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Overcoming challenges for implementing nature-based solutions in deltaic environments: insights from the Ganges-Brahmaputra delta in Bangladesh

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Abstract

The Ganges-Brahmaputra (GB) delta is one of the most disaster-prone areas in the world due to a combination of high population density and exposure to tropical cyclones, floods, salinity intrusion and other hazards. Due to the complexity of natural deltaic processes and human influence on these processes, structural solutions like embankments are inadequate on their own for effective hazard mitigation. This article examines nature-based solutions (NbSs) as a complementary or alternative approach to managing hazards in the GB delta. We investigate the potential of NbS as a complementary and sustainable method for mitigating the impacts of coastal disaster risks, mainly cyclones and flooding. Using the emerging framework of NbS principles, we evaluate three existing approaches: tidal river management, mangrove afforestation, and oyster reef cultivation, all of which are actively being used to help reduce the impacts of coastal hazards. We also identify major challenges (socioeconomic, biophysical, governance and policy) that need to be overcome to allow broader application of the existing approaches by incorporating the NbS principles. In addition

to addressing GB delta-specific challenges, our findings provide more widely applicable insights into the challenges of implementing NbS in deltaic environments globally.

1. Introduction

Deltas are often densely populated and support much of the world's fisheries, forest products and agriculture. Protecting livelihoods and ecosystem services in deltas is therefore of global importance. Human society in the 20th century fundamentally altered the nature of how deltas such as the Nile, Rhine, Colorado, Danube, Mekong, Yellow, Pearl, Yangtze, Indus, Krishna, Godavari and Ganges-Brahmaputra function (Rogers *et al* 2013). In many delta regions, structural engineering solutions such as dikes/embankments, breakwaters or sea walls have been implemented to increase protection against the threats of coastal floods and cyclones. The implementation of such structural measures generally dampens the impact of hazards and as a result, people feel safer in hazard-prone locations (Pande *et al* 2022). This increased confidence can lead to intensification of economic development in the vicinity of these structures, usually at the expense of natural ecosystems (e.g. salt marshes; mangroves, other coastal wetlands). By encouraging economic development in disaster-prone regions and by (often) degrading the natural ecosystems that themselves help reduce impacts of some of these hazards, engineering solutions (e.g. dikes/levees) can increase the potential for damages to livelihoods and property (Di Baldassarre *et al* 2019). While embankments may reduce the occurrence of flooding events, they increase the magnitude of these hazards—and their potential for damage—by preventing natural sediment deposition processes (Di Baldassarre *et al* 2013). Due to sediment capture in the upstream reaches, about 85% of the world's major river deltas have shrunk in extent and elevation during the first two decades of this century (Loucks 2019). Finally, these structural engineering solutions often use a universal, top-down design and implementation approach that simplifies and neglects local socio-environmental complexities in hydrologically active deltas.

The Ganges-Brahmaputra (GB) delta is one of the most vulnerable deltas in the world due to the combined effect of glacier melt from Himalaya, extreme monsoon rainfall, sea level rise, land subsidence, storm surges and cyclones (Gain *et al* 2011, Becker *et al* 2020). Geologically, the delta tilts from the west towards the east (Rudra 2018), with the western part in West Bengal being the oldest and more moribund while the younger, most currently active part of the GB delta encompasses the coastal area of Bangladesh. Alluvium originating from the Himalayan plateau is delivered to the delta by the Ganges and Brahmaputra Rivers. The hydro-morphologically active delta (figure 1) receives sediment and water from upstream and is subject to constant erosion and accretion. These dynamic delta processes support a large rural population and a predominantly agrarian economy (Rudra 2018). The tropical monsoon climate results in high rainfall during the summer, while the flat low-lying topography makes 80% of the land suitable for cultivation. River flooding enhances the fertility and agricultural productivity of the landscape by delivering high fluxes of sediment and carbon to the floodplain.

The delta is prone to cyclones originating from the warm waters of the Bay of Bengal to the south. Over the last several years, the delta has been impacted by a series of damaging events: Cyclone Amphan made landfall on Eastern India and Southwest Bangladesh on 20 May 2020 and more than one million people in the southwest part of the delta within Bangladesh (figure 1) were affected. The delta experiences cyclones on a regular basis. Besides Amphan, Cyclone Bulbul hit in 2019, Cyclone Yaas in 2021. Other examples of major storms ('supercyclones') that have impacted the GB delta are Cyclones Sidr (2007) and Aila (2009) which resulted in 4234 and 190 deaths respectively. The extent of damage depends to a large extent on the time of tide at which the storm hits; in the case of Cyclone Aila the effects of saltwater intrusion were still being felt more than a decade later.

Living with the effects of these disturbances from monsoon floods and cyclone impacts, communities historically practiced a sustainable system of farming in the delta, whereby ephemeral embankments were typically built around arable land for eight months of the year; these are locally known as *aushtomashi bandhs* ('eight month dikes') to protect from saline water during dry periods (November to June). *Aushtomashi bandhs* allowed sedimentation processes to replenish delta plains while also protecting cropland, and are an example of a sustainable and dynamic system adapted to the cyclical, active flows of the delta (Dewan 2021). Over time however, natural sedimentation patterns in the floodplain were impacted more and more by multiple large-scale structural interventions (Auerbach *et al* 2015). These include engineering alterations such as construction of embankments due to the 'Permanent Settlement Act' of 1793 and railway construction during the British colonial period (Iqbal 2010). Based on the findings of a 1957 United Nations mission, the East Pakistan Water and Power Development Authority (now known as the Bangladesh Water Development Board: BWDB) was established in the 1960s to construct 4000 km of permanent embankments, creating 136 polders (an area

