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Mapping Mangrove Opportunities with Open Access Data: A Case Study for Bangladesh

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Abstract: Mangroves protect coastal areas against hazards like storms or cyclones by attenuating waves and currents, and by trapping floating debris during extreme events. Bangladesh is a very vulnerable country to floods and cyclones, and part of its coastal system is thus being upgraded to a higher safety standard. These upgrades include embankment reinforcement and mangrove afforestation schemes seawards of the embankments. To further strengthen the implementation of combined green–grey infrastructure in future programs, identifying potential mangrove development sites near the polder systems is a necessary first step. We thus developed a tool to systematically identify mangrove sites throughout the coastal area based on open access data. This method identifies potential sites for mangrove development based on their distance from existing mangrove patches and suggests the required technique to implement the vegetation depending on the rate of coastline change. Our method showed that approximately 600 km of the coastal stretches placed seawards of embankments are within 10 km of existing mangroves, and could thus be potential sites for mangrove establishment. Out of those 600 km, we identified 140 km of coastline where the landwards polders are particularly vulnerable to flooding. The sites with highest restoration potential and priority are located in Galachipa, Hatiya, Bhola, Manpura, Khangona, and Boro Moheshkhali. More detailed data collection and local assessments are recommended prior to executing mangrove afforestation schemes. Nevertheless, this method could serve as a useful systematic tool for feasibility studies that identify mangrove opportunities in data-scarce areas and help to prioritize data collection at the sites of highest interest.

Keywords: mangrove mapping; mangrove afforestation; building with nature; vegetated foreshores; hybrid engineering

1. Introduction

Bangladesh was the seventh-most-affected country by extreme weather events between 1999–2018 due to a confluence of reasons [1]. Cyclones regularly sweep the coastline of the Bay of Bengal, and funnel into the narrowing shape of the bay at Bangladesh [2]. The country is also low-lying and densely inhabited, which exposes a large population to the effect of surges. Besides cyclones, massive rains during the monsoon have also caused floods across the country [3]. This vulnerability to weather events is only likely to increase over the next century due to climate change and the expected population growth, setting a strong need for coastal defense measures.

The coastal zone of Bangladesh is currently protected by a system of 139 polders. These are surrounded by approximately 6000 km of peripheral embankments, which were built in the 1960–1970s to prevent tidal flooding [4]. Their construction protected lives and livelihoods [5] and increased agricultural production by 200% to 300% in some areas [6]. Over time, river siltation combined with poor infrastructure maintenance caused drainage problems and water logging at some polders [7,8]. Moreover, since the embankments were not designed to contain surges, breaching events have taken place during some cyclones [9]. The embankment system is thus being upgraded to a higher safety standard by the Coastal Embankment Improvement Project—Phase 1 (CEIP-1), as the first phase in a potential series of projects to upgrade all polders along the coastal zone in Bangladesh.

The CEIP-1 project has several components, such as the reinforcement of 10 polders to a 25-year level of protection, and afforestation schemes seawards from embankments [10]. The scope of the afforestation works includes planting commercial species for economic purposes, and planting mangroves for coastal protection. Mangroves attenuate waves and currents [11–14], but have a limited effect on storm surges [15,16]. Since surge heights in Bangladesh often range between 3–5 m [17,18], embankments are necessary to fully protect coastal polders from flooding. However, by reducing wave impacts and wave run-up on embankments, mangroves provide additional coastal resilience, and potentially reduce the costs of upgrading embankments [19,20].

Bangladesh is the home of the largest continuous mangrove forest in the world, the Sundarbans, and it has a long history of mangrove afforestation. Mangrove planting schemes have stabilized 150,000 ha of coastal land since 1966, and additional afforestation opportunities may be present along the coastal system [21]. However, existing methodologies for mangrove opportunity mapping are limited for the case of Bangladesh. For instance, Worthington and Spalding [22] identified mangrove areas lost all over the world since 1996 and estimated their restoration potential depending on the local conditions. However, most of the mangrove losses in Bangladesh happened between 1873–1933 [23], and they have been thus neglected by their mapping methodology. Afforestation opportunities (i.e., planting in areas not previously inhabited by mangroves) would not be identified by this method either.

The aim of this work was thus to develop a systematic screening method to map mangrove opportunities seawards of embankments, which we applied to the case study of Bangladesh. The methodology was conceived as a first screening technique based on readily available data, which would help to identify sites to be investigated in subsequent more detailed studies. This methodology could also be valuable for other tropical countries facing increasing challenges with rising sea levels [24]. The following sections discuss the potential and limitations of coastal protection by mangroves, and the factors to consider in the screening methodology.

2. Theoretical Background

2.1. Coastal Protection by Mangroves in Bangladesh

The protective role of mangrove vegetation against coastal hazards results from the combination of several mechanisms, illustrated in Figure 1. Mangroves exert resistant forces against waves and currents [11,25] and fix coastal sediments in the seabed with their root system. The lower erosive forces combined with higher sediment stability reduce erosion and favor sediment deposition [26]. Sediment accumulation also reduces the water depth, limiting the highest waves that can propagate into the forest without breaking.

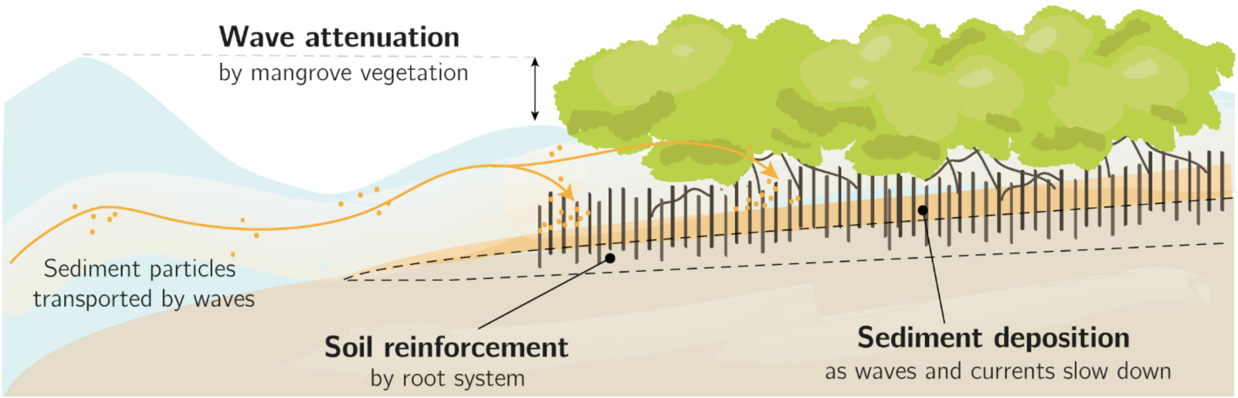

Figure 1. Diagram illustrating coastal protection by mangroves. Waves attenuate as they propagate through the forest. As a consequence, any sediment particles transported by the flow can deposit between the trees. The mangrove root system stabilizes the soil, further enhancing an increase in the bed level.

The wave attenuation efficiency of mangroves depends on several factors, such as wave characteristics, tree species, tree geometry, and the total extent of the vegetation [11,12]. In practice, this implies that the forest width required to dissipate waves is site-specific. For instance, a minimum value of 100 m is often used as a reference for coastal protection [27], but Bao [12] observed that the required width for wave attenuation depended on the forest structure, with smaller widths being necessary for taller and denser forests, as shown in Figure 2.

