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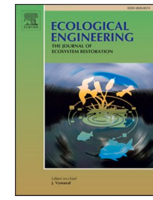

Mangrove recovery by habitat restoration using nature-based solutions

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A R T I C L E I N F O

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A B S T R A C T

This paper presents five examples of Nature-based Solutions (NbS) to restore degraded mangroves and mangrove-mud coasts. These examples are meant to provide inspiration for the restoration of other such coasts. The designs are based on a qualitative/conceptual understanding of the bio-physical system. This is obtained mainly from an in-depth analysis of historic satellite images and historic maps, while quantitative data are scarce, as is generally the case in these environments.

One example reflects the restoration of circulation and flushing in a small bay in the SW of the Caribbean Island Bonaire. Drainage channels were overgrown, and the forest was attacked from the back by hyper-salinity and the inflow of silts. The first, more urgent problem has now been addressed by re-opening a few channels, restoring circulation and flushing, and mangrove recruitment restarted.

The other four examples are from Guyana and Suriname. Though all sites are part of the greater Guiana coastal zone and driven by the same physical processes, local conditions are so different that different NbS-solutions were required to catch and arrest sufficient sediments to recreate mangrove habitat. The examples show why and how one solution works at one location, while elsewhere another approach was successful.

This paper can be regarded as a supplement to the Engineering with Nature Atlas issued by ERDC in 2024, which focuses on temperate climate environments though.

1. Introduction

Mangroves are very rich ecosystems on which more than 1500 plant and animal species depend (Mukherjee et al., 2014; UNEP-WCMC, 2014). They can sequester large amounts of carbon, up to 1000 ton per ha, which amounts to the equivalent of more than 21 Gton in 2016 across the tropics (Global Mangrove Alliance, 2021), thereby regulating carbon oxide levels in the atmosphere (Donato et al., 2011). Mangroves purify water (Ouyang and Guo, 2016), favourably affecting e.g. coral reefs and seagrass fields (Guannel et al., 2016). Healthy mangrove forests form important coastal defences reducing flood risks, in particular during storms (Gijsman et al., 2021). Last but not least, they have provided coastal communities with rich fisheries, timber and fuel wood resources (Rönnbäck, 1999; Manson et al., 2005; Giesen et al., 2007).

Ehrlich et al. (1977) proposed to value all these functions in economical terms through the concept of "ecosystem services". Since then, many papers, reports and books have been written on the ecosystem services of mangroves. Often, these services are further divided into provisioning services (food, building materials, …), regulating services (carbon sequestration, flood control, …), cultural services (biodiversity, recreation, …), etc., following a European classification system. However, the value of these services in the literature varies widely. For instance, Brander et al. (2012) estimate the regulating and provisioning services of mangrove forests at an average of about USD 4000/ha/yr (2007-prices), whereas Mukherjee (2014) reports the following values: provisioning services ca USD 18,000, cultural services ca USD 14,000 and regulating services ca USD 15,000 (all per ha per year, 2007-prices). Recently, Getzner and Islam (2020) evaluated the literature and about 250 data sets and found mean values for provisioning services of USD 5000, regulating services of USD 36,000 and

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cultural services of USD 49,000 (ha/yr, 2018-prices). However, the standard deviation to these values is many times the mean value itself, indicating an enormous spread in the data. Yet, all estimates imply considerable economic values of mangrove systems.

Getzner and Islam (2020) also provide market prices to mitigate the loss of mangroves in the form of replacement costs (people can no longer live in the degraded coastal area) and transportation costs (people and goods have to travel further), both at almost USD 100,000/ha/yr. Around 2017, the Indonesian Ministry of Marine Affairs and Fisheries (MMAF, 2017) estimated that coastal erosion by mangrove loss and subsidence along the north coast of Java caused a backfall in economic developments and costs of reparation of infrastructure at 2.2 billion USD per year.

Despite the large value of healthy mangrove forests and the large economic costs to cope with degrading/eroding mangrove coasts, mangroves have been and still are being lost at a worrying pace. Between 1980 and 2005, the worldwide area of mangroves reduced from 18.8 to 15.2 Mha (FAO, 2007), reducing further to 13.6 Mha in 2016 (Global Mangrove Alliance, 2021), 25 % of which is found in Indonesia, the majority of it in a poor state though.

To halt and/or reverse these losses, many initiatives have been and are being undertaken to restore lost mangroves and manage existing forests. This is done by central and local governments, local communities, NGO's, donor organizations, individuals, etc., sometimes based on sound ecological principles, sometimes by trial and error. To guide such efforts, many scientific papers and manuals have been published. Rather arbitrary, we refer to Lewis III (2001, 2005, 2009), the Global Mangrove Alliance (2023), Shamsudin and Raja Barizan (2011), Teutli-Hernández et al. (2020) and Philippine Tropical Forest Conservation Foundation, Inc (2020).

These publications contain a series of restoration principles and "rules" to follow, e.g. Global Mangrove Alliance (2023) for extensive elaboration on such rules. In Philippine Tropical Forest Conservation Foundation, Inc (2020) a more pointwise series of principles is given with much emphasis on the local socio-economic conditions and co-creation with local stakeholders and authorities. The first and more concise "Good Mangrove Restoration Practices" were by Lewis III (2005). We cite his principles here:

1. Get the hydrology right first.
2. Do not build a nursery, grow mangroves and just plant some area currently devoid of mangroves (like a convenient mudflat). There is a reason why mangroves are not already there or were not there in the recent past or have disappeared recently. Find out why.
3. Once you find out why, see if you can correct the conditions that currently prevent natural colonization of the selected mangrove restoration site. If you cannot correct those conditions, pick another site.
4. Use a reference mangrove site for examining normal hydrology for mangroves in your particular area. Either install tide gauges and measure the tidal hydrology of a reference mangrove forest or use the surveyed elevation of a reference mangrove forest floor as a surrogate for hydrology, and establish those same range of elevations at your restoration site or restore the same hydrology to an impounded mangrove by breaching the dikes in the right places. The "right places" are usually the mouths of historic tidal creeks. These are often visible in vertical (preferred) or oblique aerial photographs.
5. Remember that mangrove forests do not have flat floors. There are subtle topographic changes that control tidal flooding depth, duration and frequency. Understand the normal topography of your reference forest before attempting to restore another area.
6. Construction of tidal creeks within restored mangroves forests facilitates flooding and drainage, and allow for entree and exit of fish with the tides.
7. Evaluate costs of restoration early in project design to make your project as cost-effective as possible.

