop holistic coastal management strategies that prioritize sustainability and resilience. Additionally, incorporating demographic information and conducting quantitative analyses can provide valuable insights into the effectiveness of different solutions, guiding decision-making processes toward more informed and adaptive approaches to coastal protection in Bangladesh.

3.2.2. Discussion of general conceptual model

The SES-DAPSIR model shows causal connections and stands as an effective guide for grasping coastal dynamics in Bangladesh, adaptable across diverse landscapes (see Figure 2). In general, participants agreed that this diagram captures the complex dynamics of coastal systems and management responses, empowering policymakers to tailor effective strategies that address Bangladesh's specific coastal resilience needs. Moreover, the participants highlighted the following as relevant considerations to improve the framework:

1. The significance of embedding prospective plans and long-term strategies within the conceptual framework.

2. To consider urban-rural disparities and development in the next decades, underlining the importance of addressing anthropogenic drivers and potential future impacts.
3. To incorporate erosion, accretion, and rapid development pressures into the model underscore the urgency of addressing Bangladesh's coastal challenges comprehensively.
4. To take into consideration the complex relationship and trade-offs between ecosystem protection and rapid urbanization.

Following the insights gathered during the workshop, the initial diagram proposed in section 2 was improved to take into account the considerations made by the participants (see Figure 3 below):