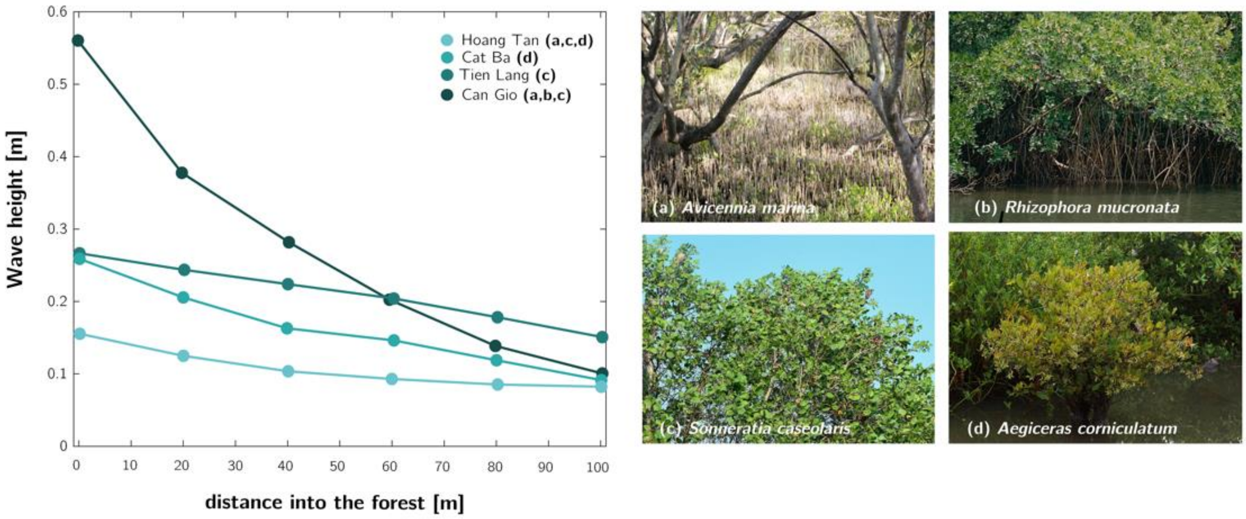

Figure 2. (Left) Wave transmission rates through four mangrove forest sites in Vietnam, adapted from Bao [12]. (Right) Pictures of the main species identified by Bao [12] in the monitored transects: (**a**) *Avicennia marina* (by Alison Klein, CC0 1.0 from Flickr), (**b**) *Rhizophora mucronata* (by Bernard Dupont, CC BY-SA 2.0 from Wikimedia), (**c**) *Sonneratia caseolaris* (by Shagil Kannur, CC BY-SA 4.0 from Wikimedia), (**d**) *Aegiceras corniculatum* (by Vengolis, CC BY-SA 3.0 from Wikimedia).

Wave attenuation also varies with wave length, as illustrated in Figure 3. Wind waves, i.e., locally generated storm waves, can experience higher wave height reduction over a 100 m belt than swell waves, which are longer waves generated hundreds or thousands of kilometers away from the shoreline. Figure 3 also suggests that a mangrove belt width of 1 km would probably be more similar to the distance required to fully attenuate the longer swell waves, and even longer widths would be required to dissipate a tsunami, with wave lengths of hundreds of kilometers.

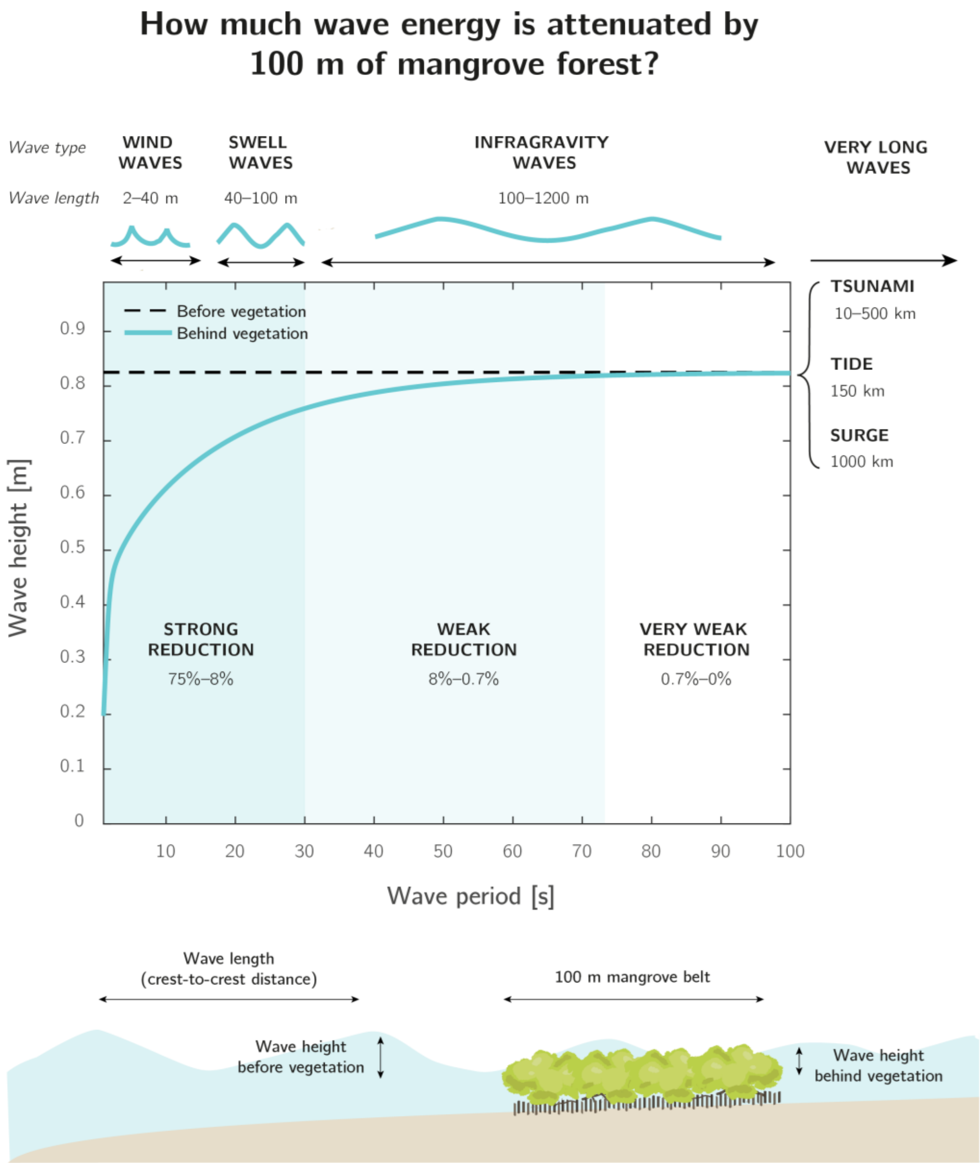

Figure 3. Diagram illustrating the amount of wave reduction for a fixed value of incoming wave height and varying wave periods through a 100 m-wide mangrove belt. The diagram was derived using the model of Mendez and Losada [28] with mangrove vegetation parameters obtained from Suzuki [29]; vegetation density of 1.1 trees/m^2 and tree diameter of 0.27 m. The results were obtained with a water depth of 1.5 m and a wave height of 0.8 m (maximum wave height possible with a breaking ratio of 0.55). The wave lengths indicated in the figure were also calculated for a water depth of 1.5 m.

This does not imply that mangroves do not provide any protection against relatively longer waves. Vegetation can stabilize and maintain a sediment level that would be unstable without vegetation, affecting both the height and the form of the coastal profile. The presence of the vegetation can also decrease the run-up height and flow velocities under tsunamis, mitigating their effects, as observed in south-east Asia after the tsunami of 2004 [30–32].

Surges can be considered as waves with very long periods, from a few hours to several days [16]. Following the reasoning illustrated in Figure 3, extensive mangrove forests would be needed to effectively dampen surges. Field observations have also shown limited surge reduction by mangroves, with attenuation rates of 9.4–24 cm/km through vegetated areas [15,33].

Since surge heights between 3–5 m are frequent in Bangladesh [17,18], some form of structure at the land side will always be needed to protect against flooding. However, surges can occur simultaneously with locally generated wind waves, with heights of 3 m at the exposed coastline [34]. The attenuation of these shorter waves by a mangrove belt would reduce the run-up height on coastal embankments, potentially decreasing the costs of slope and bank protection, and the required crest height of the structures. The economic benefit of including mangroves for coastal protection will depend on site-dependent aspects, like the costs of mangrove restoration and maintenance or the land value.