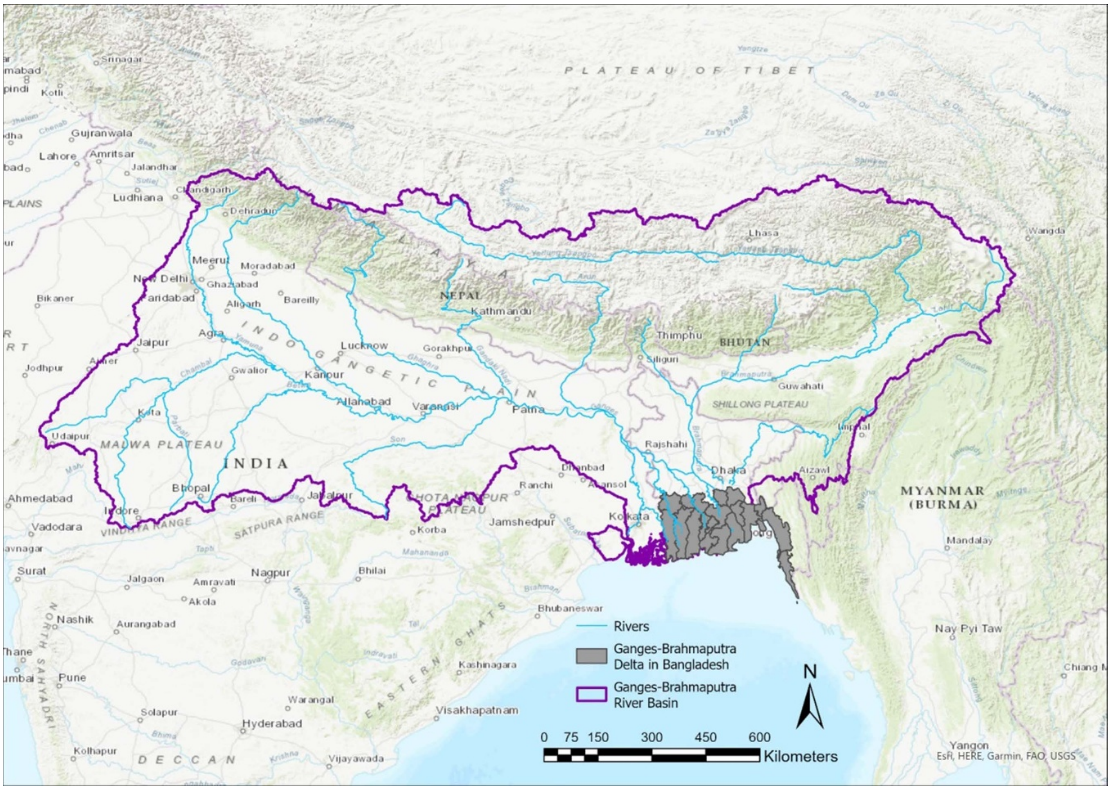

Figure 1. The Ganges Brahmaputra delta in Bangladesh within the larger river basin.

that is protected by embankment), across the entire coastal belt of Bangladesh.

With the widespread construction of coastal embankments in the 1960s, sediment that normally entered the floodplain through distributary channels could not do so anymore and started to deposit in the riverbeds instead. Consequently, the water carrying capacity of many channels has diminished, active floodplain formation has ceased, and the outlets of drainage structures such as sluice gates have become non-functional (Dewan 2021). The reduced flow and subsequent siltation in river beds may also be linked to reduced upstream river flow and distributary channel sedimentation during the dry season (Shaha and Cho 2016). This deprivation of silt deposition on floodplains has therefore long contributed to a marked disruption of river-floodplain connectivity and degradation of the regional hydro-morphology of the delta. As a result, the region now experiences long-term waterlogging after significant flooding and cyclonic events. The construction of embankments in the 1960s, while initially effective in reducing flood risk, has had the unforeseen consequence of largely irreversible impacts on local hydrology.

Currently, the GB delta faces major issues including salinization, sediment regime change, and agri-food system intensification, all of which are exacerbated by wider climate change impacts that include rising sea levels, intensifying cyclone impacts, and enhanced flooding and drought-related to altered monsoon regimes (Becker *et al* 2020). Syvitski *et al* (2009) categorized the GB delta as being 'in peril' of coastal flooding, and Renaud *et al* (2013) have noted that the delta risks tipping to a 'collapsed' state (defined here as when society chooses to abandon or can no longer protect a delta). Due to anthropogenic impacts, Szabo *et al* (2016) considered the GB delta as the most environmentally stressed of 48 deltas included in their worldwide survey.

Given the drawbacks of large-scale engineered structures, a variety of 'soft' approaches (e.g. depoldering, shoreline nourishment) are increasingly gaining traction among water management authorities who are aware of the need for balancing sustainable development with mitigation of environmental impacts. The use of nature-based solutions (NbSs) as alternative measures for addressing complex societal challenges including disaster risk reduction, especially in floodplains and along coastlines, is increasingly recognized. The potential for ecosystem-based approaches to better achieve global agendas such as the Sendai Framework for Disaster Risk Reduction (2015–2030), the United Nations' sustainable development goals, and the Paris Climate Agreement has also been recognised (Renaud *et al* 2016) and has recently gained political traction (Gómez Martín *et al* 2020). The NbS approach to managing risk is highlighted in the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services Global Assessment, the Climate Change and

Land Report of the Intergovernmental Panel on Climate Change (IPCC) and the Global Commission on Adaptation Report (Seddon *et al* 2020) and features extensively in the latest report of the IPCC (2019, 2022).

NbS is a relatively new umbrella concept (Cohen-Shacham *et al* 2016, Nesshöver *et al* 2017), embedding a wide range of conservation and sustainability measures that address specific or multiple societal challenges while simultaneously providing human well-being and biodiversity benefits (Mendes *et al* 2020) through a variety of services such as nutrient recycling, coastal protection, wave and surge attenuation, and erosion control. NbS can be fully natural (e.g. Sundarban mangrove forest in India and Bangladesh), managed natural solutions (e.g. coastal dune management programmes in the UK and Netherlands), hybrid solutions (e.g. marsh-levee systems worldwide), and environmental friendly structural engineering such as bamboo-sediment fences (Pontee *et al* 2016). NbS has been used as a conceptual approach for addressing hydro-meteorological hazards, vulnerability and risk assessment, rain-fed flood risk management and coastal protection, as well as in climate change adaptation and mitigation programs in urban areas (Shah *et al* 2020). Despite this, recent reviews conducted by Hanson *et al* (2020) and Sudmeier-Rieux *et al* (2021) found that studies evaluating application of NbS are mainly limited to the Global North context. There are still a limited number of studies that investigate the use of NbS for mitigating natural hazards in low-lying deltaic regions. Sudmeier-Rieux *et al* (2021), for example, focused on ecosystem services and functions for disaster risk reduction. Schoonees *et al* (2019) is one of the few examples so far to provide interdisciplinary guidance on the design stage of NbS for environmentally sensitive deltas (Smith *et al* 2021).

Given the paucity of studies on NbS for hazard mitigation in deltas, this paper investigates the potential of NbS as a sustainable approach, complementary to structural solutions, for mitigating the impacts of coastal cyclones and flooding in the GB delta in Bangladesh, one of the most complex and climate-vulnerable deltas in the world. We address two specific questions: (a) What are the existing solutions for reducing disaster in the GB delta and do these fall under the umbrella NbS concept? (b) What are the key implementation challenges for NbS and how can these best be overcome for better management of the GB delta?

2. Methods

The research adopted a mixed method approach involving an online international expert workshop, secondary data on NbS cases, literature review, and expert judgment for the evaluation.