From an engineering point of view, the single most important step in the rehabilitation of degraded mangrove forests is a thorough analysis of the causes of that degradation and of the physico-biological system (the natural system) at hand (in fact point 1–4 from Lewis III's list). This is particularly true for eroding mangrove-mud coasts. Its system understanding follows from the following rationale: to restore the mangrove forest, the mangrove habitat must be restored, which requires restoration of the (local) sediment balance[1)]. Thus, understanding and manipulating the local sediment dynamics becomes key in controlling coastal erosion. A handicap in this is that the required data are generally scarce, as mangrove-mud coasts are typically under-explored. Then system understanding will not surpass its conceptual phase and coastal restoration plans can only be based on best-engineering practices.

Therefore, the concept of Building with Nature (EcoShape, 2024) is advocated as it can cope with uncertainties, is adaptive, is relatively cheap and is inclusive. This concept is also known as Engineering with Nature (ERDC, 2024) and these two engineering concepts form the implementation phase of the concept "Nature-based Solutions (NbS)", which also includes the management of coastal systems and the development of sustainable livelihood for local communities. As the latter two are crucial for a durable, climate-adapted approach, we refer to the NbS-approach, though the implementation of measures (the engineering) is central in this paper. Note that ERDC published three volumes of an atlas on Engineering with Nature with tens of examples throughout the world, explaining the rationale behind the various designs. This atlas describes a large variety of coastal systems, though unfortunately does not address (eroding) mangrove-mud coasts; the present paper can therefore be considered as an extension to the atlas.

This paper describes a series of successful and promising NbS-projects in restoring mangrove forests along eroding and non-eroding coasts with the objectives to:

1. Provide inspiration to the mangrove-restoration community through a variety of engineering approaches,
2. Elaborate on the reasoning and science behind these designs, explaining how progress can be made while lacking proper data.

Though mangroves provide coastal protection, dissipating wave energy (McIvor et al., 2012), they do not protect against high water. Therefore, the World Bank (2017) developed and promotes a scheme known as Green-Grey Coastal Protection which consists of a dyke (the grey part) with a vegetation zone in front, e.g. Fig. 1. As the mangroves dissipate wave energy, wave runup is smaller, and the dyke can be lower, while daily wave loads may even be damped completely, yielding cheaper dykes and less maintenance. Moreover, part of the original ecosystem services by the mangrove fringe are restored.

Winterwerp et al. (2020) evaluate the deployment of Sediment Trapping Units (STUs) constructed with permeable (bamboo) dams to promote sediment accumulation in the green zone in front of a dyke, and along eroding coasts. STUs are typically deployed at scales of a few 100 m. These are not further discussed in this paper. In stead, we present a few other solutions, some of which can be deployed at scales much larger than STUs, i.e. up to several kilometres.

The examples in this paper can be categorized into three groups:

[1] We appreciate that this subject is a "*mer*-a-boire" with many caveats. The examples below in South America are characterized by an abundance of sediment at all scales. Elsewhere in the world, this may not be the case, as in e.g. the Mekong Delta, where the local sediment dynamics are adversely affected by developments at basin scale (Besset et al., 2019; Anthony et al., 2020). The examples addressed in this paper may than be less efficient, or even non-functional.

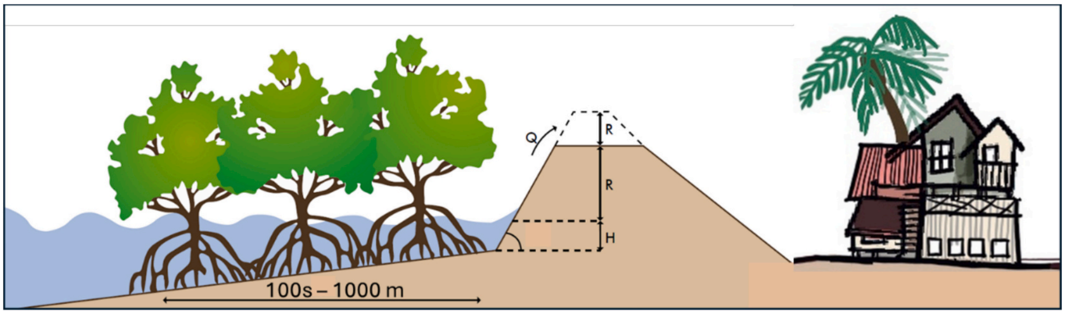

Fig. 1. Green-grey coastal defence concept (after World Bank, 2017). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

1. Examples showing how with relatively little effort the abiotic conditions (e.g. hydrology) of a degraded mangrove forest can be restored (Lewis III first recommendation),
2. Examples along an eroding coast, where mangrove habitat is generated in front of a dyke (green-grey approach) by manipulating the local sediment dynamics,
3. Examples along an eroding coast, where mangrove habitat is created by a (temporary) setback.

2. Restoring hydrology

This chapter describes a small mangrove system on Bonaire, which became degraded by uninformed management. The consequences of this management were analysed, and adverse effects were resolved by restoring circulation and flushing at strategic locations. The restoration works were carried out mainly by volunteers and took considerable time to finalize. Maintenance remains necessary.

