GUYANA
# MANGROVE-SEAWALL ENGINEERING GUIDANCE

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CONSERVATION INTERNATIONAL Guyana

Seawall at Chateau Margot, with abandoned Koker (bottom right) showing previous shoreline. © CI/John Greene

# Contents

# EXECUTIVE SUMMARY

Guyana is among the countries most profoundly threatened by climate change induced sea level rise, with 90% of the population and 75% of agricultural production situated on the low-lying coastal plain. To mount a response to this existential threat, Guyana needs to harness the same natural processes that created the North Brazil Shelf's coastal plain – from the Amazon river to the Orinoco river. The coastal plain was created over tens of thousands of years by a flux of Amazonian soil particles transported along the coast and captured in the roots of mangroves.

By taking a "design with nature" approach to study and model mudbank dynamics, we can optimally time the application of green-grey technologies (combinations of engineered infrastructure and natural solutions such as mangrove ecosystems) to speed up this natural process and reclaim/ re- grow our coast. In addition to re-building our coastland, green-grey solutions also provide benefits such as reduction of wave intensity and flooding, increasing biodiversity, and marine food security.

Based on our understanding of the dynamics of mudbank movement, we will be able to harness this abundant sediment supply to defend and expand Guyana's shoreline. This has long been the missing piece of the puzzle in Guyana's mangrove replanting efforts and is likely to greatly increase the success of restoration activities.

**This report is divided into two main outputs:**

1. Recommendations for practical Engineering Guidelines for the assessment, development and implementation of green-grey Solutions along Guyana's coast, including the identification of site specific green-grey interventions for deployment at full scale sites along Guyana's coast; and
2. A technical resources document providing the theoretical background for the guidelines, including a simple mass balance model to estimate available onshore sediment fluxes as a function of mudbank dimensions and migration speeds.

Key findings from this work are summarized below.

## FINDING 1

Analyses of sediment flow from the Amazon along the northern coast of South America indicate that in many instances natural regeneration or regrowth of mangrove forests is largely determined by the presence of mudbanks that move towards the shore. However, this process can be interrupted by the presence of hard structures too close to the waterline, such as concrete seawalls and dykes that reflect waves and thereby increase wave heights creating an unfavourable environment for mangrove colonization. The following conclusions have been drawn from analyses of current sediment fluxes:

- An estimated 250 million tonnes of sediment move along the coastline from Amazonian outflow, of which about 1% is naturally deposited along Guyana's coastline. There is sufficient sediment in the waters moving past Guyana's shores to deploy sediment trapping units to rebuild the coastline lost to erosion and wave action.
- Detached mudbanks continuously pass Guyana's shoreline and can deposit large volumes of sediment. Deployment of mud and sediment capture units in the right locations and at the right time can initiate and accelerate this process.
- When enough sediment has been deposited and accrued into intertidal mudflat, mangrove colonization can occur rapidly, though at some locations, it may take several years for optimal colonization.

## FINDING 2

At this critical developmental stage in Guyana's growth, several key green-grey interventions have been recommended at specific sites along the coast to both strengthen sea defense, as well as to provide the building blocks for long term sustained sediment capture aimed at promoting coastal accretion to restore mangrove habitats. These include:

- Opportunistic realignment (setbacks) of the existing seawalls, entirely removing damaged seawalls, and installing sediment capture units perpendicular to the existing shoreline aimed at extending intertidal mudflats that can be re-colonized by mangroves. This can be deployed in target areas such as Danzig, Mahaica (District 6 Coastline).
- Deployment of Sediment Trapping Units (STU) or Coast Perpendicular Groynes (CPG) at site specific locations along the Essequibo coast, Georgetown foreshore, East Coast, and Berbice foreshores within the next 1-2 years to take advantage of a large mudbank moving across the shoreline as well as shelter natural mangrove regeneration.

## FINDING 3

Using grey technology in combination with green designs will result in cheaper, durable and more productive solutions to protecting Guyana's coast, than if these approaches were pursued on their own. While there remains the significant need for hard (grey/ concrete) infrastructure, this report provides several realistic recommendations and tools to support the integration of Green-Grey Solutions into coastal long-term planning. These include:

- Design and implement a monitoring system to properly establish a baseline for sea level rise along Guyana's coast. This may be part of a wider cross border monitoring system with Suriname and French Guiana (who share sediment loads from the Amazon). This data will inform coastal adaptation and mitigation strategies in national planning.
- Design and implement a mud bank monitoring system for tracking mudbank movements along the North Brazil Shelf. This will inform when and where are the best deployment sites for sediment capture units to maximize benefits and reduce costs.
- Creation of an Integrated Coastal Zone Master Plan, through a multi-stakeholder mechanism, which integrates Green-Grey Solutions into future coastal infrastructural projects, as well as showcases a long-term vision for coastal Guyana.
- Utilize lessons learned from NAREI's Mangrove Restoration Project coupled with mudbank movement, and freshwater runoff data from the three main rivers to efficiently identify areas for restoration. Form a (cross-border) centre of expertise to develop, maintain and concentrate knowledge, data and experience on Green-Grey Coastal Infrastructure initiatives.
- Track mudbank movement along the Georgetown coastline (Kitty Foreshore and Kingston Beach). The mudbank will soon cover the sandy beach area identified for tourism and recreation development.

## FINDING 4

Adapting to rising seas is one of Guyana's greatest challenges as almost 90% of its population resides along the coast. Decisions made at this juncture will reverberate for generations of Guyanese citizens. Luckily, Guyana is still in a position to put nature to work alongside national development by employing pre-emptive, innovative and scalable solutions that reclaims from the sea what has been lost.