2.2. Finding Suitable Locations for Mangroves Foreshores

Identifying opportunities for mangroves along the coastal system relies on knowledge of their habitat. Mangroves grow in depositional intertidal areas with low wave action and freshwater input [35]. Natural recruitment can take place on newly accreted land that satisfies the physical conditions required by mangroves (Figure 4a), as long as there is a nearby supply of mangrove seedlings.

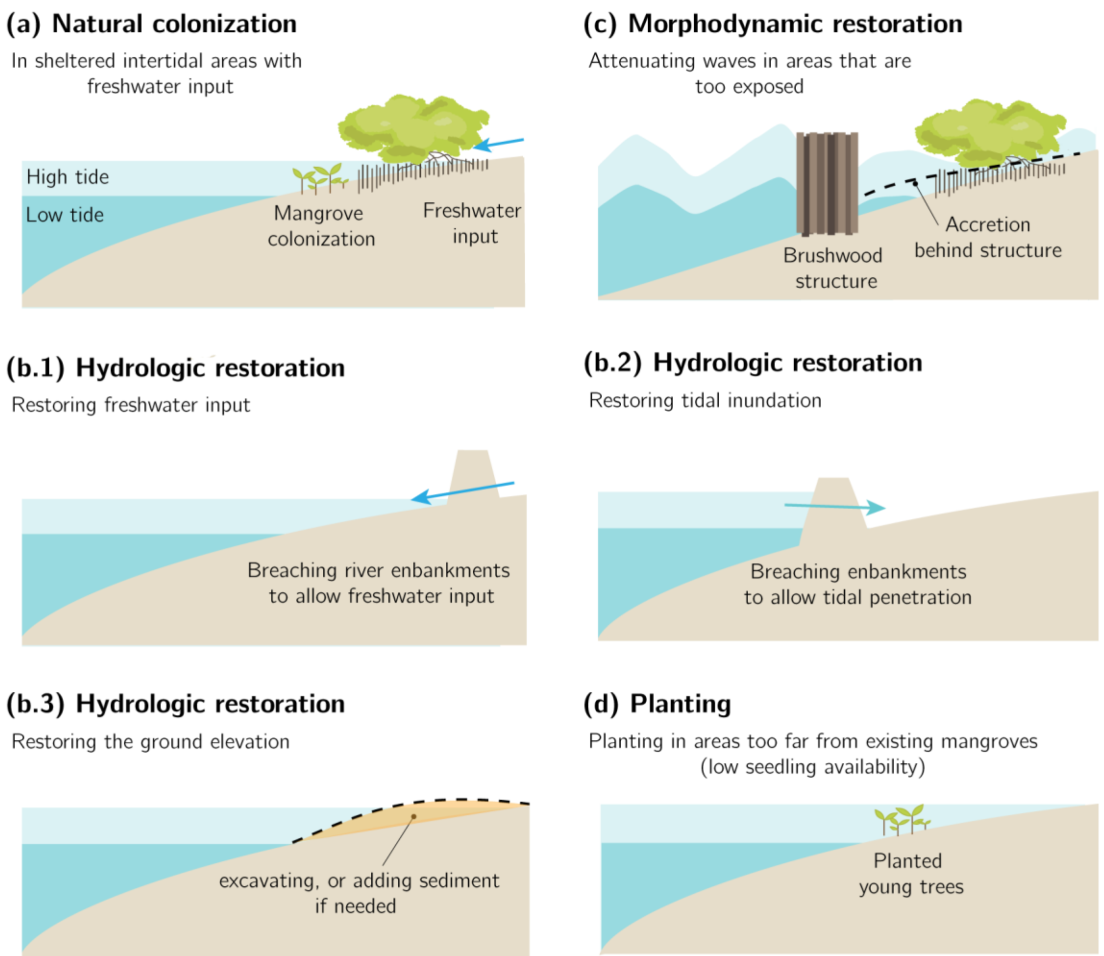

Figure 4. Diagram illustrating several mangrove restoration techniques. Mangroves grow in sheltered intertidal areas with freshwater input (**a**). If human or natural actions degrade a mangrove forest by changing the freshwater input or the local hydroperiod, hydrologic restoration measures can restore the original conditions (**b1**–**b3**). When a site becomes too exposed to wave action, leading to erosion, structures can be built to shelter the coastline and enable mangrove recovery (**c**). If the seedling availability is low at one site, planting can accelerate natural recruitment (**d**).

Similarly, if mangroves are removed at one site but the local conditions remain suitable for them, the vegetation may also recolonize naturally [36]. For instance, natural regeneration has taken place after deforestation in mangrove forests of Baja, California [37] and Kenya [38]. When a mangrove site is degraded and the habitat requirements are no longer satisfied, the habitat should be restored to enable vegetation recruitment [36]. The required technique depends on the cause of mangrove absence, as illustrated in Figure 4.

If human activities reduce seedling availability, planting schemes can accelerate mangrove establishment [36] (Figure 4d). Such planting efforts should be planned based on knowledge of the local ecology [36]. Although mangroves are generally present between mean sea level (MSL) and the highest astronomical tide (HAT), different species tend to grow in bands parallel to the coastline depending on their relative tolerance to physical factors like salinity, soil type, or nutrient content [39]. This relative distribution of the species changes from place to place.

For the case of Bangladesh, clear distribution patterns have not been identified in the Sundarbans [40], although the species *Sonneratia apetala* and *Ceriops decandra* have generally been associated with higher levels of salinity (i.e., to areas with more inundation), while *Heritiera fomes* (also known as Sunder or Sundri), was linked to lower salinity levels (i.e., to areas with less tidal inundation). The combination of multiple species, at once or in several stages of planting, is also a factor to consider in mangrove restoration designs, since biodiverse forests formed by multiple species are more resistant to pests and have higher chances of long-term survival [21].

Other forms of habitat degradation can require additional steps for mangrove establishment. Human interventions such as sediment disposal, excavation, or coastal infrastructure can alter the emergence time needed by mangroves, which should be restored to enable mangrove establishment [41] (see Figure 4b2,b3). At sites where tributaries bringing freshwater have been blocked, mangrove establishment requires restoring the freshwater input (Figure 4b1).

Some sites require restoration of the morphodynamic conditions at the coast. At locations where high wave exposure has led to coastline retreat, wood structures have been built to attenuate waves and enhance coastline accretion and create new mangrove habitats [42] (Figure 4c). This solution may not be feasible at sites with low sediment availability and high local sea level rise, since some rates of relative sea level rise may be too high to be compensated by local accretion. Moreover, geological records suggest that mangrove forests can expand seawards with up to 6–7 mm/year of sea level rise [43], limiting the possibilities for mangrove colonization in areas of large subsidence. Lastly, pollution can alter the biochemical conditions of the soil to levels that are not acceptable for mangroves [41].

Mapping all of the relevant variables to diagnose the cause of mangrove absence (land-use history, tides, waves, topography, fresh water influx, sediment properties, and soil biochemistry) is not straightforward, since it requires high-resolution data that are often scarce. Worthington and Spalding [22] developed a large-scale map indicating potential areas for restoration all over the world by identifying areas of recent mangrove loss, excluding eroded areas and urban areas, and classifying the remaining potential locations based on aspects such as proximity and size of remaining vegetation patches, and local relative sea level rise.

Since the maps developed by Worthington and Spalding [22] display locations of recent loss, they limit the restoration options in countries like Bangladesh, where mangrove degradation has taken place for a long time. For example, historical maps show that in 1775 the Sundarbans forest extended over the southwestern coast of Bangladesh until Lakshmipur [44]. However, the forest area decreased from 7500 km^2 to 6000 km^2 between 1873 and 1933 [45,46] and its limits have remained approximately the same ever since [47]. Such losses cannot be considered recent, and excluding their potential recovery would leave out a considerable portion of the coastal system.