Bonaire is a small island in the Caribbean, some 35 km long and 8 km wide, located about 100 km from the South America continent. To the SW of the island, protected from the predominant NE Trade Winds, a 280-ha large bay is found, known as Lac Bay (Fig. 2). Lac Bay is characterized by a chain of small coral islands, dividing the bay in two parts which are connected by four openings only. Over time, these openings were overgrown with mangroves, blocking largely circulation and flushing of the waters north of the islands (Moorsel and Meijer, 1993). As rainfall is only about 500 mm per year, this area is prone to hypersalinization. Moreover, silts enter the bay by surface water runoff and aeolian transports (Debrot et al., 2010). These conditions appeared detrimental for the health of the mangrove system, massive die-back was observed (Fig. 3), and urgent action was needed (see also Casal et al., 2024).

Further to the Good Mangrove Restoration Practices by Lewis III, it was decided to start with restoring a few drainage channels, restoring circulation and flushing. Design of their trajectories was based on historical knowledge and site inspections, detecting historic flow patterns and the lay-out of the island chain. A small team started the work in 2012 and gained momentum by mobilizing volunteers, digging channels by hand as heavy equipment was not available, nor could be mobilized

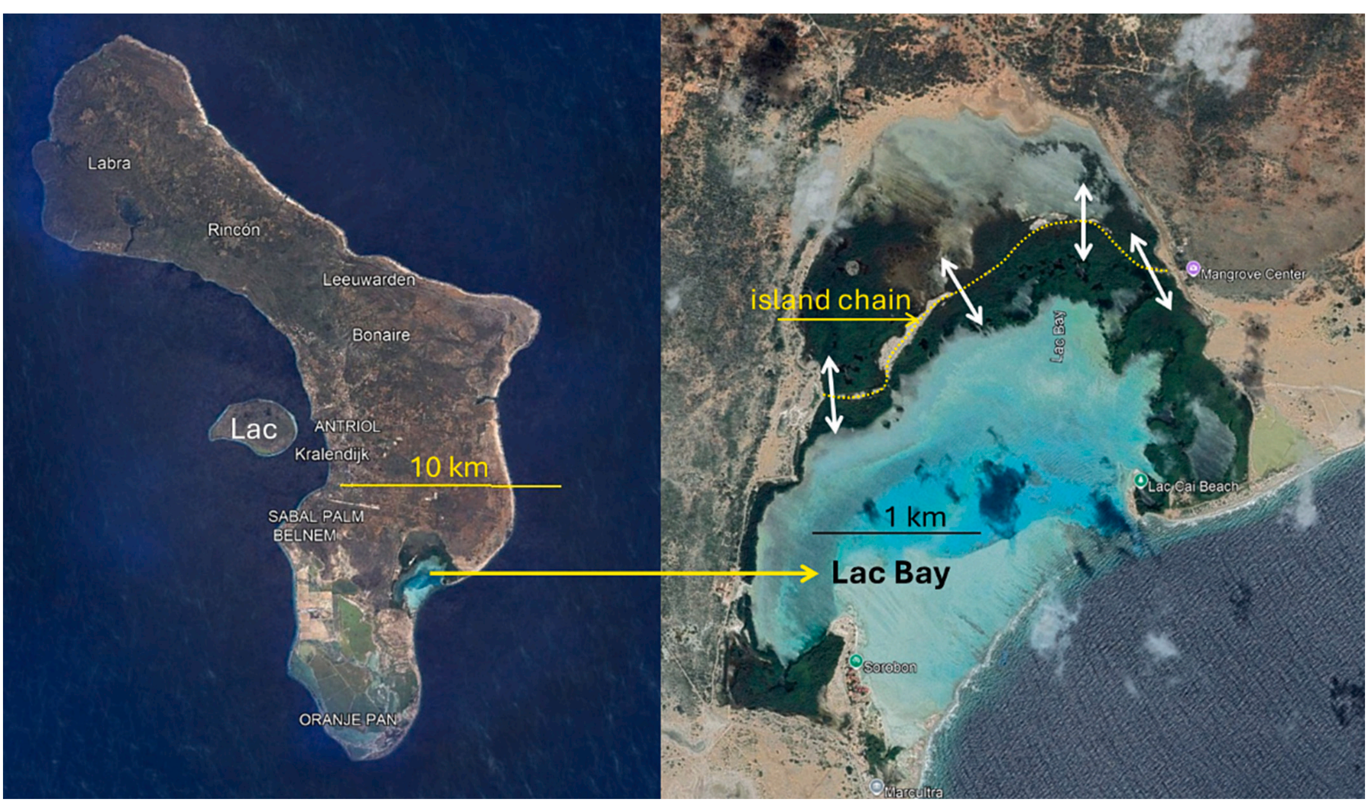

Fig. 2. Lac Bay on Bonaire with mangrove forest (Google Earth images).

Fig. 3. Die-back of mangroves in Lac Bay.

locally (Fig. 4). In 2015, 1280 m of channels were realized, and in the next five years, a total of 3450 m.

Favourable results were obtained immediately, with lower temperatures and salinities north of the chain of islands and new recruitment of *Rhizophora mangle*. Later an in-depth hydrological study was carried out (Van Zee, 2022a & 2022b), supported by some numerical modelling analyses. This study will guide activities in the coming years.

The channels must be maintained, removing new mangrove recruitment and mangrove root growth, to prevent their re-closing. Today efforts are undertaken to re-vegetize the lands around the bay to arrest erosion, preventing sediments from filling in the bay. This is a difficult policy as over-grazing by goats continues and remains a politically sensitive issue. Further, small landscaping structures, such as small dams are being erected reducing silt-laden surface water runoff.

3. Creation of mangrove habitat in front of conventional sea defence structures

This chapter and the next describe the development of green-grey coastal defence infrastructure along the coast of Guyana and Suriname. These coastlines are part of the 1600 km long greater Guiana coastline, which stretches from Cabo Cassipore in Brazil until the Orinoco River in Venezuela. The coastal waters here are extremely muddy. This mud stems from the Amazon River, and the lowlands in front of the Guiana Shield can be regarded as part of the greater Amazon Delta. Its (pristine) coastline is characterized by large intertidal mudflats and wide and dense mangrove forests, interrupted by small and large rivers. The largest is the Essequibo River in Guyana.