# INTRODUCTION

Guyana has identified green-grey coastal infrastructure solutions as a strategy to reduce climate risks for people, communities, and urban areas across the country's vulnerable coastal plain. Vegetation in front of coastal defense structures (e.g. seawalls, levees and dykes) offers excellent opportunities for adaptive and robust flood risk reduction schemes (Sutton-Grier et al, 2015; Van Wesenbeeck et al, 2017). However, thus far there are no guidelines for combined mangrove seawall designs across the world.

Here, we present a first set of guidelines drawing on the best available practice, science, and technical experience available in Guyana and globally to inform a comprehensive green-grey strategy for Guyana's coastal defense. As an initial phase of this strategy, we have developed:

1. A summarized engineering guidance describing best practices to design and build coastal protection projects that integrate mangrove restoration areas to complement seawalls, and together reduce the effects of storm surge and wind waves, and
2. A comprehensive summary of coastal processes along the dynamic and mud-rich Guyana coastline and of adaptation strategies, to be used as an accompanying technical resource to these summaized guidelines.

Both products are intended to inform actions by national and local governments, consultants, and stakeholders. They are written to support efforts to optimally plan, design, and build mangrove green-grey projects that make use of the ability of mangroves to capture and consolidate soil, and grow quickly to adapt to rising sea levels – while also providing a myriad of co-benefits for people and nature.

Please, put this guide to use and join us! Our project team has identified the following high value opportunities to apply the information in these guidelines in the next 1-2 years:

- Erect Sediment Trapping Units along the north-eastern coasts of Wakenaam and Leguan Island (mouth of Essequibo, district 1 and 2) to stabilize these coastlines and to build experience,
- Inspect (and repair) the current seawall west of De Kinderen to anticipate loss of chenier sand in response to an approaching mudbank,
- Create a temporary realignment in De Kinderen at the breached area to create mangrove habitat profiting from arriving mudbank,
- Prepare large scale MudBank Motor works near Georgetown (Chateau Margot mudbank) using the natural mudbank dynamics to create suitable locations for mangroves to recolonize. Start constructing not later than 2023,
- Prepare management plan for the sand beaches in front of Georgetown, inspect and, if necessary, re-enforce Fort Groyne.
- Prepare modelling capacity to design Coast Perpendicular Groynes along left banks of rivers, and
- Initiate site selection and prepare designs for these sites in the coming years.

# 1. MANGROVES & SEAWALLS

As the climate changes, communities need to adapt to build social, ecological, and economic resilience. It is essential to identify effective site specific adaptation strategies, that take advantage of natural processes that form the basis for life-sustaining ecosystem services.

Here we define the green-grey adaptation approach, specifically for combining mangroves and seawalls.

## WHAT IS GREEN-GREY INFRASTRUCTURE?

There is a critical need to find pre-emptive and scalable climate adaptation solutions that protect, manage, and restore nature - now and for future generations.

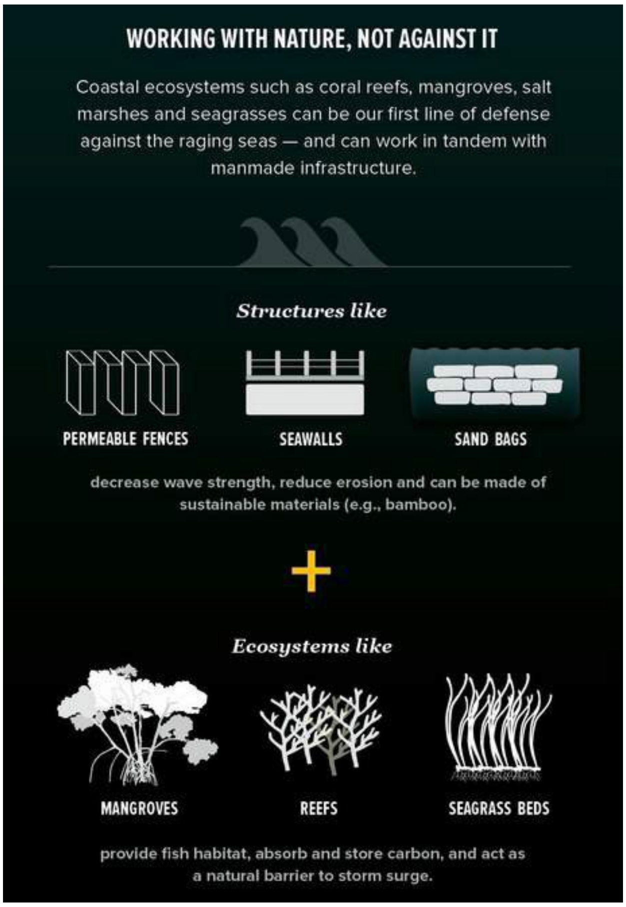
Green infrastructure such as wetlands and forests can provide nature-based adaptation solutions for flood control and water security, alongside providing co-benefits to biodiversity, livelihoods, and more. However, for communities exposed to extreme climate and disaster risks, green infrastructure alone may not provide adequate protection.

Conventional grey infrastructure, in the form of seawalls and dykes, can provide immediate protection but is often prohibitively expensive to build, maintain, and replace, and can create unintended negative impacts. By blending "green" conservation with "grey" engineering techniques, communities can incorporate the benefits of both solutions, while minimizing the limitations of using either green or grey infrastructure individually.

Green-grey infrastructure combines conservation and/or restoration of ecosystems with the selective use of conventional engineering approaches to provide people with solutions that deliver climate change resilience and adaptation benefits. This green-grey infrastructure design approach can be applied in coastal, freshwater, and terrestrial settings and accomplish a variety of project goals.