2.1. International workshop

Using Zoom video conferencing, the international expert workshop was held on 29 May 2020—just nine days after Cyclone Amphan made landfall along the Bangladesh and West Bengal coasts, and at the height of the first wave of the Covid-19 global pandemic. A trans-disciplinary team of forty researchers and practitioners participated in the workshop. The participants were selected based on the expertise in the following fields: delta management especially in the GB delta, NbSs, and coastal adaptation approaches. There were four thematic areas of the workshop: (a) roles of NbS in addressing natural disasters and risks such as cyclones and floods in the GB delta, (b) definition, principles and practices of NbS, (c) existing adaptation approaches and whether they fall under the umbrella NbS concept, and (d) addressing challenges of NbS implementation in the GB delta.

2.2. Literature review

Based on a literature search using the terms 'Nature based solution' OR 'Nature-based Solution' in the Scopus database (dated 22 March 2022), we identified 1417 journal articles published between 2012 and 2021 (figure 3). Considering other search terms such as 'ecosystem-based disaster risk reduction', 'ecosystem-based adaptation' and 'community-based adaptation', the number of publications would likely be higher. Figure 2 indicates that the number of journal publications on NbS is rising rapidly, especially in recent years. For example, publications have increased by 105% from 2020 to 2021. This increase is principally due to the adoption of NbS in a range of international policies in Europe and elsewhere.

To define and describe NbS and their principles, we conducted a review of peer-reviewed literature, unpublished project reports and other published 'grey' literature e.g. reports of the European Commission and the International Union for the Conservation of Nature (IUCN). We presented and categorized NbS cases based on available online databases for coastal/ delta protections in the world.

2.3. Expert judgement

We describe three existing adaptation approaches in the GB delta: tidal river management (TRM), mangrove afforestation and oyster reef cultivation. We analyse these adaptation approaches with respect to eight NbS principles to determine whether and to what extent they fall under the umbrella NbS concept. The following qualitative criteria are used.

- No Implementation: The principle is not implemented at all.
- Limited evidence: available studies suggest limited evidence that the NbS principle is considered in the adaptation approach.
- Robust evidence: available studies suggest robust evidence that the NbS principle is considered in the adaptation approach.

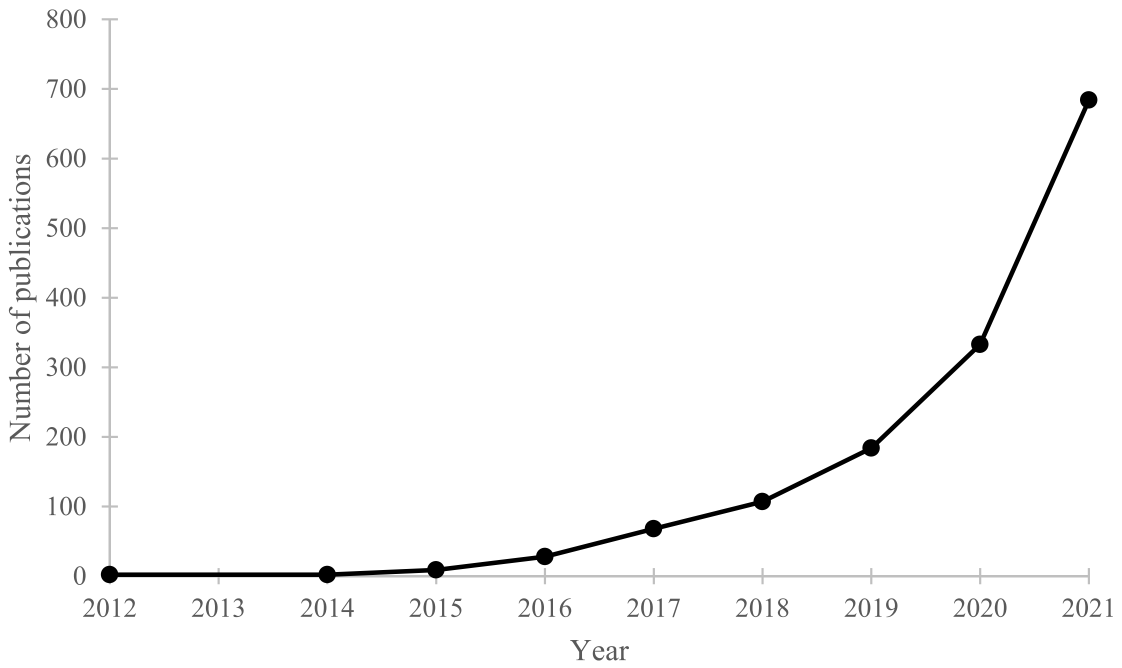

Figure 2. Yearly publications on nature-based solutions based on the Scopus database (up to 31 December 2021).

- Partial implementation: The principle is partially implemented only in a few projects, but not across a significant geographical area, nor widespread in programs and policies.
- Complete implementation: The principle is implemented extensively in projects, programs, and policies.

Based on the above qualitative criteria, six authors who live in the GB delta and who have wide experience in delta management participated as the expert panel for the evaluation. The in-depth discussion of the thematic areas in the workshop is the basis of the following sections of the article. Secondary literature, comprising mainly peer-reviewed articles, were used to supplement the expert analysis.

3. Principles of NbSs and examples

NbS have been defined as concepts for sustainable management by both the European Commission EC and IUCN, with the latter also providing a list of eight Principles (table 1) to develop NbS projects in a comprehensive way (EC 2015, Cohen-Shacham *et al* 2016). Both organisations stress that NbS are actions based on nature and ecosystems that should meet societal challenges through fully engaging stakeholders. The IUCN defines NbS as 'actions to protect, sustainably manage, and restore natural or modified ecosystems, that address societal challenges effectively and adaptively, simultaneously providing human well-being and biodiversity benefits' (Cohen-Shacham *et al* 2016). We used the IUCN NbS principles to evaluate whether we can refer existing adaptation practices in the GB delta as NbS or not.

3.1. Examples of NbSs

For coastal water management around the world we identified five relevant online databases of NbS that reduce natural hazards and risks in coastal areas: ClimateAdapt (https://climate-adapt.eea.europa.eu/), Natural Hazards-NbSs (https://naturebasedsolutions.org/), PANORAMA (https://panorama.solutions/en), thinknature (https://platform.think-nature.eu/) and OPPLA (https://oppla.eu/). While there are other databases e.g. OMReg (omreg.net) which contain case studies similar to the above-mentioned databases we restricted our engagement to the five databases listed here as these are well-developed and contain diverse case studies. From these databases, we have identified 62 major NbS case studies implemented around the world based on their relevance to reducing risks from floods, erosion, cyclones, and storm surge in coastal areas. We categorize NbS cases into six types and the number of case studies per NbS category are shown in figure 3. The categories provided are not exhaustive but, rather, highlight broader functions and objectives e.g. coastal wetland restoration of NbS. A detailed list of these NbS case studies is illustrated in table S1 of online supplementary material (available online at stacks.iop.org/ERL/17/064052/mmedia).