Fig. 4. Re-opening drainage channels in mangrove forest.

Fine sediments (mud) are mainly transported in the form of huge mudbanks, which measure some 20–40 km along the coast, extend to the 10–15 m isobath, are thus 10–15 km wide and may be 5–10 m high (Allison and Lee, 2004; Anthony et al., 2011). These banks are detached from the shore, migrating at a speed of about 1–3 km/yr in western direction. At any time, there are 15–20 mudbanks in the Guiana coastal system. The shallows behind a mudbank fill up rapidly with mud, often fluid mud, forming large and wide intertidal mudflats. These are colonized rapidly with mangroves, inducing significant accretion of the coastline. In between the mudbanks, the inter-bank phase, the coast is subject to wave action from the ocean, eroding the coast again. During one mudbank cycle, the coastline may accrete and retreat by many 100 s m up to a few kilometres.

In the interbank phase, thin lenses of sand are generally found on the upper reaches of the mudflats, the so-called cheniers (Augustinus, 1989; Anthony et al., 2014). These sands originate from the Amazon (the very fine fraction) and a coarser fraction from local rivers, the Maroni River (also known as the Marowijne) in particular. They play a crucial role in stabilizing the coastline during the interbank phase. Where the coastline becomes depleted of cheniers, while migrating westwards, coastal erosion rates become high.

The cycle of coastal accretion and retreat, induced by the passing mudbanks, is disturbed by the erection of seawalls/dykes too close to the waterline, as these reduce sediment accommodation space and often reflect waves, enhancing their erosive capacity. The entire 130 km long coastline east of Georgetown, Guyana, has been degrading in this way, and mangrove fringes are small and sparse, if any. This adverse cycle of cause and effect is further elaborated in e.g. Anthony and Gratiot (2012) and Winterwerp et al. (2013).

The tidal range varies between about 1.2 and 2.5 m at neap and spring tide, respectively. Tidal currents are mainly cross-shore. Together with the alongshore (residual) ocean current, the Guyana Current), a zig-zag, westerly directed current of a few dm/s is induced. The alongshore current velocities decrease rapidly close to the shore because of the shallowness of its coastal waters.

Winds (Trade Wind) are mainly from the NNE-ENE quadrant, and long waves come from that direction as well.

This large-scale system understanding forms the basis for the NbS-interventions at smaller scale elaborated upon in the next sections.

3.1. Coast-perpendicular structures (groins)

The embanked coastline at Anna Regina, located on the west (left) bank of the Essequibo River, Guyana (e.g. Fig. 5) was very fragile. Note that the Essequibo River is the largest in the Guiana coastal system, with a freshwater discharge varying between about 2000 and 9000 m^3/s, with a mean of about 5600 m^3/s. To stabilize this fragile coast by, reducing erosion and promoting sedimentation, the National Agriculture Research Institute (NAREI) of Guyana proposed a green-grey coastal defence approach with coast-perpendicular groins made of geotextiles. The rationale behind their design was as follows.

The Trade Winds and waves are in the direction of the orientation of the river mouth, which is also the direction of the incoming tide (Fig. 5). Hence, these onshore driving forces are opposite to the freshwater outflow of the river. Thus, complex three-dimensional currents are expected in the river mouth, further affected by salt-freshwater induced density currents. However, at Anna Regina, near-shore velocities must be along the coastline, i.e. in alongshore direction and are expected to be fairly large. This implies that groins are applicable (Simm et al., 2020). These induce horizontal eddies in between, catching suspended sediment from the ambient waters, which accumulate in the groin fields.

In 2016, NAREI placed four 500 m long geotextile groins 2 to 2.5 km

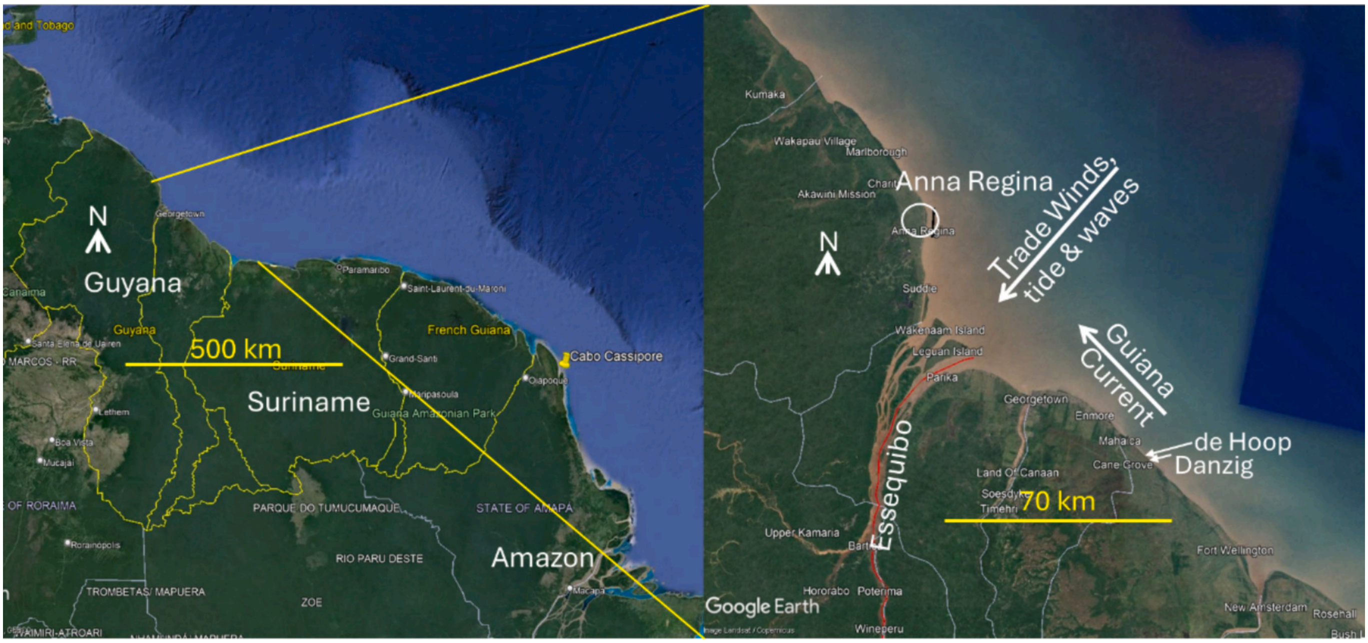

Fig. 5. The Essequibo River mouth (Guyana) in the greater Amazon delta with Anna Regina on the river's left bank and the de Hoop and Dantzig sites (Mahaica region) (Google Earth satellite images).