An example of green-grey infrastructure is where natural coastal ecosystems – such as mangroves, salt marshes, inter- tidal flats, seagrasses, and coral reefs – are combined with grey infrastructure such as seawalls and dykes, for wave attenuation and flood control by natural ecosystems with the benefits of engineered structures.

In addition, conservation and restoration of natural coastal ecosystems can extend the lifespan of grey




infrastructure, while also supporting fisheries, regulating water quality, and sequestering carbon. The combined solution can therefore be more comprehensive, robust, and cost-effective than either solution alone.

## COMBINING MANGROVES & SEAWALLS

Vegetation in general, but especially trees such as mangroves, reduce incoming wave heights at the toe of a seawall, depending on water levels and wave characteristics. Mangroves also trap sediments in their roots, allowing bed level to rise in elevation with sea level if sediment supplies are sufficient. These traits make mangroves in front of seawalls an efficient technique to manage the effects of changing external conditions, such as increasing wave heights and sea level rise.

Sufficiently broad vegetated foreshores can considerably decrease wave height and consequently wave impact (Brinkman et al., 1997; McIvor et al., 2012, 2013), thereby reducing the required seawall crest height and material costs. The amount of wave reduction strongly depends on specific vegetation characteristics, such as vegetation height, density and stem diameter (Anderson et al., 2011).

Nature-based solutions and coastal zone management should start with master planning and an in-depth analysis of the natural system (Van Wesenbeeck et al., 2021a). The design of coastal green-grey infrastructure interventions should be informed by a thorough understanding of the natural system at all relevant scales. This infrastructure should be designed and managed as dynamic systems, in which for example, the width of the mangrove greenbelt may vary over time. The minimum width of the greenbelt should be such that the design criteria are met under extreme conditions.

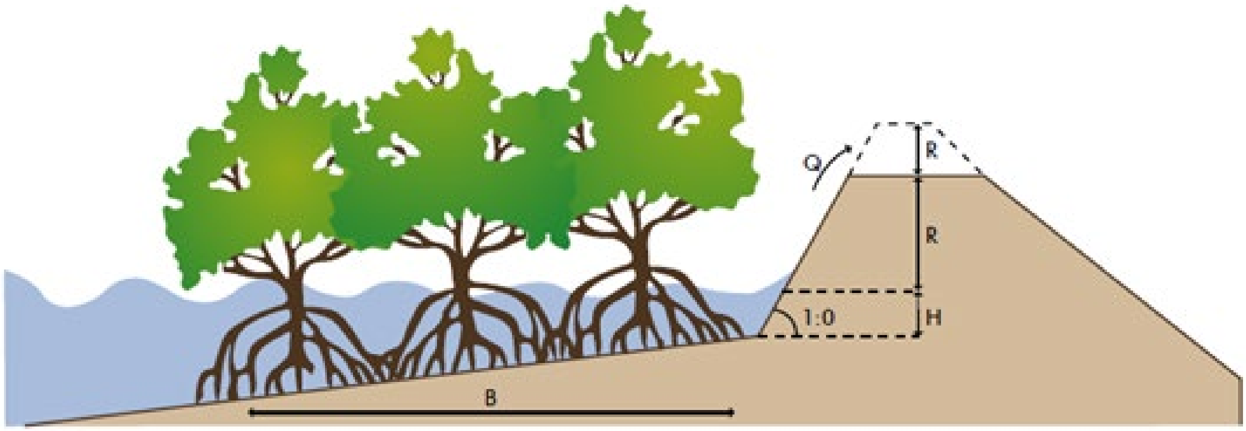



**Figure 1. Combination of mangroves with a seawall or levee and the parameters influenced by the presence of mangroves (World Bank, 2017)**

# SITE SELECTION

Setting priorities in the application of the Green-Grey Coastal Infrastructure concept is a political process, informed by physical aspects such as:

1. Urgency, determined by the status and integrity of existing coastal infrastructure and potential damage and casualties in case of failure (risk assessment), implying:
   - assessment of the status and integrity of the grey coastal infrastructure (the existing seawalls),
   - evaluation of the existing mangrove forest (status, health, type, extent, and availability of propagules),
2. Location and migration speed of mudbanks, and
3. Availability of fresh water sources.

All stakeholders are involved in site selection, discussing their possible involvement and the objectives/targets to be achieved.

Additional Site Selection guidance is available in Chapter 2 of the Practical Guide to Implementing Green-Grey Infrastructure.

# 2. SITE DATA COLLECTION

With a site selected, the project goals clearly defined and the design team assembled - the design development process begins, and includes:

Consulting master plans and ensuring the design team includes experts with local, regional, and national understanding of coastal dynamics. The mangrove-seawall design will require information acquired through master planning, site assessments, and an understanding of all components of the natural system.

## MASTER PLANNING

Implementation of Green-Grey Coastal Infrastructure along Guyana's shoreline requires long-term commitment from and planning by the national government and other authorities/ institutions. This can be achieved by making Green-Grey Coastal Infrastructure part of an Integrated Coastal Zone Management (ICZM) Master Plan. Such a Master Plan should embody a holistic and integrative approach to address complex social and ecological issues in the coastal area. It seeks to engage participation and cooperation of all stakeholders to realize the overall goal of having a sustainable and resilient Guyana coast by harmonizing sectorial objectives (environment, economic, social, cultural and recreational). Any Master Plan must start with explicitly formulating the objectives and sub-objectives to be met – these sub-objectives may differentiate along different coastal regions/districts.