Of the 62 cases, 21 are coastal wetland restoration intended to reduce tidal surges, storm surges. This includes restoration of coastal salt marshes and tidal floodplains disconnected from tidal water flow by seawalls or dikes through embankment

Table 1. Principles of nature-based solution (Cohen-Shacham *et al* 2016, 2019).

NbS principles	Description
Nature conservation norms	NbS is neither an alternative to nor a substitute for nature conservation.
Implementation	NbS can be implemented alone or in an integrated manner with other solutions to societal challenges such as a combination of seawalls and mangroves to protect a coastline from storm surges.
Site-specific contexts	NbS are determined by site-specific natural and cultural contexts that include traditional, local and scientific knowledge.
Societal benefits	NbS produce societal benefits fairly and equitably, promoting transparency and broad participation.
Biological and cultural diversity	NbS maintain biological and cultural diversity and the ability of ecosystems to evolve over time.
Landscape scale	NbS are applied at a landscape scale. If this is implemented at a specific site level, it is important to consider the wider landscape-scale context and consequences.
Trade-off between economic benefits & ecosystem services	NbS recognize and address the trade-offs between the production of a few immediate economic benefits for development, and future options to produce the full range of ecosystem services.
Integral part of broader policies	NbS are an integral part of the overall design of policies, and measures or actions, to address a specific challenge.

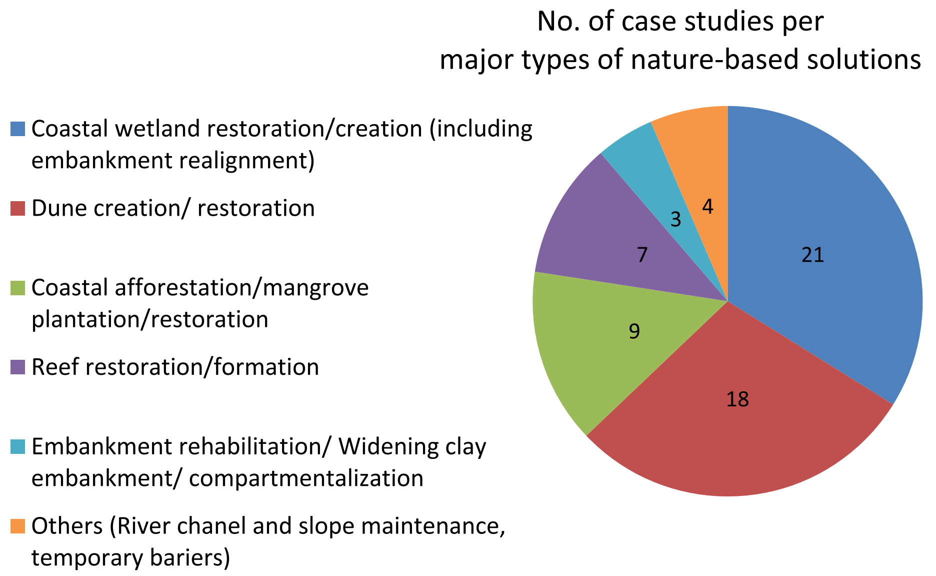

Figure 3. Major types of NbS for managing water related natural hazards in coastal areas.

realignment or strategically planned breaching of dikes and erosion control (Manson 2018). Coastal wetlands are often constructed in conjunction with the realignment of embankments and dredging of channels. Rehabilitation/maintenance of embankments, river channels and bank slopes are implemented to maintain natural flood and erosion control features of floodplain. Beach replenishment or restoring natural dunes is another commonly practised NbS approach for reducing coastal erosion and reducing flood risk. Coastal afforestation including mangroves and other types of plantations is another widely implemented form of NbS to reduce impacts of cyclones and storms in tropical regions. In Indonesia and Suriname, temporary semi-permeable barriers of wooden poles are used to trap sediments in estuaries and facilitate land formation and mangrove establishment (Winterwerp *et al* 2016). Another innovative NbS for reducing tidal surge is restoring or creating oyster and coral reefs along shorelines, as has been implemented in pilot studies in several countries including Bangladesh, the United States of America, and the Netherlands (Chowdhury *et al* 2019a).

4. Evaluation of existing adaptation approaches in the GB delta with respect to NbS principles

While there is an implicit recognition that the loss of mangroves and their ability to diffuse storm surges

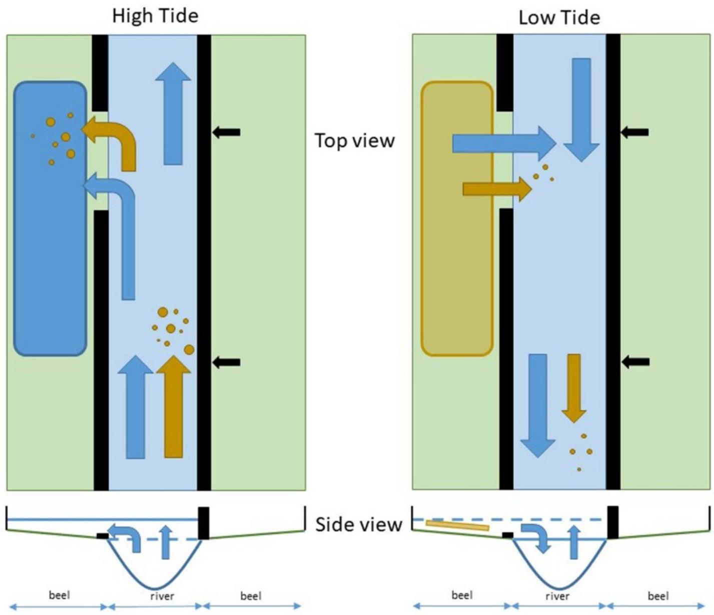

Figure 4. Tidal river management approach for delta landscape management showing high tide and low tide operation. Through this process of managing water flows, sediment is deposited preferentially in the floodplain, allowing agricultural improvement and increased crop production.

significantly increases the impact of cyclones on the GB delta, local adaptation approaches are yet to be analysed against the principles of NbS in the region. In the wake of recent coastal extreme events such as Cyclone Bulbul in 2019, Cyclone Amphan in 2020 and Cyclone Yaas in 2021, policymakers in-the region are showing heightened interest in initiatives like 'building back better' and 'green recovery' (GED 2020). So far, NbS and their multiple benefits have not been explicitly included as design features in coastal protection schemes.