apart. These were highly effective and within a year intertidal mudflats developed, high enough for mangrove colonization Fig. 6). Note that Deltares and Conservation International (2022) recommend a spacing of 3–4 times the length of the groins. The length of the groins depends on the local flow velocities; large flow velocities allow for longer groins. The NAREI design is close to the dimensions recommended by Deltares and Conservation International.

Avicennia germinans is the predominant mangrove species along the open coast of Guyana. Other prominent species found along the Guiana Shield are *Laguncularia racemose* and *Rhizophora mangle*. However, there are no data or maps available, nor anecdotal stories by local people on substantial mangrove fringes since a very long time, possibly back to the end of the 19th century. Yet, all recruitment was natural, the propagules likely originating from a mature mangrove forest, known as La Belle Alliance, further to the East.

The results of this intervention are shown in Fig. 6, showing rapid mangrove colonization within two years after the placement of the groins. In 2023, a few 100 m wide, dense mangrove forest developed, protecting the seawall behind from the ocean waves and (re-)establishing a local mangrove ecosystem.

3.2. Coast-parallel structures: Detached breakwater

Away from the rivers, (tidal) currents in the Guiana's foreshore are mainly perpendicular to the coastline. Then cross-shore structures, such as groins are not effective. On the contrary, Sediment Trapping Units

Fig. 6. Development of green-grey coastal defence infrastructure around Anna Regina (Google Earth satellite images). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

(STUs) may become very efficient (Winterwerp et al., 2020). However, along the open Guiana coast, wave activity is severe in the interbank phase, and STUs require then very solid structures and much maintenance.

Under those conditions, detached, permeable breakwaters, generally constructed by rows of piles, are applicable. These must be detached from the shoreline to allow for the build up of intertidal mudflats behind (the mangrove habitat) and consist of a series of elements (rows) with opening in between to facilitate entrance of sediment-laden water. An optimal configuration implies a length of one series of about twice the distance of the breakwater from the shore. The openings in between the series must amount to about 5 m (Deltares and Conservation International, 2022).

These breakwaters are permeable to minimize wave reflection, preventing scour in front. The rule of the thumb is that the piles are spaced at 20–50 % of their diameter to optimally dampen incoming wave energy. About 10 % of the incoming wave energy is reflected in case of round piles (Gijón Mancheño, 2022).

In 2023, NAREI constructed three series of permeable breakwaters of 250 m length, some 20 m offshore, e.g. Fig. 7. Some months after the erection of the breakwaters, a large amount of mud was already collected, as shown in Fig. 7.

3.3. *Coast-parallel structures: Artificial chenier*

As explained in Section 3, cheniers play a crucial role in stabilizing the coastline of the Guiana's. The recovery of the coast around the Crematorium in the Weg naar Zee province in Suriname (Fig. 8) is a good example of their role in the local coastal dynamics.

The Weg naar Zee coast has been eroding for decades in response to the disturbance of the natural cycle of erosion and accretion by uninformed coastal management (Anthony et al., 2011, 2018). Yet, mudbanks continue to pass the coast, and cheniers are still being formed.

Fig. 9 shows a series of satellite images of this coastal stretch. Since 1970, the coastline retreated by many 100 s meters, threating two religious monuments, i.e. the Temple and the Crematorium (Fig. 9a). However, the coastline around the Crematorium stabilized naturally around 2015, whereafter rapid accretion with mangrove recruitment occurred. Inspection of a series of historical satellite images showed that this recovery was initiated by the formation of cheniers (sandbars) some 500 off the 2015-coastline (Fig. 9b). In the following years, large amounts of mud accumulated behind these cheniers, and the mudflats were rapidly colonized by a dense mangrove forest (Fig. 9c). During the last few years, the coast retreats a bit as the chenier sands are washed onshore by waves – this is a natural process along the Guiana coastline.

The newly formed mangrove forest is a few 100 m wide, up to 500 m, and forms a robust, natural sea defence of the hinterland.

In the past, cheniers were also formed further to the East of the Temple; coast-parallel sand ridges in the landscape are evidence of this (Fig. 10). However, for reasons not well understood, chenier formation does no longer occur here, and the coastline continues to erode. Efforts to catch muds on the local foreshore with permeable dams, stabilizing the foreshore, and thereby halting or even reversing erosion, were not successful.

Erosion continues and flooding risks increase, hence action is required. Construction of a classical sea dyke is possible, but expensive, as the subsoil is very soft, with little bearing capacity. Inspired by the natural recovery around the Crematorium, the construction of artificial cheniers is proposed. In this scheme the natural chenier configurations are taken as an example, and a few 10s m wide and 500 m long sand bars are constructed some 500 m off the coast with dredging equipment. With a height up to about mean sea level, wave activity is likely to shape the cheniers into a natural form. Openings in between the cheniers allow for the inflow of sediment-laden seawater.

Though the formation of mudflats with a dense mangrove forest may take some years, the hinterland is protected from wave action immediately after the erection of the cheniers, stopping wave-induced erosion of the coast immediately.