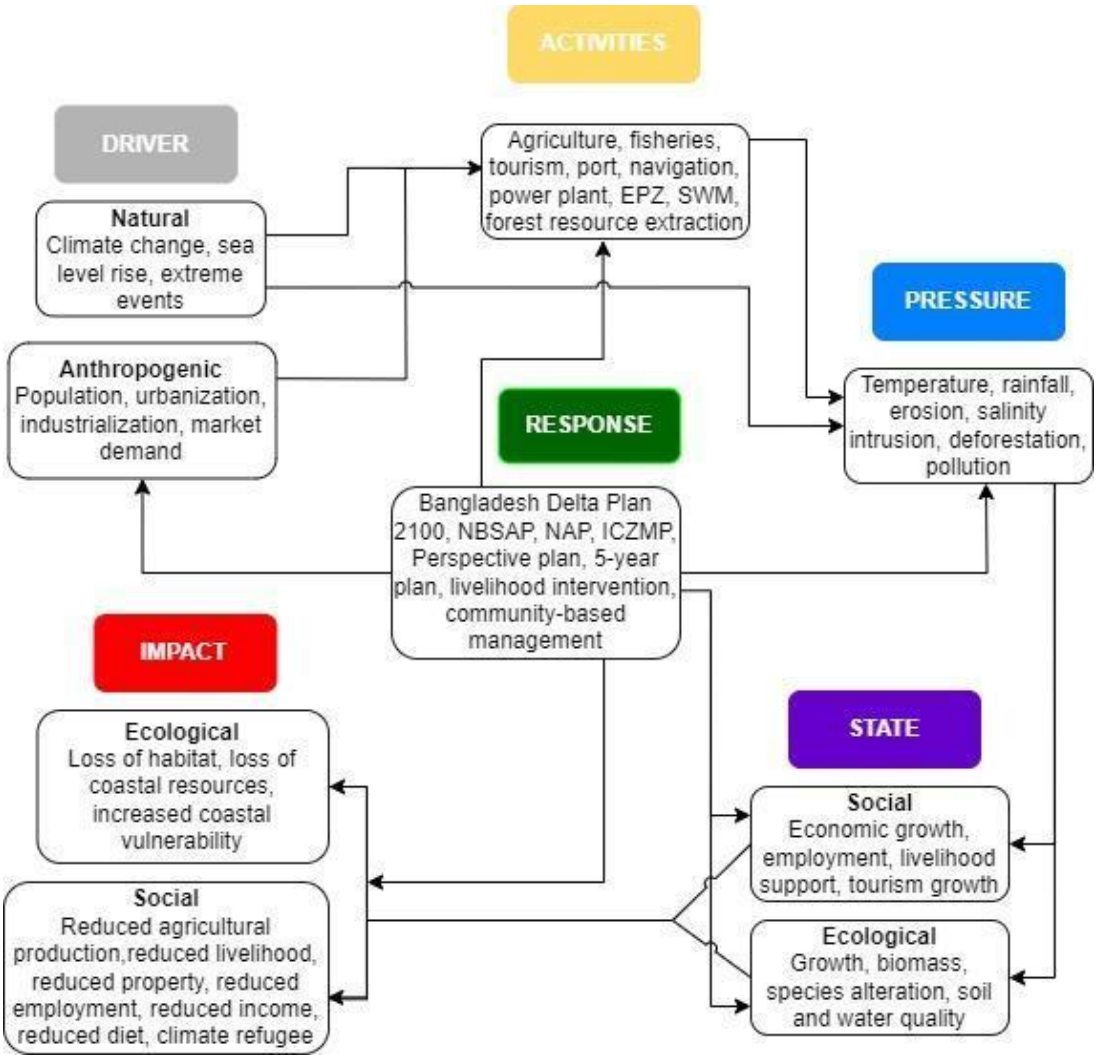


Figure 3. SES-DAPSIR conceptual model of a coastal SES, improved after the workshop.

3.2.3 Survey about relevance of mangrove ecosystem services in coastal Bangladesh

During this workshop, surveys were also conducted to understand stakeholders' perspectives and priorities concerning ecosystem services provided by coastal ecosystems. The analysis of surveys is key to obtain insights about the relative importance of ecosystem services and developing targeted strategies. Table 3 presents the main findings, which provide valuable insights into stakeholders'

perceptions and priorities regarding the importance of mangrove ecosystem services in coastal Bangladesh. The most important ecosystem services identified were the reduction of storm surges and coastal erosion protection (*regulating*), biodiversity (*supporting*), tourism and recreation (*cultural*), as well as agricultural production and breeding grounds for marine species (*provisioning*).

Service	Perceptions and priorities
Provisioning	Agricultural production and breeding grounds for marine species were identified as important provisioning services, reflecting the economic importance of these activities.
Regulating	Reduced storm surges and coastal erosion protection were highlighted as crucial regulating services, addressing major concerns related to coastal hazards.
Cultural	Tourism and recreation emerged as significant cultural services, indicating the potential for economic and recreational opportunities associated with coastal ecosystems.
Supporting	Biodiversity was recognized as the leading supporting service, highlighting its importance for ecosystem health and resilience.
Overall importance	Respondents considered regulating services, particularly protection from tsunamis and storm surges, to be the most important category overall, underscoring the importance of coastal protection measures in coastal Bangladesh.

Table 3. Prioritized ecosystem services by stakeholders in Bangladesh.
Source: Survey carried out in the *Scientific-policy workshop with key stakeholders*, Fondazione Eni Enrico Mattei, 2023.

4. Discussion and policy recommendations

4.1. Comparing the view of different stakeholders with regards to coastal adaptation strategies

Understanding the view of different groups of stakeholders is key to address climate adaptation strategies, however each of them might agree or have conflicting views about what is considered to be relevant for the analysis. For this reason, Table 4 compares the opinion of local communities against that of science and policy stakeholders in relation to the three types of infrastructures for each of the three areas of study.

In Nijhum Dwip, local communities perceive green infrastructure, particularly mangrove forests, as highly beneficial to preserve all ecosystem services, aligning with the importance of nature-based solutions emphasized by scientists and policy makers. However, there is a discrepancy in the perception of grey infrastructure, with communities viewing its contribution as lower compared to green infrastructure, while scientists and policy makers recognize its common practice for immediate threat mitigation. Regarding mixed infrastructure, both groups acknowledge its potential for achieving higher ecosystem service contributions, albeit with different emphases: communities focus on its overall benefits, while scientists and policy makers stress the need for collaborative efforts to integrate mixed strategies effectively.