In the context of reducing natural hazards in the coastal areas of GB delta, we identify three key NbS: (a) TRM, (b) coastal greenbelt and mangrove afforestation, and (c) oyster reef cultivation. Compared with oyster reef cultivation, there is currently significantly more information available regarding TRM and mangrove afforestation schemes which have been implemented for a relatively long time.

4.1. TRM

Embankment realignment, locally known as TRM, refers to a Bangladesh government strategy of deliberate breaching or cutting of embankments or dikes to allow sediment-laden tidal flows onto the floodplain during the monsoon (figure 4). This community-driven approach is designed to reduce the effects of waterlogging and floodplain sediment starvation (Dewan *et al* 2015). Initially, the focus of TRM was on providing a solution for waterlogging problems and a means to overcome vested local institutional power relations such as between local farmers and shrimp farm owners (Gain *et al* 2019b, Masud *et al* 2020). TRM is now also recognized as a climate change adaptation measure and an eco-engineering innovation. Bangladesh has formulated a longer-term strategy up to the year 2100 for delta development (GoB 2018), within which TRM is acknowledged as an important adaptation tool. Recent studies (Gain *et al* 2019a, Adnan *et al* 2020b) identified several normative criteria for successful implementation of TRM. The biophysical criteria include the location and area of the TRM site, depth and width of the adjacent rivers, tidal prism, sediment concentration in water, and the level of river salinity.

TRM operation involves: (a) restoring tidal flooding (twice a day) through temporary and partial removal of embankments where current sluice gates are located; (b) scouring the adjacent river bed; and (c) allowing deposition of sediments within the floodplains. According to Masud *et al* (2020) and Gain *et al* (2017), TRM has been shown to have the potential for application in 35 river floodplains in the Khulna-Jessore-Satkhira districts, but also has the potential for expansion to other floodplains across the southwest part of the GB delta. However, TRM has so far been implemented only in 12 floodplains (see figure S1 of online supplementary material), and the majority of these were deemed unsuccessful because of institutional barriers such as the inability to resolve conflicts between local communities and implementing agencies, mismatches between the biophysical conditions (e.g. upstream-downstream), community attributes (e.g. trust, reciprocity, social capital, shared knowledge, leadership) and rules based design principles (Gain *et al* 2019a).

4.2. Mangrove afforestation

Mangrove afforestation can effectively contribute to the reduction of disastrous flood impacts (Gijón Mancheño *et al* 2021). Establishing a mangrove belt in sea-facing coastal areas is globally recognized as an effective approach for mitigating cyclone and storm surge risk. Bangladesh's mangrove forests protect over 1 million people and save over US$1.5 billion every year, according to a global flood damage and mangrove benefit model (Menéndez *et al* 2020). Establishing protective coastal greenbelts through mangrove afforestation is an established practice in Bangladesh and, so far, the country has around 0.196 million ha of planted mangrove trees (Forest Department of Bangladesh, 2020). Through various programs and projects, Bangladesh Forest Department covered around 192 000 hectares of coastline with greenbelt up until 2013. The Centre for Environmental and Geographic Information Services has proposed a total of 126 748 hectares of additional land under greenbelt and coastal afforestation (CEGIS 2017). Mangrove afforestation in Bangladesh started in the 1960s with the prime objective of enhancing natural land reclamation processes in newly formed coastal mudflats, islands, and intertidal areas. The Sundarbans Reserve Forest, an established and internationally protected mangrove preserve, has demonstrated the effectiveness of mangroves in mitigating the impacts of cyclonic storm surges, leading to afforestation efforts in other areas of the coast following the 1991 cyclone (Sadik *et al* 2018).

The implementation of coastal afforestation in the early 1990s was integrated with coastal embankment rehabilitation, in which protection of river banks from erosion was considered as another co-benefit of mangrove plantation. A recent numerical modelling study found that a 2.1 km width of mangrove belt could have reduced the surge height of Cyclone Sidr in 2007 by 5–6 cm at sites located within the inland river system and by 14–18 cm in coastal locations (Dasgupta *et al* 2019). The planting of mangroves in intertidal areas outside of polders is also considered a soft engineering measure for preventing bank erosion in Bangladesh. Despite these demonstrable benefits, unavailability of land, difficulties in co-management and maintenance, and lack of monitoring are major challenges that limit the efficacy of coastal afforestation programs (Saenger and Siddiqi 1993, Gijón Mancheño *et al* 2021).

4.3. Oyster reef cultivation

Artificial oyster reefs can protect the coast through wave attenuation and erosion protection, and can provide food and livelihood security (Chowdhury *et al* 2019b). Oysters also act as ecosystem engineers (Hossain *et al* 2013). Oyster reef cultivation has the potential to be an NbS for protecting subtropical coastlines. Oysters can form conspicuous habitats that influence tidal flow, wave action and sediment dynamics in the coastal ecosystem and, in doing so, reduce hydrodynamic stress and modify patterns of local sediment transport, deposition, consolidation, and stabilisation (Walles *et al* 2016). There is potential for artificial oyster reefs in many coastal areas and *chars* (ephemeral sand-bar islands), where hydroclimatic coastal hazards are intense and resources are not available to fund other forms of protection. Artificial oyster reefs created on a pilot scale in the eastern part of the GB delta in Bangladesh were found to be effective in reducing wave heights and encouraging sedimentation, but might not be applicable across the GB delta due to high rates of suspended sediments compared to the eastern coast (Chowdhury *et al* 2019b).

4.4. Evaluation of the above examples using NbS principles

The main objectives of TRM are to reduce waterlogging through sedimentation in the floodplain and increase navigability in the river. Hence, TRM does not directly contribute to nature conservation goals. However, TRM can help increase biodiversity for agriculture and fisheries (Masud *et al* 2020). By contrast, coastal greenbelt establishment, mangrove afforestation, and oyster reef cultivation offer greater complementarity to nature conservation goals. All these approaches promote the provision of several ecosystem services in the coastal floodplains of south-west coastal zone in Bangladesh and have been implemented either alone or in an integrated manner. Successful implementation of these approaches depends on local contexts that include traditional, and scientific knowledge, and giving meaningful involvement to people living in and being stakeholders in the ecosystem (Gain *et al* 2019a). If TRM can be applied normatively, it can produce equitable social benefits by promoting transparency and broader participation. However, the application of normative criteria is not fully observed in any of the NbS examples described here. Equitable benefits for society are partially evident for the TRM and mangrove afforestation. Coastal greenbelt is integrated into overall policies for coastal adaptation in the GB delta. Other NbS schemes are still at the pilot stage and thus not yet embedded in regional or national policies.

Based on the above description, we then compared whether TRM, mangrove afforestation, and oyster reef production have been implemented in the GB delta and evaluated the extent to which NbS principles are being applied (figure 5). The evaluation is carried out based on data gathered during the workshop (see section 2). The qualitative criteria and procedure described in the method section are used for the expert judgement evaluation.