The classification by Worthington and Spalding [22] also defines eroded areas as unrestorable, while erosion mitigation measures are being investigated in countries like

Indonesia, Vietnam, Thailand, and Surinam [29,48]. Their method could also be improved by accounting for the flood risk of landward areas, to focus the efforts on the most vulnerable locations. We consequently (1) made an inventory of open access data, based on which we (2) developed a screening methodology to map potential mangrove areas for the case study of Bangladesh.

3. Materials and Methods

3.1. Description of the Study Area

Bangladesh is located at the north of the Bay of Bengal, bounded by India at the west, north, and east, and by Myanmar at the southeast. The country lies on the Gangetic delta, formed by the deposition of sediment transported by the Ganges, Brahmaputra, and Meghna rivers [49]. The western part of the coastal system is covered by the Bangladeshi side of the Sundarbans, the largest continuous mangrove forest in the world (Figure 5). The central part of the coastal system mostly consists of low-lying polder areas, whereas the eastern coastal region consists of relatively narrower polders developed over steeper ground, as can be seen in Figure 2.3. of Dasgupta [50].

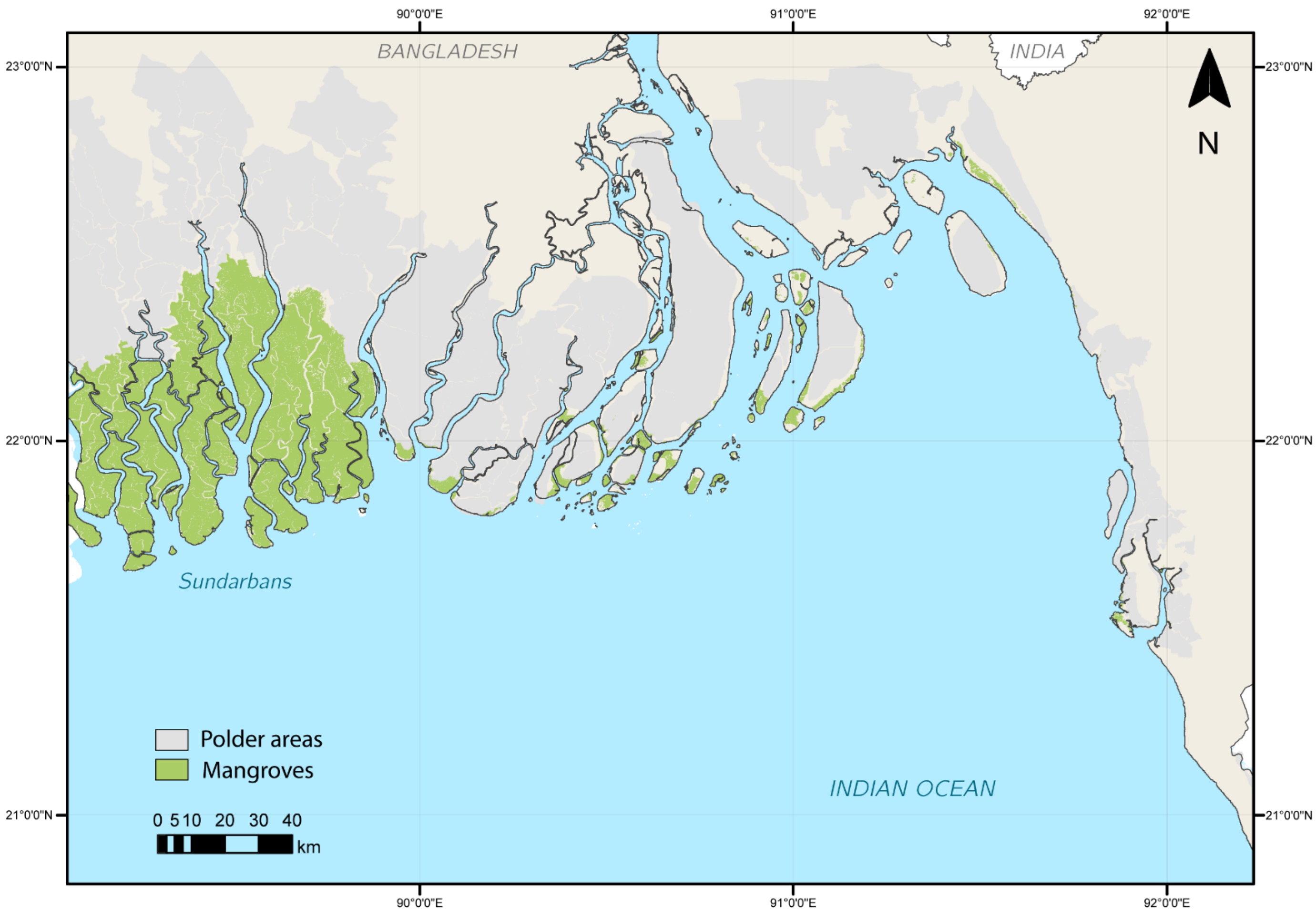

Figure 5. Coastal system of Bangladesh, showing mangrove areas (green) and embanked polder areas (grey). The large green area at the west is the Bangladeshi part of the Sundarbans, the largest continuous mangrove forest in the world. The Sundarbans is shared by Bangladesh and India, and the Bangladeshi side constitutes approximately 60% of the total area of the forest.

3.2. Open Access Databases

Table 1 summarizes the open access sources identified in the present study, including digital elevation data, tidal data, relative sea level rise data, and GIS data providing the location of rivers, tidal flats, and mangroves. Both wave and bathymetric data were scarce, and we could not identify data sources covering the full coastal zone.

Table 1. Open access data sources identified in the present study.

Dataset Type	Description	Source
Digital elevation model	CoastalDEM® is a digital elevation model at 90 × 90 m resolution, with a maximum vertical accuracy of −0.29 m.	Kulp and Strauss [51]
Coastline change	The Aqua-monitor tool provides the rate of coastline change, and sediment composition (sandy or not sandy), since 2016, in transects every 15 m along the coastline.	Luijendijk [52]
Intertidal areas	Global intertidal provides maps with tidal flat areas until 2016	Murray [53]
Mangrove cover	Global Forest Watch provides the areas of mangrove coverage from 2001 to 2018 (https://www.globalforestwatch.org, accessed on the 1 May 2020)	Global Forest Watch
Rivers	Maps of rivers of Bangladesh (https://data.humdata.org/, accessed on the 1 May 2020).	LGED
Tidal range	Tidal range measurements	Bricheno [54]
Country boundaries and regions	Boundaries of the country and its regions (https://gadm.org, accessed on the 1 May of 2020)	GADM
Sea level rise	Global predictions of relative sea level rise	IPCC [55]

3.3. Screening Methodology

Based on the existing data sources, we developed a method to identify potential mangrove sites along the coastline. The criteria for site selection are explained below, and schematized in Figure 6:

1. **Suitability of a site as potential habitat:** we considered sites within 10 km of existing mangroves as potentially suitable for colonization. This limit was based on dispersal distances observed by Clarke [56] for *Avicennia marina* seedlings. In practice, the dispersal distances will vary between mangrove species, and will depend on the local hydrodynamic processes. However, this value provides a preliminary indication of the areas that could recruit naturally. The existing mangrove sites were obtained from the maps by the Global Forest Watch (Table 1).
2. **Method needed to implement vegetation:** the techniques needed to vegetate a site were based on the rates of coastline change from the Aqua-monitor tool [52]. We assumed that natural colonization would happen at locations with expanding coastlines near existing mangroves, and if seedling availability was low, or natural processes were too slow compared to coastal protection targets, they could be complemented by planting efforts. At sites with retreating coastlines, erosion mitigation measures, such as bamboo structures or nourishments, would be needed.
3. **Prioritization criterion based on vulnerability**: we evaluated the level of priority based on the flooding risk of landward areas using the ground elevation measurements from CoastalDEM® [51], and 3 scenarios of relative sea level rise (RSLR) from IPCC [55]—+0.3 m (expected value in 2050), +1 m (worst case scenario in 2050), and +2 m (worst case scenario in 2100). Since polders comprise inhabited areas and valuable assets, their protection was prioritized compared to non-polder areas. Moreover, polders are blocked from any sediment input by the tide, which means that, unlike unembanked areas, they have no mechanisms to accrete and keep up with rising sea levels. Polders that would be below MSL in the RSLR scenario of +1 m in 2050 were given the highest flooding risk, and we prioritized vegetated foreshores seawards of them.