Institutionalization and enforcement are key for effective implementation of ICZM. In the different phases of drafting an ICZM plan implementing local measures and monitoring and maintaining the coastal defenses both 'vertical' and 'horizontal' cooperation between different governmental authorities increase effectiveness. Vertical cooperation refers to aligning the strategy planning on national level of ministries with the local levels of the democratic councils in the coastal villages. Regional cooperation between the Guyanese government and neighboring countries is another example that can help in optimizing the ICZM plan and implementation through the exchange of knowledge on ecosystem behavior and effectiveness of coastal protection measures. Horizontal cooperation of the relevant agencies across different sectors should lead to coordination and integration of activities and avoid policy conflicts.

Stakeholders need to be engaged throughout the process of the ICZM planning and design of projects. Relevant stakeholders for Green-Grey Coastal Infrastructure projects can be identified with e.g. a power-interest matrix. In Guyana, local community beneficiaries of mangrove ecosystem services were identified to include fishermen communities, those employed in the tourism, sugar, or rice industries or in agriculture more generally, beekeepers, coastal ecotourism operators, indigenous communities, women, and communities that live along the coast. In addition to the benefits of coastal defense utilizing Green- Grey Coastal Infrastructure, these community beneficiaries will profit additionally from the restoration of mangrove habitat. Small-scale economic use of the mangrove fringes, such as (crab)fishing, honey production, etc. may be encouraged to stimulate local stakeholder involvement. Also, eco-tourism may add to rising awareness and some additional economic activities for the local communities. The Bio-Rights concept was developed and applied in Indonesia to involve local stakeholders in coastal management and eco-system services in return for short term (financial) incentives.

Nature's response to any measures within a Green-Grey Coastal Infrastructure approach follow the time scales of the natural system, dictated by the natural sediment fluxes and the migration velocity of the mudbanks, the latter measuring many decades. This implies patience and persistence.

Therefore, a Master Plan must cover a period of about one century and contain the following ingredients:

1. A plan to involve all stakeholders through the entire process from initial schemes to final implementation,
2. An outline on awareness raising, communication, collaboration, training and education,
3. An outline of the understanding of the natural system and the results of possible further studies,
4. Evaluation of the status of grey coastal infrastructure, and assessment of future design conditions and requirements,
5. An overall monitoring/survey plan to establish location and size of the mudbank complexes and their migration velocity; assessment of the intertidal mudflat extensions and development,

6. Assessment of priorities and site selection; establishment of type of interventions,
7. Explicit formulation of objectives and targets for each selected site.

A scheme to evaluate lessons-learned and update the Master Plan accordingly – it is recommended that interventions, successes, and failures are punctually recorded in a logbook available for future generations of coastal managers.

# DATA COLLECTION

For each site selected, data on the natural system must be collected and brought together and analysed to develop a good and complete understanding of the functioning of the natural system. Such system understanding and implementation of the lessons-learned is key to a successful application of the Green-Grey Coastal Infrastructure approach. Likely, site-specific data must be collected as well:

1. Inventory of stakeholders at all levels,
2. Inventory of regulations, required approvals, land ownership (if relevant), etc.,
3. Status and integrity of existing seawalls (the grey coastal infrastructure),
4. Status of mangrove fringes and their extension, mangrove biodiversity, if any,
5. Historic overview of local coastal developments (i.e. stable, erosive, accreting, landuse),
6. Location and migration characteristics of local mudbank, if any,
7. Bathymetry and local soil conditions with regard to the construction of coastal infrastructure,
8. Wave conditions (height, period, direction, frequency),
9. Water levels and tidal ranges,
10. Current velocities and suspended sediment concentrations for designing Coast-Perpendicular Groynes,
11. Fresh water sources and quantities,
12. Hisorical resource maps, and
13. Abundance of mangrove propagules – pathway of propagules by natural processes.

All data must be analysed and archived in a database. This database must be kept up to date with new data collected during monitoring and maintenance activities.

# EVALUATING INTEGRITY OF EXISTING STRUCTURES

Lees (2009) extensively described the sea defense structures and their status at the time. The condition of existing sea defense structure must be updated frequently as part of the green-grey coastal infrastructure approach. Here, a brief, largely qualitative overview is provided of the different types of sea defenses in Guyana and their historic application. This overview is not complete because of lack of accessible data.

According to the most recent estimates, sea defense structures along the Guyana coast, includes (Lees et al., 2009):

- 100 km of concrete seawalls
- 170 km of earthen embankments (of which 50 km are in critical condition with no mangrove left and in urgent need of rehabilitation);
- 130 km of natural mangrove fringes, said to be eroding rapidly.

In reality these individual types of sea defenses are often mixed, either by design (e.g. earthen slopes behind mangroves) or as a result of management.

The current state of the existing coastal flood risk management structures must be thoroughly inspected before implementing any new measures. The Shore Zone Management System (SZMS) is a GIS enterprise database system and was established in 2011 as a monitoring and strategic planning tool for the Sea and River Defense Division (SRDD). It contains survey data for approximately 244 km of coastal flood risk management structures for regions 2, 3, 4, 5 and 6 (Planet, 2016).

# EVALUATING SEDIMENT DYNAMICS

The key to applying the Green-Grey Coastal Infrastructure approach in Guyana is managing the large sediment fluxes in its coastal waters – the good news is that there is still abundant sediment. These fluxes are largely governed by the migration of large mudbanks, 10 – 40 km long, 10 – 20 km wide, 5 – 10 m high, and migrating at 0.5 – 3 km/year, possibly containing the equivalent of one year of Amazon River mud supply.