According to the evaluation in figure 5, coastal greenbelts and mangrove afforestation meet all

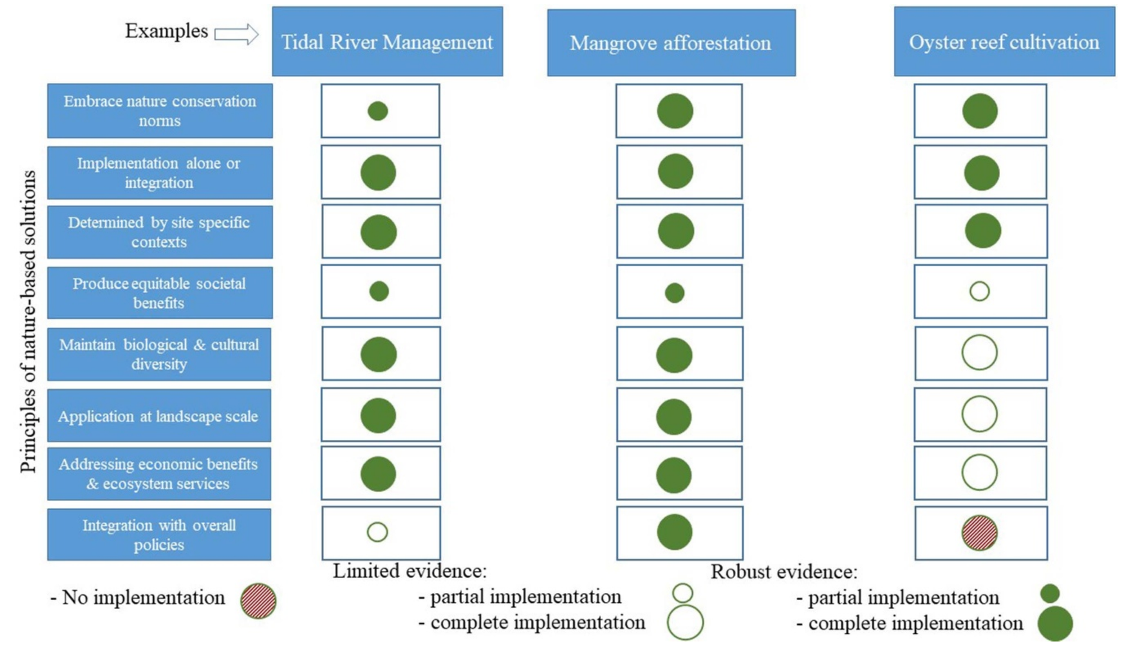

Figure 5. Evaluation of existing approaches in the Ganges-Brahmaputra delta in terms of how they address the eight nature-based solution (NbS) principles. Circle colour indicates extent of implementation (solid green = full implementation; hollow green = partial; solid brown = no implementation). Circle size indicates relative depth of evidence (larger circle = more evidence).

principles of NbS, followed by TRM and then Oyster reef cultivation. Oyster reef cultivation is piloted only in one research project in Bangladesh and while it has high potential, the evidence is limited for the GB delta. In addition, implementation of Oyster reef cultivation has not yet been considered in government level planning and strategy.

5. Challenges and way forward for the implementation of NbS

There are many socioeconomic, biophysical, governance and policy-related challenges to implementing NbS in the GB delta. These are presented in figure 6 along with suggestions to address them and are discussed in more detail below.

6. Challenges for NbS implementation

The challenges facing broader application of NbS in the GB delta can be categorized into four types: socio-economic, biophysical, governance and policy. Often, these challenges are synergistic and occur in combination.

6.1. Socioeconomic challenges

There are persistent challenges to 'making space for nature' in the GB delta, which is one of the most densely populated areas in the world (Szabo *et al* 2018). The delta is characterised by heavily modified landscapes through aquaculture and polders and a low-income population with high dependence on ecosystem services e.g. groundwater resource, fisheries, and agriculture (Adams *et al* 2020). The coast in Bangladesh with an area of more than 47 000 km^2, crowded with many ageing engineered structures e.g. 139 polders, also contains a dense network of rivers and channels. The implementation of any intervention close to the coast in Bangladesh is limited by space constraints. Similar observations are found in other coastal areas for example, in the United Kingdom (Pethick 2002).

Historically, structures such as polders were implemented to increase agricultural production and reduce flooding (Masud *et al* 2020). While the embankments initially boosted crop productivity inside polders by reducing the overall risk of damaging flooding events, they increased the magnitude and damage potential of floods when they do occur by preventing sediment deposition on delta floodplains. By starving polders of sediment, the impact of land subsidence is enhanced. Yet, the strong perception remains with coastal managers that polders provide protection. The continued high demand for engineering-based solutions is thus a major challenge for NbS implementation.

6.2. Biophysical challenges

In coastal Bangladesh, where physical processes are highly dynamic (Brammer 2014), changes in land use patterns e.g. agriculture to aquaculture are likely to continue into the future with the consequence of increased flood damage in the coastal region (Adnan *et al* 2020a). Uncertainty as to the trajectory of regional climate and anthropogenic changes also have

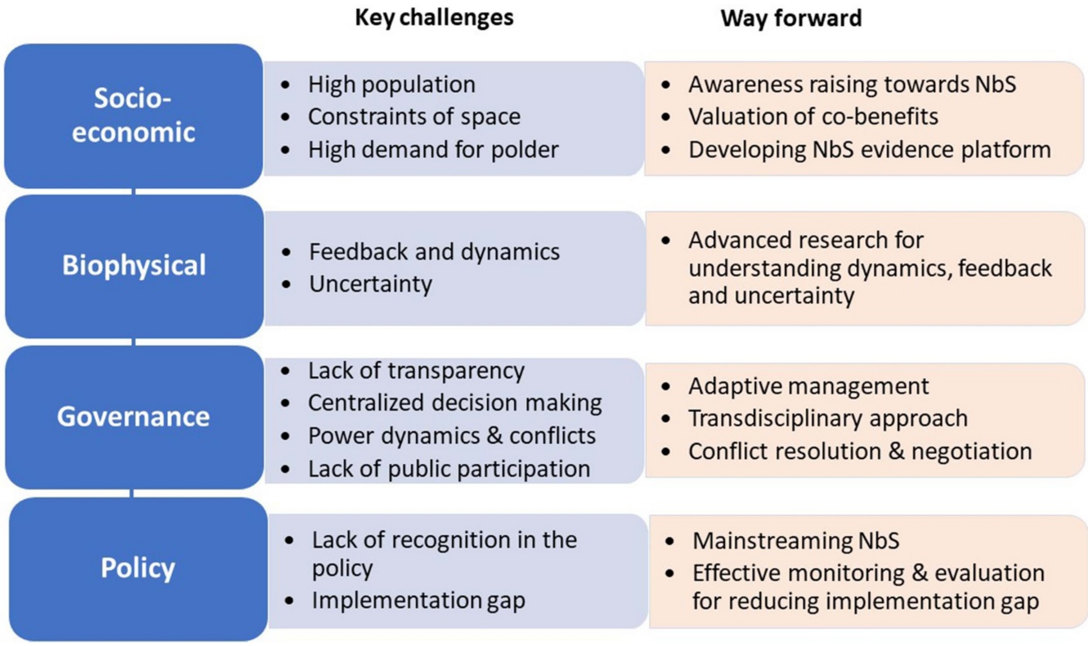

Figure 6. Challenges and way forward for the implementation of NbS in the Ganges-Brahmaputra delta.