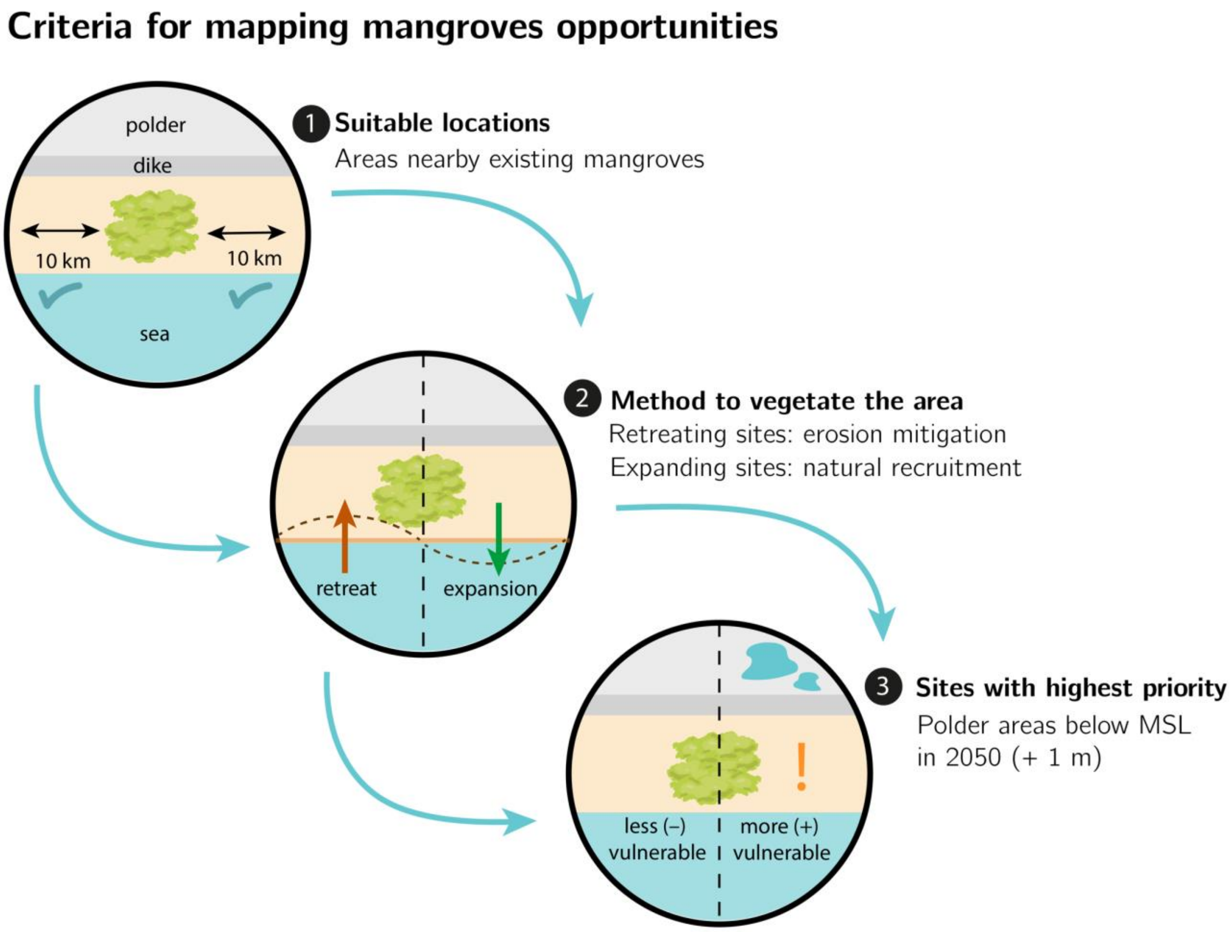

Figure 6. Criteria for mapping mangrove opportunities. (**1**) Coastal sites located less than 10 km away from existing mangroves are considered as potentially suitable for mangrove recruitment. (**2**) The technique needed to vegetate a site is chosen based on the coastline behavior. Expanding coastlines could be colonized naturally and planting schemes could be conducted if more detailed studies show the need to do so (e.g., if seedling availability is too low or if the natural establishment is too slow for coastal protection purposes). Retreating coastlines would require erosion mitigation measures. (**3**) Vegetating foreshores fronting polder areas with low ground elevations is prioritized.

4. Results

The sites identified as potentially suitable for foreshore afforestation are shown in Figure 7. Our method suggested that approximately 600 km of coastal stretches seawards from embankments are located within 10 km of existing mangrove patches. Out of those 600 km, we prioritized six sites based on their flood risk, which constitute approximately 140 km of coastline. Their location, polder number, and the techniques recommended to implement mangrove vegetation are indicated in Table 2.

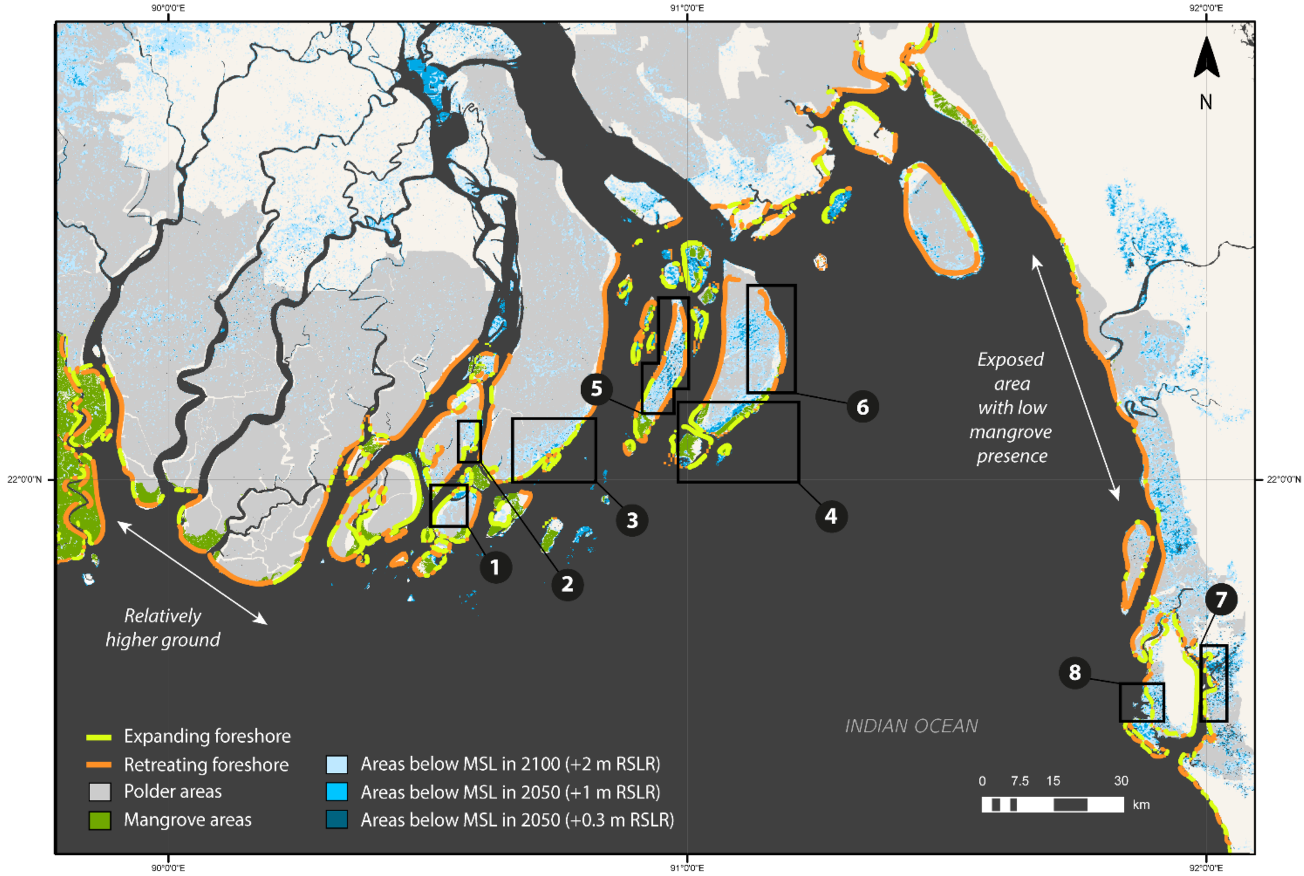

Figure 7. Map showing mangrove development opportunities in Bangladesh.