In Char Alexender, communities also perceive higher levels of ecosystem services contributions from green infrastructure compared to grey infrastructure, reflecting their preference for nature-based solutions due to their cost-effectiveness and environmental alignment. This contrasts with the perspective of scientists and policy makers, who acknowledge the importance of nature-based solutions but also highlight the challenges faced by traditional grey infrastructure. Regarding mixed infrastructure, communities believe it increases overall ecosystem service levels, while scientists and policy makers emphasize the necessity for collaborative integration and integrated economic valuation efforts to optimize its effectiveness.

In Hatiya, both communities and stakeholders perceive green and grey infrastructure similarly, acknowledging their medium to high contribution to ecosystem services. However, communities see green infrastructure as particularly crucial for supporting services, while scientists and policy makers emphasize the challenges faced by grey solutions. Concerning the mixed strategies, communities perceive a greater performance and provision of services, indicating overall benefits, while scientists and policy makers stress the need for collaborative efforts to develop holistic coastal management strategies.

Area	Infrastructure Type	Local Communities' Perceptions	Scientists/Policy Makers' Perceptions
	Green Infrastructure	Medium to high contribution to all ecosystem services perceived	Nature-based solutions (like mangrove restoration) crucial for coastal protection

Mangrove forests in Nijhum Dwip	Grey Infrastructure	Low to medium contribution to ecosystem services perceived.	Common practice for immediate threat mitigation, but faces challenges like high costs and potential ecological harm.
	Mixed Infrastructure	Perceived as achieving higher contribution for all ecosystem services.	Leverage strengths of both nature-based and grey solutions for sustainable coastal resilience, addressing challenges of each.
Revetment in Char Alexender	Green Infrastructure	Higher levels of ecosystem services achieved compared to grey infrastructure.	Nature-based solutions are prefered due to their cost-effectiveness and alignment with environmental priorities.
	Grey Infrastructure	Low to medium contribution to ecosystem services perceived.	Traditional grey infrastructure faces issues like high construction costs and potential ecological harm.
	Mixed Infrastructure	Adoption of mixed strategies perceived to increase overall ecosystem services level.	Need for collaborative efforts to integrate nature-based and grey solutions effectively into coastal management plans.
Earthen polder and mangroves in Meghna Estuaries, Hatiya	Green Infrastructure	Medium to high contribution to ecosystem services perceived, especially for supporting services.	Recognized as crucial for coastal protection, but challenges exist in quantifying impacts and integrating them into management plans.
	Grey Infrastructure	Medium to high contribution to ecosystem services perceived.	High construction costs and potential ecological harm are major challenges for grey solutions.
	Mixed Infrastructure	Adoption of mixed strategies increases overall ecosystem services level.	Collaborative efforts needed between government, researchers, and local communities to develop holistic coastal management strategies.

Table 4. Comparison of Local Communities' and Scientists/Policy Makers' Perceptions of Coastal Infrastructure in Bangladesh.

Source: Fondazione Eni Enrico Matei, *Questionnaire for Field Survey, Development of Questionnaire for Mangrove SES for the Sundarbans within the framework of NbS*, 2023 and Survey carried out in the *Scientific-policy workshop with key stakeholders*, Fondazione Eni Enrico Mattei, 2023

4.2 Strengthening society for coastal adaptation processes in Bangladesh

In the urgent pursuit of climate resilience and sustainability, governments and state institutions have the key task of mobilizing collective action. Parallel to the collaboration among stakeholders, it is necessary the development of national engagement strategies that empower citizens with the knowledge and tools to organize and take independent action in addressing climate challenges. As societies grapple with the complexities of climate change, a paradigm shift is necessary—one that transcends mere technical solutions and embraces a holistic transformation of societal values and behaviors.

It is within this context that the concept of a 'virtuous cycle' gains prominence, as it elucidates how active collaboration between the public, businesses, and government can catalyze a profound social shift towards sustainability and resilience (Ledwell et al., 2023). This virtuous cycle, as depicted in Figure 4, represents an iterative process wherein societal engagement and cooperation serve as catalysts for transformative solutions. Beginning with the identification and inclusion of the perceived priorities of the public, this process progresses to the formulation of responsive policies. Subsequently, it incentivizes and promotes the participation of businesses and academia as transformative agents, propelling the transition towards a sustainable reality. Ultimately, a shift in society's behavior initiates a new set of demands, further advancing sustainability and climate-resilience in a continuous feedback loop.