Approximately 220 – 260 Mton/yr of sediment is transported in the form of mudbanks and in suspension along the Guianas coastal system, of which about 5 – 6 Mton is deposited yearly. It is therefore concluded that in Guyana's coastal system abundant sediment is available for green-gray coastal infrastructure. Measurements and a subsequent extrapolation of the data showed that during the formation of the Chateau Margot mudflat about 3 – 7 Mm yr, or about 1 – 2 Mton/yr of fine sediment was deposited. As no data are available on the loads of sediment mobilized during the migration of a mudflat, estimates of these loads are made by analyzing the displaced volume of a migrating, idealistic mudflat with a rectangular planform and triangular cross section. This analysis suggest that sufficient sediment is being mobilized to form intertidal mudflats with mangrove habitat even in front of a dyke or seawall.

Behind a mudbank, mild wave conditions are stimulating the formation of intertidal mudflats providing habitat for mangroves, and coastal accretion is generally observed (Figure 3). In the interbank area, on the other hand, waves can approach the shoreline unaffected, inducing coastal erosion. This natural process of accretion and erosion is disturbed along major parts of the Guyana coastline by the erection of reflective seawalls, and mangrove fringes have largely disappeared over the last few decades (Figure 4).

Restoring these mangrove fringes therefore not only provides a green belt to protect the "grey" seawalls, but also can restart the natural process of accretion and erosion. Hence, the green-grey design goal is to develop a few kilometres wide mangrove green belt in front of a seawall, so that its width will not reduce below a few 100 m during an interbank period.

At some locations, the interbank phase is characterized by the presence of sandy deposits, called cheniers. This coarse sediment is very important for the morphological development and the protection of the coastal hinterland.

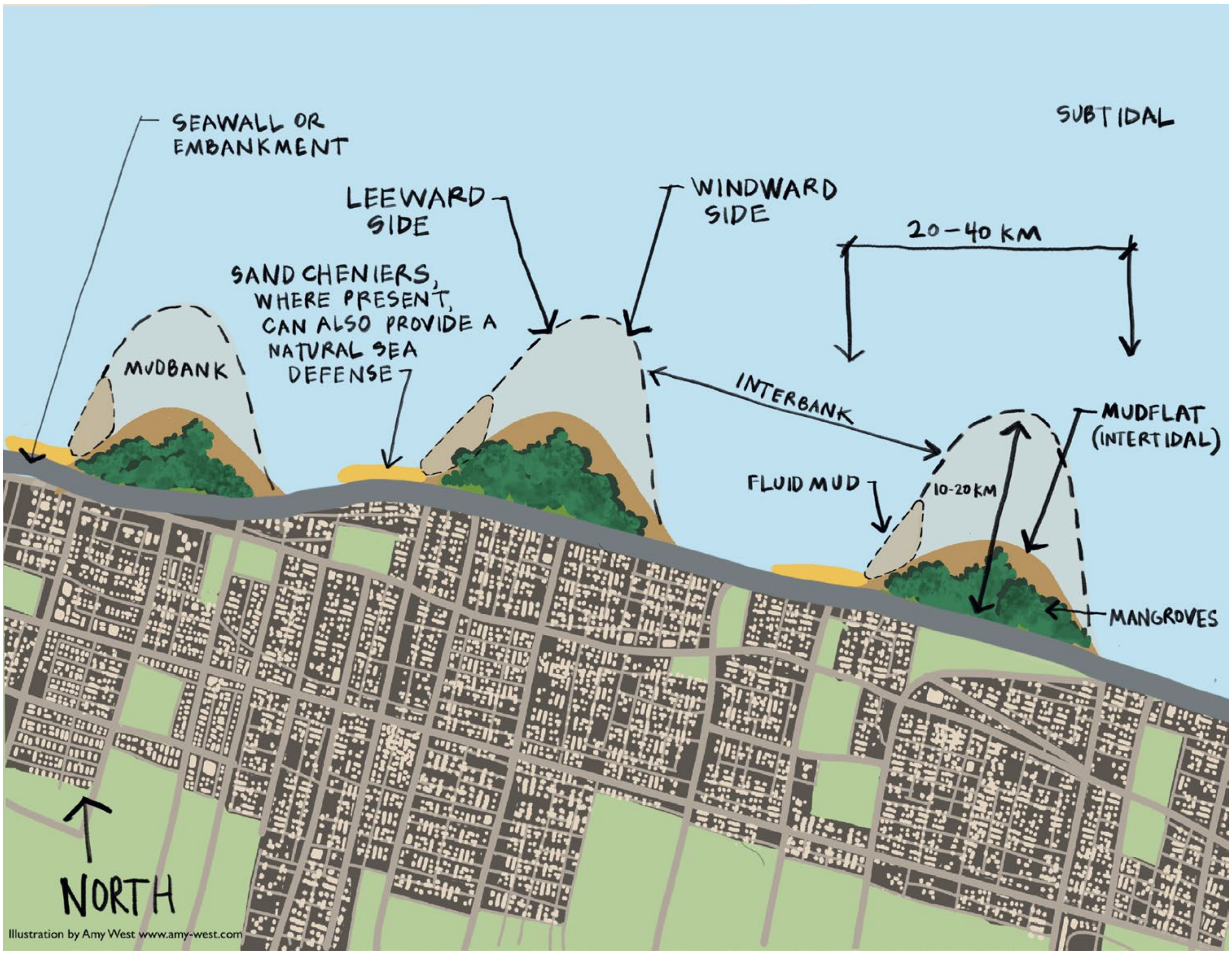



**Figure 2. Mudbank migration terms and vocabulary**

Figure 3. Natural mangrove colonization behind mudbanks

Figure 4: Disturbed mudflat formation along Guyana's coastline.

# EVALUATING MANGROVE AREA, TYPE & EXTENT

Prior to planning and construction of specific green-grey coastal infrastructure measures, existing mangrove forests should be inspected, including the extension of the mangrove fringes, biodiversity (species and zonation) and health, and availability of mangrove propagules.