Table 2. Selected sites for mangrove-vegetated foreshores, including the polder number, and general technique recommended to vegetate each area.

ID	Location	Polder	Vegetation Implementation Technique
1	Galachipa	P55/3	Natural recruitment/planting
2	Galachipa	P55/4	Natural recruitment/planting
3	Bhola	P56/57	Natural recruitment/planting
4	Hatiya South	P73/2	Natural recruitment/planting
5	Manpura	P58/1–3	Erosion mitigation/Natural recruitment/Planting
6	Hatiya North	P73/1	Erosion mitigation/Natural recruitment/Planting
7	Khangona	P66/3	Natural recruitment/planting
8	Boro Moheshkhali	P69	Natural recruitment/planting

The Sundarbans forest (western limit of Figure 7) was not included in the analysis since mangroves have natural mechanisms to keep up with rising sea levels, and we assumed that natural recruitment processes will continue there without any need for human interference. The polder area east from the Sundarbans, along the coast of Barguna, had low vulnerability to relative sea level rise, so it was given low priority and excluded from the site selection.

Locations 1–4 correspond with expanding coastlines fronting polder areas of low ground elevation. These four sites are located near existing mangrove patches, so the newly accreted land could be colonized naturally by mangroves. Erosion mitigation measures may be needed at some specific stretches of sites 1 to 4 (see Figures 8 and 9).

Locations 5 and 6 also front areas vulnerable to flooding, but they require erosion mitigation measures along most of the coastline.

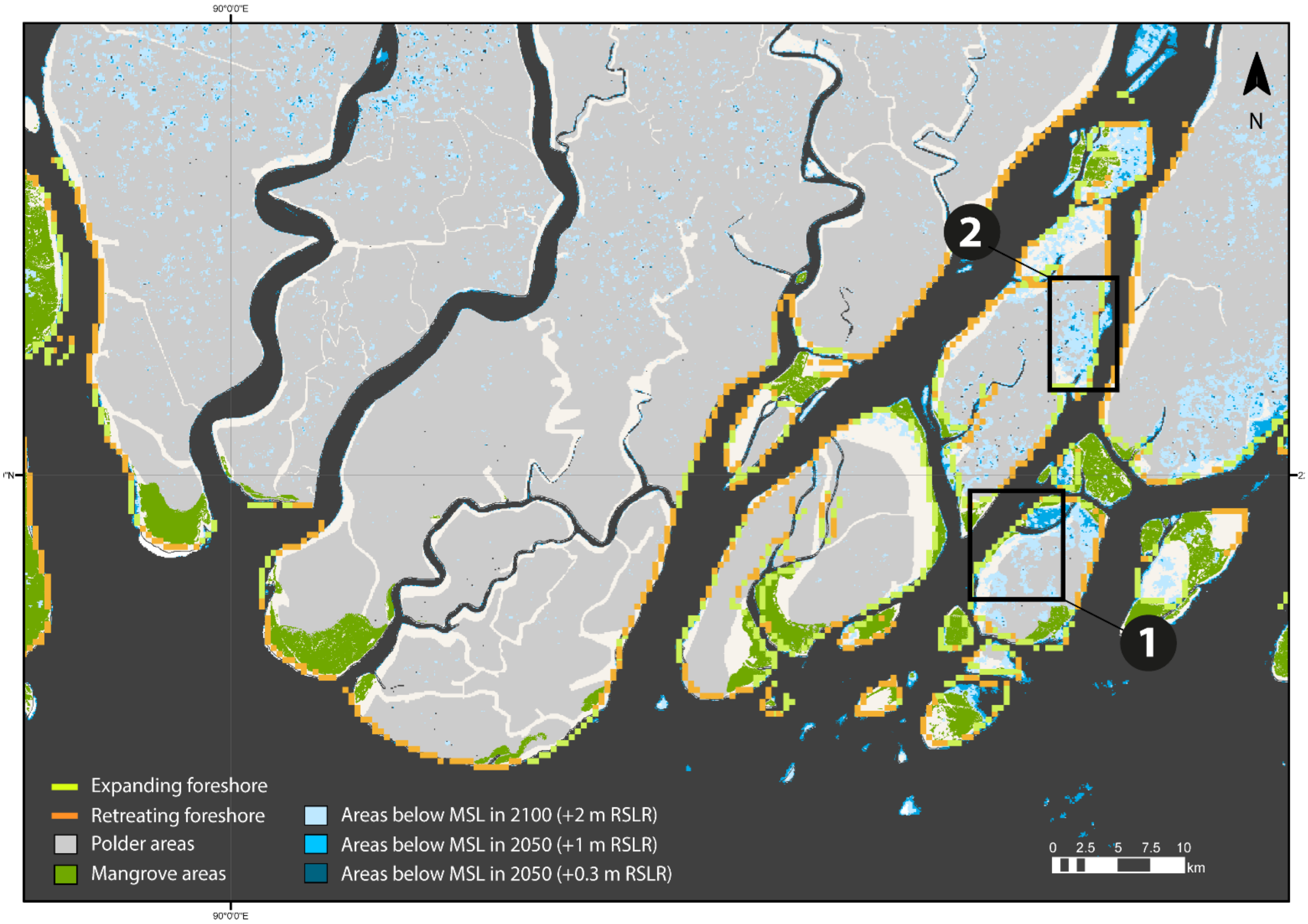

Figure 8. Potential sites for vegetated foreshores (west).