4. Creation of mangrove habitat by a (temporary) setback

The mudbanks and cheniers along the Guiana coast migrate westwards. The cheniers are continuously migrating by common littoral processes, i.e. wave-induced currents transport the chenier's sands to the West. The mudbanks, on the contrary, become mobile under storm conditions only. During such episodic events, large amounts of mud are redistributed in the coastal zone, some of which reach the shoreline, covering the tail of the cheniers there. Thus, the westward migrating chenier becomes depleted of sands: the chenier thins or erodes entirely in front of a migrating mudbank (Deltares and Conservation International, 2022). Then the coastline behind can no longer withstand the ocean waves and often breaches (when protected by a seawall) or retreats (when still pristine).

This sequence of events, leading to a breach in the seawall at Danzig (Fig. 1) on September 29, 2019, could be reconstructed form a series of Google Earth satellite images spanning 2000–2022, as shown in Fig. 11. The horizontal axis depicts the distance along the coast, with Danzig at km 365, the vertical axis time. The approximate leading and trailing edge of the two mudbanks at either side of Danzig are indicated with a black dotted line – the white area in between these lines represents the interbank phase. In the interbank phase, waves can approach the shoreline undisturbed, which is clearly visible on satellite images; all images containing breaking waves are indicated by a blue field. No breaking waves implies the presence of a mudbank or of fluid mud, the latter generated by a migrating mudbank. The waves not only push the cheniers to the West, they push the sands also further onshore,

Fig. 7. Detached pile-groin breakwater at de Hoop, constructed in 2023.

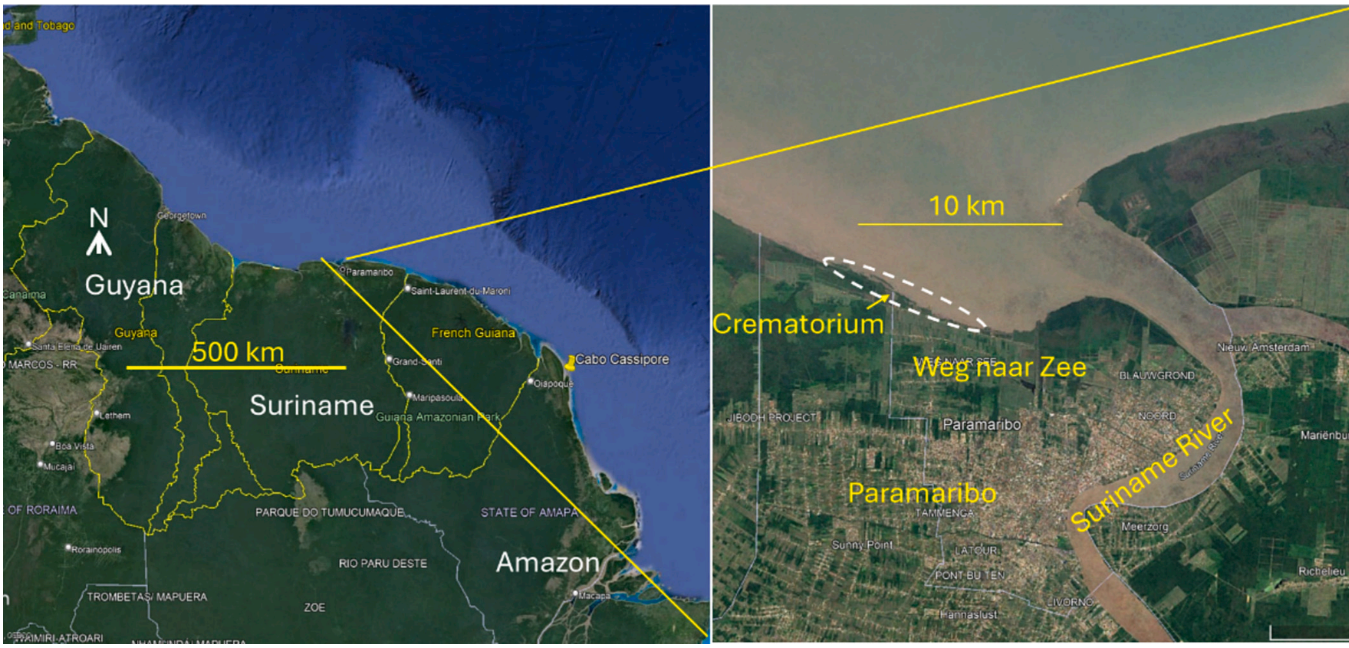

Fig. 8. The Weg naar Zee province, north of Paramaribo (Suriname) and Crematorium. The white dotted ellipse refers to Fig. 9 (Google Earth images).