It is important to monitor mangrove recruitment, especially whether new mangroves seedlings survive and grow and whether the mangrove greenbelt is expanding or retreating, in relation to the mudbank migration cycle (bank and interbank phases).

The influence of existing interventions on the mangrove health should be carefully monitored, in particular the development of mangrove habitat and colonization, to determine whether additional proactive mangrove management measures are necessary to speed up the natural colonization process.

# EVALUATING FRESHWATER RESOURCES

Though mangroves are salt-tolerant, seedlings need some freshwater to start their life. Often rainwater is sufficient – that is why in sub-tropical areas, mangrove propagule production synchronizes with the rainy season.

However, in Guyana, mudflat formation generally occurs during the drier periods of the year, when wave activity is fiercer. To overcome this phase shift, the abundant freshwater pumped into the coastal system from draining the hinterland can be used. Proper control of the direction of outflow of this drainage water can provide favorable conditions for mangrove colonization as soon as the habitat conditions (the mudflat) are adequate. Directing such outflow can be done through the design of the green infrastructure and guiding walls.


Seawall breach at Danzig, Mahaicony, with flooded rice fields in the background. © CI/John Greene

# 3. IDENTIFYING DESIGN THRESHOLDS

The first two steps of any conceptual design are:

1. Establish the design conditions, i.e. the required safety standard and the return period of anticipated water levels (including setup) and wave heights/periods based on extreme value analysis – these design conditions may differ per site, depending on a risk assessment. For instance, required safety standards for coastal infrastructure protecting a densely populated hinterland may differ from sparsely populated areas.
2. Setting goals for the intervention within a specified time frame – such goals are likely site-specific. This section summarizes the literature and field measurements along the Guyana coastline on the wave dampening capacity of mudflats and mangrove fringes. The aspect of wave dampening per meter width of the mangrove fringe is a critical variable by which restoration works will influence overall project design.

## GUYANA'S WAVE CLIMATE

The offshore wave climate in Guyana is mainly determined by swell originating from the Atlantic Ocean. Nearshore, the contribution of the wind-generated waves is insignificant compared to the swell component. However, behind mudbanks and in river mouths the wind generated waves are dominant. The intensity of the wave action is highest from December to February and lowest around August and September and synchronizes with the Trade Winds (NEDECO, 1972). The NEDECO (1972) report indicated that typical wave periods amount to about 8 seconds, yielding wave lengths in the order of 100 m.

From an analysis of wave data (see technical reference material for detail), it can be concluded that the:

- Average offshore significant wave height varies between 1.25 m in July/August to about 2.0 – 2.25 m in December/January;
- Historical maximum offshore significant wave height is 4 m and occurred in December 1998.
- Overall mean significant wave height varies by +/- 0.5 m during July/ August and increases to +/-1 m during the months of December to January.
- Average peak wave period varies between 6s – 10s with an average of 8s.
- Peak wave period is fairly constant during July to August; but during September to April the offshore peak period can increase up to 16 s. This increase was observed 3 – 5 times per year and may be attributed to tropical storms or hurricanes in the Atlantic Ocean or Caribbean Sea.
- Wave direction offshore varies between 45°N (northeast) and 75 °N (east-northeast). During the months of May to August the wave direction is fairly constant with a slow shift from 75°N to about 45 °N;

Further, significant wave heights gradually reduce from

- approximately 2.5 - 3 m at 60 km offshore to 1.25 - 1.5 m at 20 km offshore. This equates to a 50% reduction in wave heights as they travel onshore.

## MANGROVE-MUDFLAT WAVE DAMPENING MECHANISMS

As waves propagate from deep water towards Guyana's coast, they are transformed through the processes of refraction, shoaling, bottom friction and possibly wave breaking. Refraction refers to the turning of the waves towards shallower water due to the depth or current induced changes of the phase speed (Holthuijsen, 2010).

Without vegetation (mudbank/ mudflat only), when wind waves approach the shore, the change in depth causes them to shoal, i.e. increasing in height and maintaining their wave period while becoming steeper. When the steepness exceeds 0.78 – 0.88, they break onto the shore, dissipating energy. Waves become depth limited when the depth of the water is approximately half of their wavelength. As depth-limited waves approach the shore, they lose energy through bottom friction and possibly viscous dissipation within the soft mud on the bed.