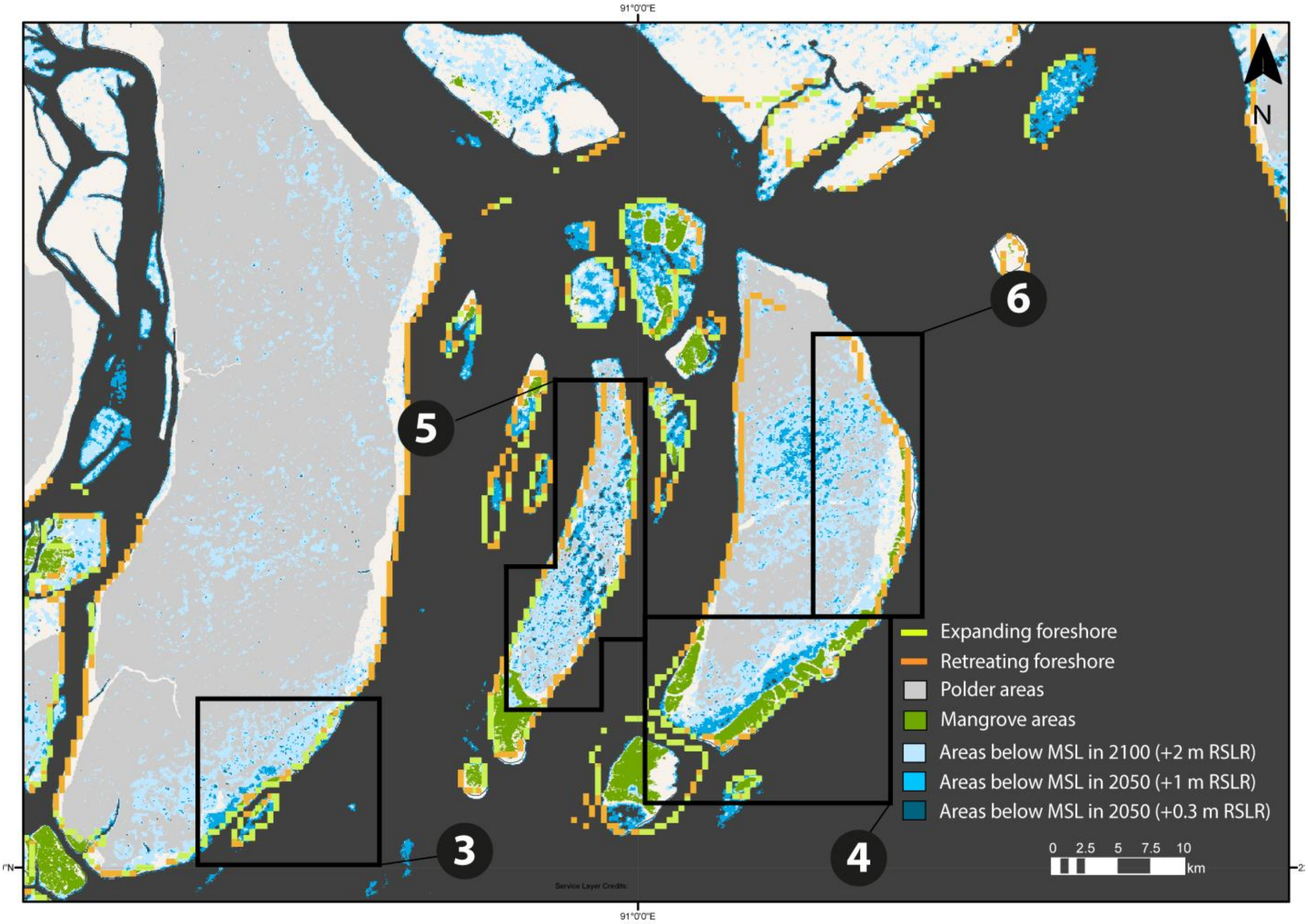

Figure 9. Potential sites for vegetated foreshores (center).

The coast at the eastern side of the country is mostly eroding and mangrove vegetation is almost completely absent. Sites 7–8 are relatively more sheltered from waves due to the presence of Maheshkhali island (Figure 10), and they correspond to expanding coastlines seaward from polders with high vulnerability to rising sea levels. Mangroves are already present close to these sites, so both locations have high potential for natural recruitment or planting schemes.

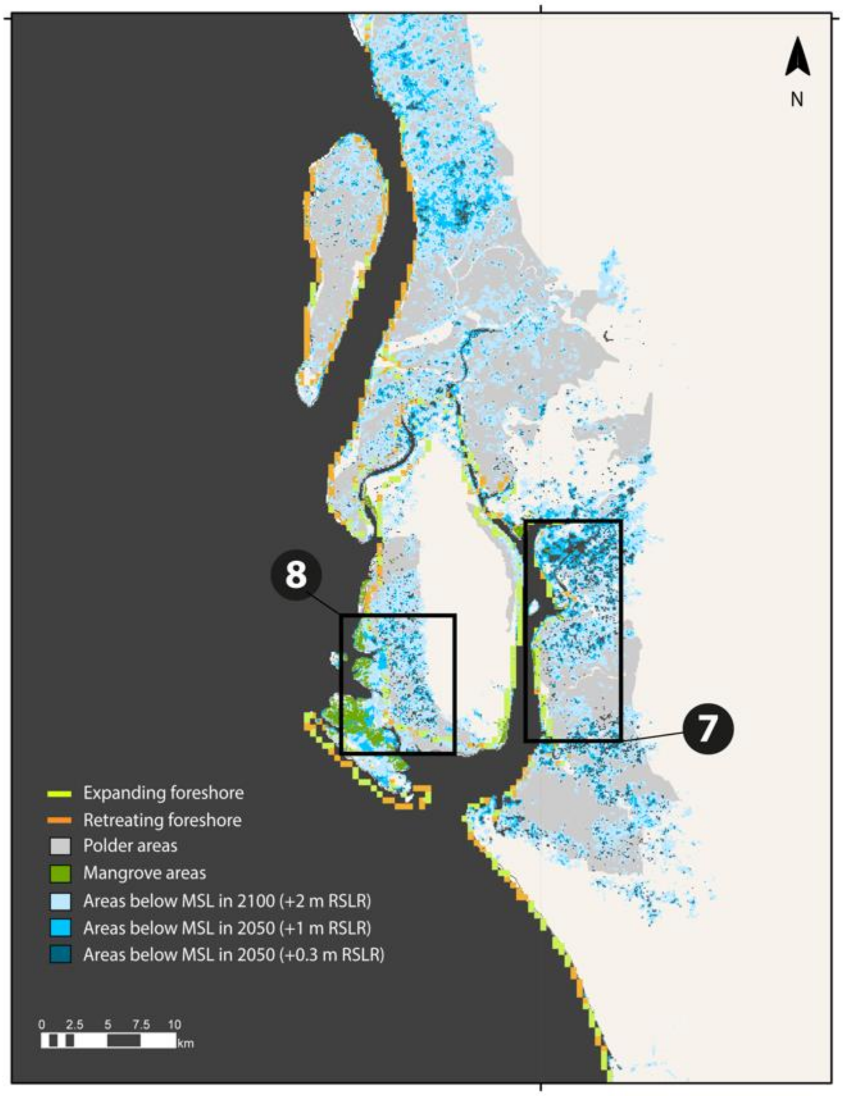

Figure 10. Potential sites for vegetated foreshores (east).

Implementing mangrove foreshores at the locations illustrated in Figures 7–10 could reduce the loads on embankments, thus decreasing the cost to upgrade them. In order to explore the impact of a vegetated foreshore on the design of a dike, we estimated the required dike height with and without a mangrove belt seaward of the embankment. The crest height of a dike is designed so that the maximum discharge over the structure does not exceed a maximum threshold during design conditions. Figure 11 shows the needed embankment height to obtain a maximum overtopping discharge of 5 l/m/s, where the discharge is calculated with the equation of Van der Meer [57]:

$$q = \sqrt{g \cdot H_{m0}^{3}} \cdot \frac{0.026}{\sqrt{\tan\alpha}} \cdot \gamma_b \cdot \xi_{m-1,0} \cdot e^{-\left(2.5\frac{H_{crest}-H}{\xi_{m-1,0} \cdot H_{m0} \cdot \gamma_b \cdot \gamma_f \cdot \gamma_\beta \cdot \gamma_v}\right)^{1.3}}, \quad (1)$$

where q is the overtopping discharge per meter, g is the gravitational acceleration, H_{m0} is the spectral wave height, α is the angle of the outer slope, $\xi_{m-1.0}$ is the breaker parameter, γ_b is the influence factor for a berm, γ_f is the influence factor for roughness elements on the slope, γ_β is the influence factor for oblique wave attack, γ_v is the influence factor for vertical wall, H_{crest} is the crest level, and H is water level.

For coastal embankments, slopes of 1:8, armor layers (corresponding with $\gamma_f = 0.55$), and berms (with $\gamma_b = 0.89$ for a 5 m wide berm placed at the still water level) are often implemented. We assumed perpendicular wave incidence (so $\gamma_\beta = 1$) and no vertical walls ($\gamma_v = 1$). The dark blue line was calculated with a design wave height of $H_{m0} = 3$ m, and a surge height of $H = 5$ m, which result in a minimum crest height of $H_{crest} =$ 6.1 m.