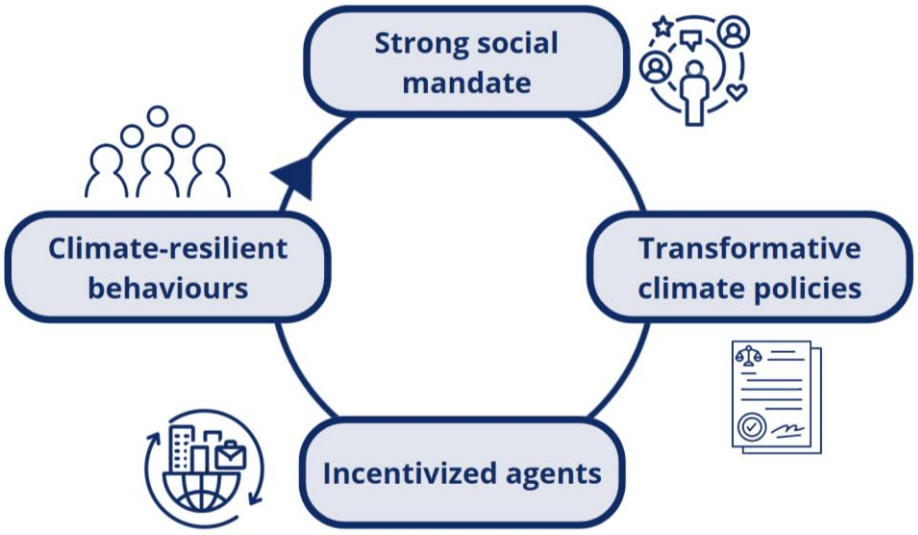


Figure 4. Virtuous cycle (Source: Adapted from Ledwell et al., 2023).

To initialize the virtuous cycle in the face of climate change, governments must actively engage with the public through comprehensive implementation of the elements of Action for Climate Empowerment (ACE) outlined by the UN Framework Convention on Climate Change. These include education, training, public access to information, awareness-raising campaigns, fostering public participation, and fostering international cooperation. By embracing these pillars, governments can empower individuals and communities to become informed stakeholders in the fight against climate

change, enabling them to contribute meaningfully to decision-making processes and policy formulation.

People are intimately familiar with the tangible effects of climate change, often experiencing its impacts firsthand. Their lived experiences provide invaluable insights into where and when aid and action are most urgently needed. Thus, engaging citizens in decision-making processes regarding solutions and measures to address the existential threats posed by climate change is paramount. Beyond mere dissemination of scientific and technical information, individuals shape their attitudes and behaviors towards public projects based on considerations aligned with their values and beliefs (McLoughlin et al., 2019; Ledwell et al., 2023). Moreover, fostering acceptance and buy-in from communities necessitates the crafting of tailored narratives that not only recognize their concerns but also embody their values and reflect their identity (Ledwell et al., 2023). These concerted efforts ensure that citizens are not only informed but also actively involved and equipped to contribute meaningfully to climate action initiatives. Table 5 provides a tangible illustration of how Bangladesh has aligned its strategies with the ACE framework, exemplifying the inclusion of civil society in the decision-making process.