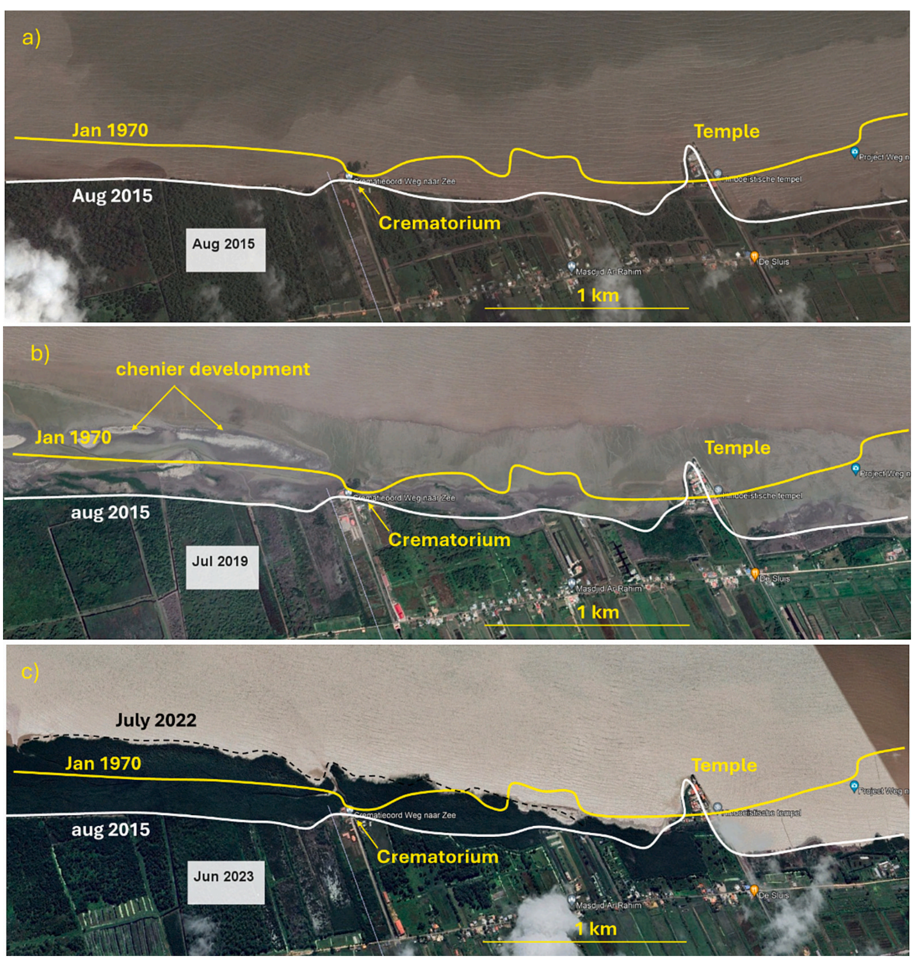

Fig. 9. Chenier development around the Crematorium and mangrove recruitment with coastlines in 1970, 2015 and 2022/2023.

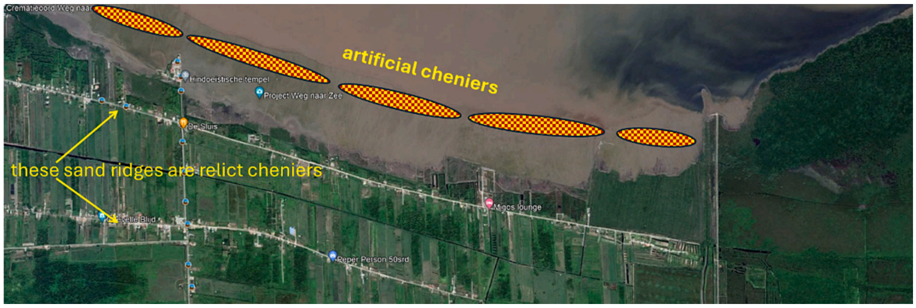

Fig. 10. Conceptual design artificial cheniers around Weg naar Zee (Suriname) to restart natural coastal dynamic processes.

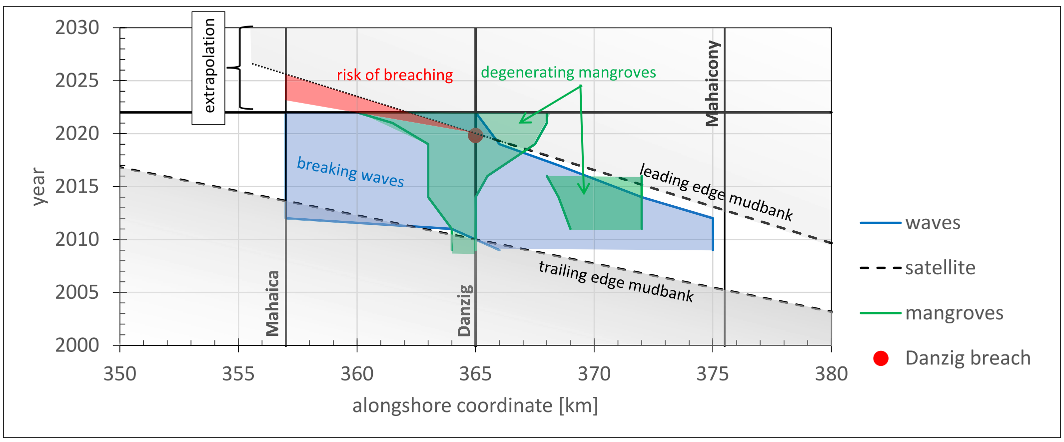

Fig. 11. Timeline of Danzig breach with approaching mudbank, and degeneration of mangrove fringe and chenier (East is to the right of the graph).

unfavourably affecting the mangroves behind. Degenerating mangrove fringes can also be detected from the satellite images. When all chenier sands and mangroves stands have gone, the seawall is directly attacked by the waves, and this caused the seawall at Danzig to collapse. Fig. 11 also indicates that with the mudbank's migration, a breaching-risk window develops further to the West of Danzig. Such diagrams can be useful for coastal managers to anticipate on future risks, as mudbank migration can be well established from satellite images.

The breach of the Danzig seawall flooded 300 ha of agricultural lands with seawater. The authorities immediately erected an earthen emergency dam, some 250 m inland from the original shoreline to protect the hinterland from further flooding. This generated a "bay" in front of the emergency dam of about 1.3 km length and 250 m width, referred here as the Danzig Bay. In 2021 efforts to restore the original seawall failed, and authorities were forced to construct some 650 m of the new seawall 150 m more inland from its former location, e.g. Fig. 12.

The initial Danzig Bay measured about 30 ha. It was filled in with mud from the approaching mudbank rapidly and then naturally colonized with mangroves within one year. A year after the completion of the new seawall, September 2022, the larger part of these mangroves was still present and in a healthy state. However, the last available Google Earth image of April 2023 shows that all these mangroves are dead now, without doubt because of the lost hydrological connections of the area by the dykes around.

The sub-bay, created by the new seawall of 150 × 650 m^2 was filled in with soft mud as well, but still not vegetated, possibly because the mud is still too soft.