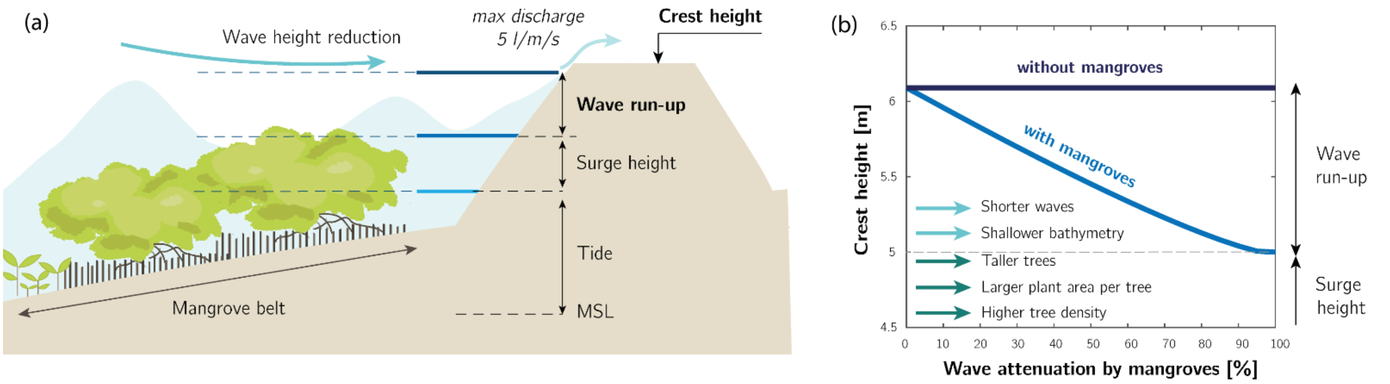

Figure 11. (**a**) Estimated water levels of an embankment. (**b**) Required embankment height to have a maximum discharge of 5 l/m/s, with and without wave attenuation by a mangrove belt.

The lighter blue line was obtained by reducing the wave height to simulate the effect of mangroves, while keeping the surge height constant. Wave attenuation rates range from 5% [58] to 100% [11] over 100 m of mangrove forest (see McIvor [59], or Horstman [14] for a full review). Assuming 8% reduction over 100 m, and that the wave height reduces linearly with the distance into the forest over the first 500 m (see Figure 4.1. in Barbier [60]), a mangrove belt of 500 m could cause a 40% reduction of the wave height, decreasing the minimum necessary height of the embankments from 6.1 m to 5.5 m. This crest height reduction would directly translate into a decrease of the building costs.

5. Discussion

By reducing the wave loads on the structure, mangroves would not only reduce the necessary crest height of a structure, but they also could decrease the costs for slope and bank protection, or even completely eliminate the need for revetments. However, implementing vegetated foreshores requires addressing several considerations.

Firstly, we identified areas with potential for mangrove establishment, but the suitability of potential sites should be investigated in more detail. Our model does not include relevant factors such as the local hydrology, soil properties, or wave action at the coast. These factors should be assessed locally and compared to the mangrove habitat requirements [61,62]. Remote sensing techniques may constitute a valuable source for these parameters. The combination of datasets of the physical parameters with maps indicating the presence of mangroves and deep learning methods could provide more accurate habitat identification techniques. Expanding the mapping methodology with additional restrictions may limit the presence of mangroves at some of the locations highlighted in Figure 11, but it could also identify new mangroves opportunities. For example, our approach focuses on mangrove opportunities along open coastal areas, but there may be additional potential sites at more upstream locations. Identifying those would require tidal and DEM data with higher resolution and accuracy than those listed in Table 1.

Secondly, bed-level changes seawards from the embankments could change the wave run-up height and the required crest height with respect to the estimates of Figure 11. Process-based models [63] could estimate how the coastline is likely to change over time under different scenarios, and how the vegetation could develop. This approach would require more detailed morphodynamic data, and information about the local mangrove species and soil properties. The estimated coastline morphology and vegetation properties could be implemented in probabilistic design models, such as Vuik [19,20], in order to assess impact of mangroves on other structure failure mechanisms, such as erosion of the dike cover.

Thirdly, although mangroves can reduce the loads on coastal infrastructure, afforestation involves an economical investment, and mangroves occupy areas that could have other productive applications. A complete cost–benefit analysis would require pondering the construction and maintenance costs of raising the embankments versus developing and maintaining a mangrove belt, and comparing the benefits derived from productive land uses, such as farming or aquaculture, with those of the mangrove ecosystem services. This type of analysis could also indicate which mangrove belt width could be most cost-effective. Moreover, it is also important to assess how other ecosystem services could affect the protective role of the vegetation, for instance for activities like wood harvesting [64].

Mangroves can also be physically degraded during extreme events, for example due to breakage or uprooting by waves or currents [65]. The possibility of vegetation failure should thus be considered in dike designs, due to both mechanical and biological causes. Low diversity has been associated to large-scale death events due to pests in single species stands of mangroves [66–68], but this aspect has received relatively less attention in planting schemes. Spatial statistical techniques can offer powerful tools to evaluate risks associated with low biodiversity [69] and to create more resilient afforestation plans.

Implementing mangroves in coastal protection plans would also require more accurate ways to estimate the flood risk. Our method indirectly evaluates flood risk by prioritizing polder areas (enclosing valuable assets) and low-elevation polders (with potentially larger flooding depths), but it does not estimate the value of the assets nor the flood characteristics in case of dike failure. Hotspot detection tools [70] would be particularly valuable for policymakers, as they would provide quantitative ways to identify the most vulnerable areas. More accurate flooding models, including ones that show the potential effect of surges, would also be necessary for precise predictions of the flooding depth and speed, e.g., as done in Jonkman [71]. The combination of such tools would provide more accurate assessments of the risk reduction provided by a mangrove belt.

Once an optimum mangrove width is selected, it will take time for mangroves to grow. The growth period will depend on the local species and the afforestation technique, and the embankments should provide enough safety against wave attack while the mangrove belt is developing. Due to the inherent uncertainties in the evolution of the bed level and the vegetation, the foreshore should be monitored regularly by measuring (1) the bathymetries and (2) the vegetation properties, such as number of seedlings and their geometry. The monitoring data would enable readjustment of the restoration strategy if necessary, or protection of the profile in case of erosion by building bamboo structures or nourishing sediment. If the restoration targets are not satisfied after the expected growth time, the embankment could then be reinforced to ensure the safety of landward areas.

The natural adaptability of mangroves to rising sea levels [26,43], in combination with grey infrastructure and robust monitoring systems, can provide a resilient tool to protect coastal areas. Our methodology offers a systematic approach to integrate vegetated foreshores and embankments in coastal protection schemes, which compensates data scarcity by using open access data sources. This mapping method could thus be applied to identify potential mangrove sites in data-scarce areas, constituting a useful tool to integrate nature-based flood defenses in coastal protection and adaptation plans.

6. Conclusions

A screening method was developed to identify potential sites for mangrove establishment using open access data sources and applied to the case study of Bangladesh. The method is based on the possibility of new habitat creation along the coastline. Potential sites were selected nearby existing mangroves, based on data from the Global Forest Watch (2020), and prioritized in terms of the vulnerability to flooding of landward areas, determined from CoastalDEM® [51]. We recommended techniques to vegetate each site based on the coastline behavior from the Aqua-monitor tool [52], with accreting sites being suitable for natural recruitment or planting, and eroding sites requiring erosion mitigation measures. Polder areas were prioritized in the site selection, given that they protect inhabited areas and valuable assets. The sites with highest restoration potential and priority are located at the mouth of river Meghna, in Galachipa, Hatiya, Bhola, and Manpura, and at the south-east coast of the country, in Khangona and Boro Moheshkhali. Additional information about the local mangrove species, bathymetry, and wave climate would be needed to more accurately assess the suitability of the potential sites, and to quantify how much coastal protection could be provided by a mangrove belt. Overall, this methodology provides a systematic and accessible tool to find potential mangrove sites in data-scarce areas, and to integrate building with nature solutions in coastal protection plans.

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