Definition	Measure adopted
Education. "Incorporating climate change across all aspects of formal and informal education is the starting point for effective climate action" and adaptation.	The Ministry of Education has adopted a syllabus which promotes the study of climate change. Several public and private universities have introduced courses on climate change, adaptation to climate change induced disasters, and risk mitigation. In higher education, the Institute of Water and Flood Management (IWFM) under Bangladesh University of Engineering and Technology (BUET) provides diploma and master's courses in the same line.
Training. "Vocational training in key climate-related sectors to develop practical and technical skills for securing a just transition to a low-carbon, climate resilient future that leaves no one behind"	The Institute of Disaster Management and Vulnerability Studies, affiliated with the University of Dhaka (DU), serves as a vital academic and research institution, emphasizing the importance of training in disaster management and vulnerability. Bangladesh universities collaborate with foreign partners to offer joint programs in intensive climate change research and training at the post-graduate level. Additionally, the Bangladesh Public Administration Training Centre (BPATC) conducts specialized training on climate change for public service cadres, highlighting the nation's dedication to addressing environmental challenges effectively.
Public Awareness. "involves governments providing early warning information and safety instructions, or it can be a media campaign highlighting the impact of climate change on human and environmental health, or a public-sponsored radio programme to inform small-holder farmers about climate-resilient farming"	Assistance from UNDP has led to the integration of disaster risk reduction and climate change adaptation skills into the National Curriculum and Textbook Board, ensuring that school-age children are equipped with essential knowledge (Cela et al., 2014). Furthermore, various non-governmental organizations (NGOs) and civil society organizations (CSOs) are actively engaged in raising awareness about fundamental concepts of climate change, associated risks, and potential strategies for addressing these issues (The Asia Foundation, 2012).

Public participation. "Providing the public with an opportunity to share their views and perspectives in decision-making processes enhances the quality of decisions and often results in a high rate of compliance with the policy or regulation being implemented."	In addition to involving local communities action in national strategies, institutes like the Department of Women's Affairs (DWA) promote the participation of specific populations to reduce social gaps. In this case, through including DWA representatives in Disaster Management Committees (DMC), ensuring women's involvement in preparedness and disaster management, and providing livelihood assistance to women and children impacted by natural disasters.
Public access to information. "Information on the climate crisis should be readily accessible and freely available to the public, so they are equipped with the tools to play an active, meaningful role in climate policy and action".	The Disaster Management Information Network (DMIN) Portal, managed by the Ministry of Disaster Management and Relief, serves as a centralized hub for sharing critical disaster management information and programs. Additionally, the Integrated Coastal Resources Database (ICRD) supports the implementation of the Integrated Coastal Zone Management Plan (ICZMP) in Bangladesh. The Water Resources Planning Organization 's National Water Resources Database (NWRD) meets the increasing demand for reliable water sector data, ensuring transparency and accessibility for stakeholders.
International cooperation. "Enhance support to national efforts, allow for aggregation and joint efforts and create opportunities for knowledge exchange to foster greater climate action."	The International Centre for Climate Change & Development (ICCCAD) prioritizes the intersection of climate change and development, providing top-tier short courses tailored for personnel from NGOs, universities, and government entities. As the pioneering international center situated in a developing nation, it uniquely bridges development and climate change, striving to enhance capacity among individuals grappling with adaptation challenges within development contexts. This underscores the significance of international cooperation in addressing multifaceted issues like climate change and development.

Table 5. Action for Climate Empowerment measures adopted in Bangladesh.
Source: Adapted from Action for Climate Empowerment (ACE) of the UN Framework Convention on Climate Change; Ledwell, C., Ray, D. B., Hameed, N., & Sawas, A, (2023), *Public Engagement on Climate Change Adaptation*, NAP Global Network; and Ministry of Environment, Forest and Climate Change, Government of the People's Republic of Bangladesh, (2018), *Third National Communication of Bangladesh to the United Nations Framework Convention on Climate Change*, People's Republic of Bangladesh.

Lastly, it should be noted that our research efforts align closely with the principles delineated within the Action for Climate Empowerment (ACE) framework as outlined by the UN Framework Convention on Climate Change. While the core of this policy brief lies within specific aspects of public participation and international cooperation, we envision our work as a stimulus for adopting additional approaches to climate action, encompassing diverse elements of the ACE framework such as public awareness and public access to information. Through rigorous academic inquiry and collaborative action, more resilient adaptation strategies can be forged, safeguarding the well-being of present and future generations amidst climate change in coastal regions in Bangladesh and across the globe.