the potential to affect NbS strategies. Monsoonal river discharge and sediment loads of the Ganges and Brahmaputra Rivers are some of the highest in the world and drive significant river avulsion and lateral movement (Goodbred *et al* 2014). However, spatially variable modifications in rivers and tidal hydrodynamics attributed to infrastructure building both upstream of and within Bangladesh since the 1960s have themselves altered natural river processes (Gazi *et al* 2020). For instance, coastal polders have reduced channel network connectivity in the most southwestern region of coastal Bangladesh by eliminating natural intertidal flooding on the landscape and through sediment trapping in channels (Wilson *et al* 2017). Sediment trapping in 'dead-end' channels in southwest Bangladesh has resulted in the emergence of reclaimed or 'khas' land that is commonly at the centre of land tenure disputes (Das *et al* 2012). In contrast to the tidal-dominated southwest, poldered areas in the south-central region are less susceptible to channel siltation but more exposed to undercutting and erosion by strong river currents and storm surges (Akter *et al* 2016). Salinity incursion across the coastal region is also spatially variable and reflects proximity to the Meghna River distributaries that convey fresh water to the coast (Brammer 2017). Due to these biophysical dynamics, one-size-fits-all sustainable management solutions are no longer appropriate for the GB delta.

6.3. Governance challenges

NbS are intended to promote broad participation and enhance transparency. However, there is a recognized lack of transparency and accountability in environmental decision-making processes in Bangladesh. According to the Democracy Index 2019 compiled by the Economist Intelligence Unit, Bangladesh is considered as a 'hybrid' regime—ranked in 80th position out of 165 countries globally—of democracy (EIU 2019). Given the overall democratic situation, decision making in Bangladesh is highly centralized, yet fragmented. The existing form of decentralisation in Bangladesh has created conflicts with existing local government institutions (Dewan *et al* 2014). The BWDB consists of mainly engineers and hydrologists who, while they have limited capacity to involve local people and stakeholders, play the central role in decision making for delta management. The multi-functionality of NbS however creates vested interests among diverse groups of stakeholders who often have conflicting outlooks and priorities; this can result in social dilemmas (Van Loon-Steensma *et al* 2016). In the GB delta, brackish water shrimp cultivation which is mainly owned by powerful elites have caused conflicts because of its salinization impact on the agricultural lands marginal farmers depend on. The conflicting incentives and regulations (Mutahara *et al* 2018) as well as cognitive factors such as a lack of awareness of ecosystem services (Razzaque 2017) provided by NbS also hinder the uptake of NbS in the GB delta.

6.4. Policy challenges

Historically, the planning process in Bangladesh has been either technology-dominated e.g. 1964 Master Plan, quick economic return-centric e.g. 1972 IBRD study, private sector-focused e.g. liberalization of groundwater irrigation in the 1980s, unbalanced integration focused e.g. 2004 National Water Management Plan, or inadequate in terms of local participation e.g. the national-level Bangladesh Delta

2100 Plan. In Bangladesh, there is no specific policy on NbS that encompasses available relevant and appropriate concepts. However, there are several policies, plans, and strategic documents that implicitly emphasize NbS as a solution. The Bangladesh Climate Change Strategy and Action Plan (BCCSAP), for example, considers the planning and implementation of non-structural floodproofing measures for addressing environmental challenges. The Country Investment Plan (2016–2021) emphasizes the enhancement of ecosystem services and the improvement of habitat and human health benefits. The Bangladesh Delta Plan 2100 also recommends the creation of Climate Proof Bangladesh without harming its environment or ecosystems. These policy documents indirectly mention the characteristics of NbS but do not specifically and adequately focus on NbS as a strategy. The poor financial models and flawed approaches to economic appraisal have up to now led to under-investment in NbS. Despite the comprehensive work on well-functioning ecosystems and their services in recent years, Bangladesh still lacks competitive economic traction, stand-alone effectiveness, and efficacy regarding numerous forms of NbS. This is primarily due to lack of public support, and lack of practical understanding due to the variety of stakeholders, their interests, perception and preferences.

7. Addressing the challenges

7.1. Socioeconomic

For managing existing demands towards engineering solutions, it is essential to increase awareness of NbS through education and advocacy among local people, policymakers, planners, and researchers. For example, a recent project, Knowledge and Learning Mechanism on Biodiversity & Ecosystem Services (EKLIPSE) funded by the European Commission incorporated education and advocacy for NbS. The long-term environmental and ecological benefits of NbS over short-term economic benefits of conventional structural solutions can be advocated and demonstrated. Emphasis needs to be made on total economic valuation including option and bequest values of ecosystem services over typical cost-benefit analysis and internal rates of return (Ghosh and Mondal 2013).

An NbS evidence platform, incorporating results of scientific evaluation could be of significance to share NbS experiences and success stories for wider dissemination and successful implementations. Major NbS platforms are reviewed in section 3 above. In addition there are other platforms such as the EKLIPSE and the NbSs Initiative led by the University of Oxford (Faivre *et al* 2017). There is a need for rapid development of similar platforms in the GB delta incorporating both *ex-post* and *ex-ante* analysis (Adnan *et al* 2020b).

Biophysical: To succeed in deltaic environments, NbS should be designed to be flexible and adaptive with as clear understanding as possible at the outset of their limitations and downsides. To address biophysical challenges, it is necessary to understand the complex interactions between geomorphological, hydrometeorological, and anthropogenic environments of the delta (Adnan *et al* 2020b; Nicholls *et al* 2018). Nicholls *et al* (2016) provide an integrated assessment of sustainability dynamics in the GB delta to explore physical and social outcomes under different scenarios and policy choices. Johnson and Hutton (2018) identified socioeconomic and environmental drivers of poverty by using spatial and census data. Following similar studies, the magnitude of physical processes in conjunction with spatially variable feedbacks between polders and physical dynamics will need to be considered in the design and implementation of any NbS scheme going forward. The risks associated with various forms of NbS should be fully assessed, considering their potential impacts through time and space, and resilience to future environmental changes. Due to spatially variable dynamics of both biophysical and socioeconomic properties, it is essential to consider adaptive management approaches for NbS, which includes experiments of alternative measures to identify the best solution aligning with local environmental and socio-cultural settings (Sadat-Noori *et al* 2021).