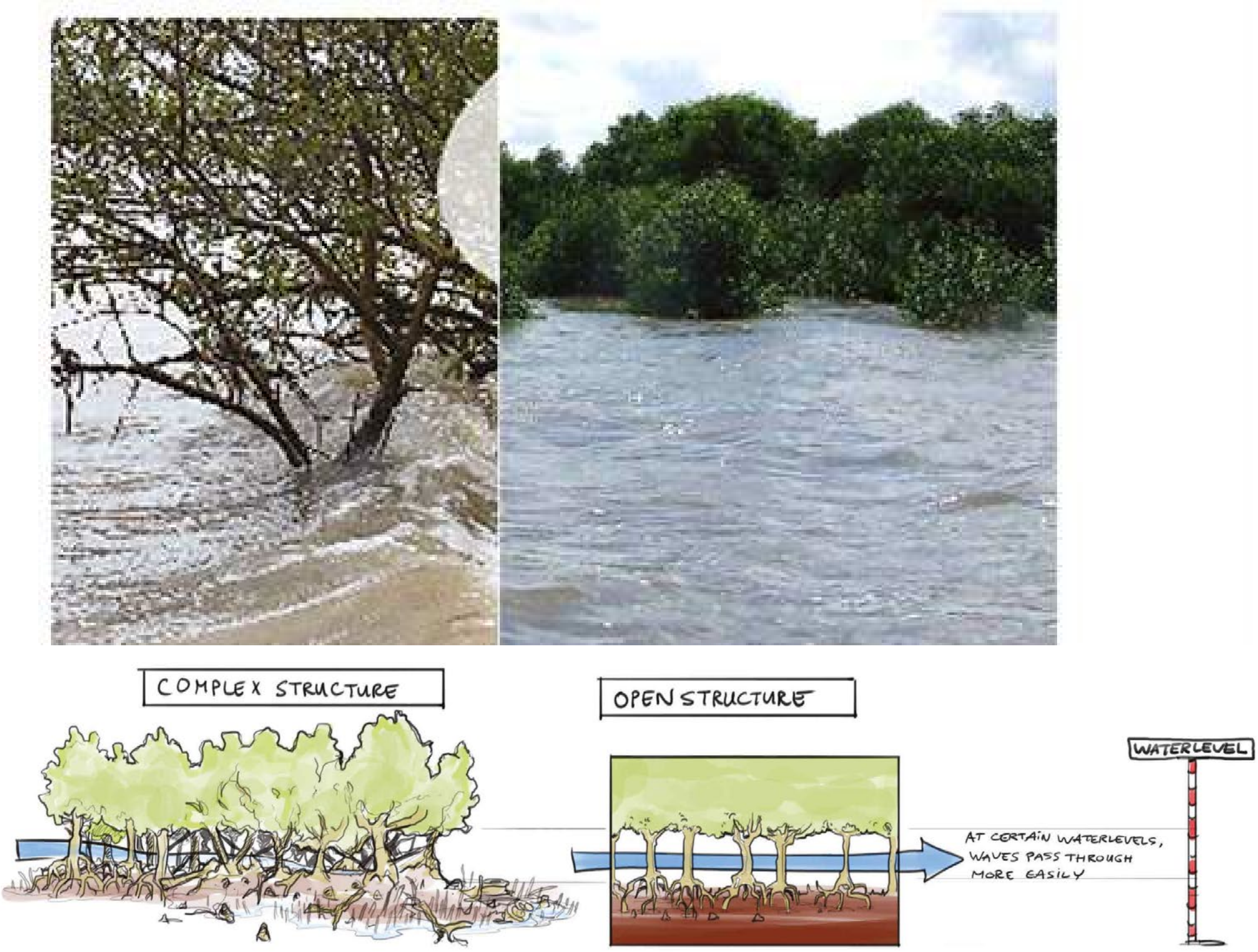



**Figure 5. Wave attenuation is attributed to the vertical variation in the mangrove dimensions and the complexity of the root network (Spalding et al., 2014).**

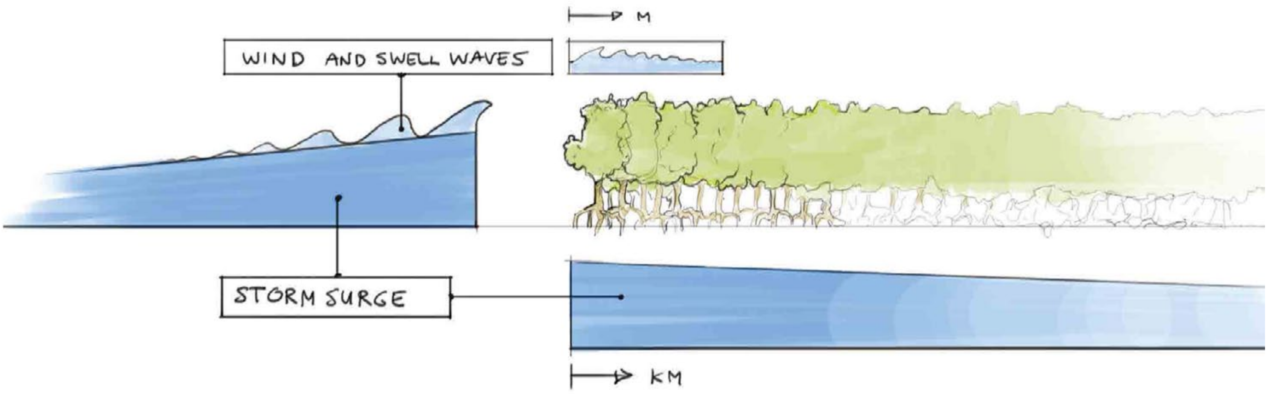



**Figure 6. The propagation of the wind and swell waves along the coastline, both in the presence of vegetation and without (Spalding et al., 2014).**

Mangroves have been shown to exhibit high attenuation rates over a short distance with variations across mangrove species and density, topographies and incident wave height. McIvor et al. (2012), observed that wave heights can be reduced by between 13 – 66% over 100 m of mangroves. While a reduction of 50 – 99% was reported across a 500 m width of mangrove forest (Dekker, 2006, Kit, 2016, Spalding, et al., 2015, Spalding, et al., 2014). The rate of wave height reduction in the direction of wave propagation is defined as the reduction in wave height (ΔH) as a proportion of the initial wave height (H,0) over a distance (Δx) travelled by the wave (see Equation 1).

Equation 1. The relation for the attenuation of wave energy

$$\alpha = -\frac{\Delta Hs,0}{Hs,0}\cdot\frac{1}{\Delta x}$$

Dalrymple et al. (1984) provides the following relation, explicitly specifying the damping rate as a function of mangrove characteristics:

Equation 2. Relation for the damping rates within mangrove fringes.

$$\frac{H_s(x)}{H_{s,0}} = \frac{1}{1+\alpha x}; \quad \alpha = F\left(H_{s,0}, T, h, C_D, D, N\right)$$

where the damping coefficient α is a function of the incoming wave height and period (H and T), the local water depth (h) ,0 and the thickness of the mangrove stems (D), their density (N) and a bulk drag coefficient (C). This explains why the damping rates decrease non-linearly within the mangrove fringe.