5. Conclusions

Coastal infrastructures are crucial climate change adaptation strategies and they dependent on the specific social, economic and ecological characteristics of the area of implementation. Nature-based solutions (NbS) help communities adapt to climate change while protecting biodiversity. NbS includes nature-based infrastructure (NBI) like mangroves, which offer flood protection and other ecosystem services. Grey infrastructure, such as embankments, provides engineered protection and economic benefits. A hybrid approach combining NbS with grey infrastructure enhances community resilience and well-being by leveraging both natural and engineered solutions. For the case of Bangladesh, structural and nonstructural adaptation strategies have been put in place to mitigate coastal risks. The first include constructing embankments, polders, and cyclone shelters, which protect against floods and cyclones, though challenges like erosion and maintenance persist. Additionally, dyke cropping integrates agriculture with flood management, enhancing productivity and food security. Nonstructural measures, such as coastal green belts using mangroves and salt-tolerant crops, also play a vital role. Lastly, Integrated Coastal Zone Management (ICZM) combines environmental conservation with socioeconomic development, involving community participation and stakeholder engagement.

This paper employed a qualitative approach to understand the benefits and challenges of three different types of coastal infrastructure in the south central coastal of Bangladesh. Nijhum Dwip Island, Char Alexander and the Meghna Estuaries of Hatiya were selected for the analysis since each of them represents a relevant example of green, grey and mixed infrastructure, respectively. The present study employed the SES-DAPSIR framework as a comprehensive analytical tool for understanding socio-environmental dynamics and guiding decision-making processes in the three areas of study. By integrating insights from social-ecological systems thinking with the DAPSIR framework, stakeholders can develop inclusive and effective coastal adaptation strategies tailored to local contexts. For this reason, our research design involved a two-fold approach: to conduct surveys with local inhabitants based on a structured questionnaire and to discuss a conceptual model with science and policy makers during a workshop. The goal of these two activities was to grasp their opinion in relation to the existing coastal infrastructures in place as well as the ecosystem services they provide.

The main finding of this work is to highlight the potential ecological impacts and costs associated with grey infrastructure, advocating for a balanced approach that combines green and grey solutions. Firstly, local communities on Nijhum Dwip island, Char Alexander, and Hatiya favor green infrastructure for its high contributions to ecosystem services, while grey infrastructure is seen as less effective. They prefer hybrid approaches that integrate green and grey solutions for superior benefits, especially in combating storms and salt intrusion. Secondly, science and policy stakeholders emphasize the importance of mixed solutions for coastal protection in Bangladesh. They recognize the ecological benefits and long-term viability of nature-based solutions, though they also consider the cost-effectiveness of grey infrastructure. The SES-DAPSIR model helps understand coastal dynamics, and participants suggest improvements like embedding long-term plans, addressing urban-rural disparities, considering erosion and development pressures, and balancing ecosystem protection with urbanization. Lastly, this type of stakeholders considers regulating services provided by coastal infrastructure to be the most important category overall, particularly protection from tsunamis and storm surges.

Given that the views of different stakeholders might differ in relation to what are the best coastal adaptation strategies, it is important to analyze it in a comparative way and to bridge them through participatory exercises. In Nijhum Dwip, locals highly value green infrastructure, like mangroves, aligning with scientific emphasis on nature-based solutions, but they see grey infrastructure as less beneficial, unlike scientists and policymakers who value its immediate threat mitigation. Both groups see potential in mixed infrastructure but with different focuses. In Char Alexander, locals prefer green infrastructure for its cost-effectiveness, contrasting with policymakers who also recognize grey infrastructure's challenges. Both groups see value in mixed strategies, but policymakers stress the need for integrated efforts. In Hatiya, both groups view green and grey infrastructure positively, with locals prioritizing green for supporting services and policymakers noting grey's challenges. Overall, fostering societal resilience and empowerment is essential for sustainable coastal adaptation. Governments must prioritize public engagement through initiatives such as the Action for Climate Empowerment (ACE) framework, which emphasizes education, training, public awareness, and participation. By empowering citizens with the knowledge and tools to organize and take independent action, governments can catalyze transformative social change towards sustainability and resilience.

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