The developents around Danzig can be regarded as a non-intentional setback, i.e. a full-scale experiment in coastal management. The coastal developments between 2019 and 2021 prove that a such setbacks along the Guiana coastal system will facilitate mangrove regeneration, providing they are synchronized with the natural processes in the system, i.e. the dynamics of mudbanks.

Moreover, if managed properly, part of the land and mangrove forest reclaimed can be recultivated with the conditions that a mangrove fringe of some 500–1000 m is kept (Deltares and Conservation International, 2022). Then we refer to a temporary setback. This concept is also known as transitional polders, based on a double dyke configuration, and in The Netherlands known as a "Wisselpolder" (De Mesel et al., 2013).

Fig. 12. Mud infill into Danzig Bay, mudflat development and mangrove colonization (drone image of September 22, 2022).

5. Summary and discussion

The design of coastal protection by sea dykes is taught at every coastal faculty across the world. Extreme water levels, surges and wave conditions must be established and extrapolated to acquire design conditions. Soil mechanical studies are often required assessing the bearing capacity of the soil on which the dyke is to be constructed. Various engineering rules can be found in e.g. the Coastal Engineering Manual (USA Corps of Engineers, 2002), with which height and width of the dyke can be assessed, its construction materials and the likely necessary bed protection are selected. Such manuals may be regarded as recipe for designing coastal protection. Though it is appreciated that following these recipes may be challenging from a technological and/or engineering point of view, the design process is fairly straightforward and supported by an overwhelming amount of experience. We refer to the traditional approach of coastal defence.

Coastal protection with Nature-based Solutions (NbS) requires this information as well, though possibly at a less detailed level, given the adaptive characteristic of this approach. However, contrary to the traditional approach, the NbS-approach requires also information on currents, sediment dynamics, the ecosystem, etc. In general, these vary largely across a multiple of spatial and temporal scales. The various restoration manuals, referred to in the Introduction are therefore necessarily quite abstract and cannot serve as a recipe.

Nature-based Solutions are therefore site-specific. NbS-approaches must thus be based on a sound understanding of the local bio-physical system and understanding of the functioning of the various NbS-elements available. The Engineering with Nature Atlas (ERDC, 2024) is therefore so valuable, as it provides the bio-physical design arguments for a range of NbS-solutions in a wide variety of environments. As it does not contain examples of mangrove-mud coasts in the tropics, this paper may be regarded as a supplement to this Atlas.

In this paper we show with a few examples how a sound understanding of the bio-physical system steers a successful restoration of degraded mangrove forests, even though quantitative data are scarce. Note that the tropical environments, home to these mangrove-mud coasts are generally poorly studied and data are scarce. In that case one must rely on historic maps, historic satellite imagery and conceptual thinking, while system understanding becomes highly conceptual. Important questions to address, further to Lewis III (2001, 2005 and 2009), are amongst others:

- Have conditions be favourable form mangrove recruitment in the past?
- Can hydraulic circulation and drainage be restored sufficiently?
- Is there sufficient sediment to restore mangrove habitat?
- Can the sediment reach the degraded mangrove habitat and accumulate there?
- Is there sufficient space for a sustainable mangrove fringe?

The conceptual system understanding referred to above can be very powerful, addressing these questions and steering site-specific Nature-based Solutions, The examples in this paper show how improved drainage, coast-perpendicular groins, coast-parallel structures (breakwaters, cheniers) and (temporary) setbacks do initiate mangrove rehabilitation, though have their own specific niche of deployment. When the restored mangrove forest is large enough, it may become self-maintaining. All interventions discussed in this paper were carried out with modest engineering equipment and were all reversible. The latter is an essential feature of the adaptive NbS-approach.

In a previous paper, Winterwerp et al. (2020) discussed the use of permeable groins/dams in Sediment Trapping Units (STUs). These configurations were deployed for ages in the Dutch-German-Danish Wadden Sea at a scale of about 200 km. This required long-term planning, dedication and maintenance, which required a high degree of local organization. STU configurations were lately deployed along mangrove-mud coasts, at much smaller scales though, i.e. the scale of a few 100 m. Upscaling to large coastal systems is possible, but requires major institutional and socio-economic efforts, often difficult to mobilize in the rural areas where the NbS-approach is very suitable.

The present paper provides a few alternative Nature-based Solutions, which can be scaled up easily to many kilometres of coastline. In particular, solutions deployed at open sea on lost parcels of land are very attractive from a political and socio-economic perspective. Note that landownership must be addressed ahead, but this is the case with all coastal protection measures in the coastal zone.

It is appreciated that scarcity of data involves engineering risks in relation to the integrity of structures, and their efficiency as Nature-based Solutions. The collapse or mal-functioning of e.g. STUs may be annoying but yields small risks with respect to physical damage and budgetary investments. With the adaptive Building with Nature approach a better STU design can then be based on lessons-learned. At larger scale, improper design of e.g. (temporary) setbacks or artificial cheniers may induce severe damage to a coastal system, the socio-economic conditions of the hinterland, and even have adverse effects elsewhere along the coast. Such designs must therefore be informed on more quantitative data, to be collected locally, obtained from more or less detailed numerical modelling and/or otherwise quantification of the conceptual model. Evaluating such risks is part of the best-engineering practices addressed in this paper. Personal site-inspection and communication with local stakeholders is a must in this approach.

CRediT authorship contribution statement

Johan C. Winterwerp: Writing – original draft, Methodology, Investigation, Formal analysis, Conceptualization. **Annalise Bayney:** Writing – review & editing, Resources, Funding acquisition, Conceptualization. **Sabine Engel:** Writing – original draft, Supervision, Funding acquisition, Formal analysis, Conceptualization. **Luandra Jack:** Writing – review & editing, Resources, Investigation, Formal analysis, Conceptualization. **Kene Moseley:** Supervision, Project administration, Methodology, Funding acquisition, Formal analysis, Conceptualization. **Bob Smits:** Writing – review & editing, Validation, Supervision, Resources, Funding acquisition, Formal analysis, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

No data was used for the research described in the article.

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