Governance: The implementation of NbS requires transparency in governance processes, and incorporation of locally based knowledge from citizens, practitioners, and policymakers. A paradigm shift from a solely structural approach to one with a focus on NbS, integrated with existing approaches, requires a political commitment by the national government. In Bangladesh, the BWDB which plays the central role in decision making for NbS implementation needs to restructure its approach to water management by engaging multidisciplinary experts rather than solely civil/water resources engineers. Alongside this, it will be necessary to integrate actors at different socio-spatial and socio-political levels to properly implement NbS. There is thus an urgent need to strengthen coordination mechanisms among the respective authorities at the local level and, vitally, to meaningfully involve the public. A multi-level and nested approach to NbS including horizontal and vertical cooperation between government entities should consider stakeholder mapping in a transdisciplinary way that supports co-creation of knowledge in co-design and co-management aspects (Gain *et al* 2017). This will include managing diverse interests and skillsets among stakeholders, conflict resolution mechanisms and negotiation skills.

Policy: NbS related policies that are integrated into the major policies, plans and strategic documents such as Nationally Determined Contribution, National Adaptation Plan (NAP), BCCSAP for mainstreaming the NbS, should be effectively implemented. There is a significant gap between stated policies and their implementation in Bangladesh (Mohibbullah *et al* 2021). An opportunity to close this gap is the Bangladesh Delta Plan 2100 (GoB 2018), which also advocates for adopting NbS where possible and it has already created a huge interest among bi-lateral and multi-lateral development partners. The government is currently further developing the Bangladesh Delta Plan 2100 providing more clarity on its strategies, programs, and their implementation. Scientists can also help reduce the gap by appropriate mechanisms of monitoring and evaluation to ensure co-benefits to society, natural capital/ecosystems, and the economy.

8. Conclusion

The GB delta is highly vulnerable to multiple hazards such as cyclones and coastal floods. Though geomorphological processes in southwest Bangladesh are still actively forming the GB Delta in a geological sense natural sedimentation in the floodplain is hampered due to human interventions including the construction of coastal embankments. These traditional engineering structures are costly to both construct and maintain and, importantly, they are non-adaptive, as they need to be rebuilt, upgraded or maintained in the face of future climate changes. Traditional structural measure such as embankments, considered as single protection measures, seem to be inappropriate to address growing climate disasters such as cyclones. Instead, NbSs are increasingly being considered as adaptive, resilience, cost-effective and sustainable approach for climate change adaptation in the coasts (Morris *et al* 2019). NbS, as a complementary approach to traditional engineering, has the potential to reduce the impacts of various natural disasters. Recent studies such as Islam *et al* (2022) have shown how TRM approach can reduce flooding from waterlogging in the floodplain and restore navigability in the river.

In this study, we evaluate the potential of three alternative practices (i.e. TRM, mangrove afforestation, and oyster cultivation) for disaster management through the lens of NbS Principles. Applying the IUCN Principles (Cohen-Shacham *et al* 2019), TRM and mangrove afforestation are defined as NbS, while oyster reef cultivation in the eastern part is still far off from meaningfully adopting NbS principles, and is not likely to be widely effective in Bangladesh. TRM and mangrove afforestation as evidenced by several ongoing projects in the GB delta adopted most of the NbS Principles except No. 4 (equitable societal benefits). The principle no. 4 has partially been considered for both TRM and mangrove afforestation. There was limited evidence for the application of principle no. 8 in TRM. The wider applicability of NbS approaches and initiating projects over greater spatial scales face multiple challenges in the GB delta. In this paper, we identify key socioeconomic, biophysical, governance and policy challenges and make suggestions as to how to address these moving forward given the urgency caused by the numerous threats to delta lives and livelihoods exacerbated by climate change.

To widen the academic understanding of NbS between key stakeholders, more action research is needed. This requires collection of NbS success stories. The major gaps between policy and implementation can be reduced by developing different and accessible toolkits i.e. guidelines, manuals, specifications of NbS integrated solutions. Early career professionals could also receive targeted training in NbS, while financing is another gap. The latter could be addresses for example by developing a NbS check-tool for the Bangladesh Planning Commission so that the policy makers can assess how effectively NbS is being advocated in project planning and budgeting.

The results of this study highlight that structural engineering solutions which often create feedbacks hindering recovery from climate extremes can no longer be the only option for disaster risk management in the GB delta. Several approaches such as TRM and coastal afforestation have significant potential to as a disaster risk management tool—if existing challenges are minimized through planned implementation. Scaling-up NbS is however a major challenge for lower-middle income countries like Bangladesh. Specifically, we need to co-create demand for NbS with and among local communities, while at the same time effectively demonstrating benefits to policymakers. This can be done through enhancing capacities of local people and the implementing agencies. NbS also needs to be better advocated and integrated into national-level Bangladesh planning and policy documents e.g. the 8th five-year plan, Bangladesh Delta Plan, Bangladesh Climate Change Strategy and Action Plan, NAP. This requires horizontal and vertical coordination among relevant government agencies. Finally, and most importantly, to minimise gaps between policy and practice, appropriate institutional frameworks need to be urgently and effectively enabled.

Our findings have implications not only for the GB delta, but also for coastal areas of low- and middle-income countries e.g. in South Asia, Southeast Asia, the Caribbean Islands and Africa. These countries are characterized by a high degree of socio-economic vulnerability e.g. high poverty, low literacy and climate change impacts expressed through rising frequency and impact of extreme events (Lechner *et al* 2020). However, a one-size-fits-all approach will not work for all these countries; across South and Southeast Asia for example, there are local-level variations in terms of topography, governance, and socioeconomic and ecological aspects. A recent study (IORA Ecological Solutions and Vertiver 2021) synthesizing the best practices of NbS in India listed similar gaps and challenges in terms of implementing NbS approaches, including data deficiency, population density, and implementation gaps.

Here, we highlight how, while the NbS approach has been mainly applied in the Global North, adoption in low- and middle-income countries including Bangladesh has, up to now, been relatively limited. We identify opportunities for, as well as constraints against, NbS implementation in a Bangladesh context. Assessment of existing adaptation practices against NbS Principles identifies key challenges for the specific GB delta context, and recommendations for more effective NbS implementation. In addition to addressing GB delta-specific challenges, our findings provide more widely applicable insights into the challenges of implementing NbS in deltaic environments globally.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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