# WAVE ATTENUATION IN GUYANA

Numerous studies have measured the attenuation of wind and swell waves in mangroves with laboratory, field or numerical modelling approaches with respect to the vegetation types, the attenuation rates, the influencing factors as well as the approach taken with the respective references. (Kit, 2016)

These studies found a reduction in wave height as waves passed through mangroves to varying extents. The level of wave attenuation varied between 0.0014m[1] and 0.012m.[1] These attenuation rates suggest that across a 500 m wide mangrove forest, wave height would be reduced by 50 to 99%.

Table 1 summarizes the reduction in wave height across the width of a mangrove fringe based on the summary of measured and model studies covered by Table 1.

**Table 1. First-order estimates for wave dampening along the Guyana coast.**

| Type of Slope | Width of Mangrove Fringe (m) | Reduction in Wave Height (%) |
|---|---|---|
| Mild Slope | 100 m | 13-66% |
| Mild Slope | 500 m | 50-99% |

Available studies are not mutually comparable because other environmental parameters differed (e.g. incoming wave height, wave period, bottom slope (and thus shoaling effects), water depth). Nevertheless, they provide first-order estimates for wave damping along the Guyana coast.

**Figure 7. Pneumatophores which project from the bed substrate of the mangrove forest.**

# DESIGN BOUNDARY CONDITIONS & RETURN PERIODS

For the design of flood risk and sediment management measures, typically a safety standard is used in terms of a return period of certain water level and wave conditions. The return period is a statistical recurrence interval and is expressed as a number of years (e.g. conditions that occur once in 10 years). It states how often a certain condition (e.g. wave height of 2.0 m) is exceeded on average.

This is based on the probability of exceedance of that condition and is therefore a statistical parameter. Hence, the return period does not indicate when that condition occurs, nor its short time frequency (e.g. a once-in-a ten-year event may occur in two subsequent years).

The selection of the return period should match with the desired and feasible design lifetime. Within the design lifetime of a measure (structure or green-grey solution) the probability of exceedance of extreme conditions should be low enough to be acceptable.

Usually, the return period for the design of coastal protection measures is selected by the responsible authorities based on a desired safety and acceptable risk level, taking into account socio-economic aspects. For example, a measure can be designed for conditions that are exceeded typically once in 10 years (i.e. a return period of 10 years) or once in 100 years. The conditions for 100 years will be more severe than that of 10 years, and the associated costs to achieve that safety level will be higher accordingly. This use of return periods is a well-known method for conventional 'grey' measures. For 'green' measures, however, this is a rather new concept. Since green measures have a more dynamic character (e.g. mudflat, mangrove) than that of a grey measure (e.g. seawall, levee), the associated lifetime can be much shorter (e.g., 5 years in a dynamic coastline) or considerably longer (e.g., 100 years for a stable mangrove forest).

For the design of conventional coastal protection structures at the Guyana coastline a return period of 30 years has been used (pers. comm. Roberto Narine). A method to derive the design wave height based on extreme value statistics is outlined in the technical references, where an offshore significant wave height of 2.8 m was determined as the design condition with a return period of 30 years for a specific site near New Amsterdam in district 8 based on the long-term statistics of the period 1979-2017.

This governing design wave height with a 30-year return interval of 2.8 m is proposed as input for design computations of conventional coastal protection structures (e.g. wave overtopping and structural stability) and can also be used for the design of green-grey infrastructure elements at this particular site. Using the same method, the governing wave height can be determined for the design of green-grey infrastructure elements along other parts of the coastline.

# 4. DESIGN CONCEPT DEVELOPMENT

Together with the system understanding and data collected, a conceptual design for each site is made. This conceptual design is communicated with all stakeholders for comments and feed-back, and where necessary modified to ascertain stakeholder participation. Possibly, some iterations are required. Thus, the conceptual design plan contains the following elements for each site:

- Summary and analysis of relevant data,
- Targets and objective of the interventions in consideration of sea level rise projections,
- Overview of stakeholder and managing authority involvement and participation,
- Overview of necessary permits, approvals, etc.
- Design conditions, i.e. return period and relevant water levels, setup and wave height and period,
- Choice of green-grey coastal infrastructure elements, their locations, orientation, quantity/length, and timing and sequence of construction,
- A mangrove management plan, necessity of planting, sowing and/or anchoring propagules, and freshwater management,
- A preliminary debris management plan,
- A preliminary monitoring and maintenance plan,
- A first cost estimate.

## GREEN-GREY COASTAL INFRASTRUCTURE ELEMENTS

The ultimate objective of the green-grey coastal infrastructure approach is to restore mangrove habitat, for example, in intertidal mudflats as much as possible and as fast as possible. We have identified six infrastructure interventions to achieve this objective:

1. Permeable bamboo fences to dissipate wave energy, operational for a few years (Figure 8),
2. Permeable concrete groynes to dissipate wave energy during an interbank period (Figure 9),
3. Coast-perpendicular groynes to trap alongshore sediment fluxes (Figure 10), and
4. Temporary realignment to accelerate mangrove habitat (Figure 11).
5. These elements can be combined to make:
6. Sediment Trapping Units, i.e. rectangular calm water basins where sediment can settle, constructed from permeable bamboo fences – these are erected on intertidal mudflats (Figure 12),
7. MudBank Motor concept to accelerate natural mudflat formation behind mudbanks and protect existing mangrove fringes during interbank periods – this concept consists of placing Sediment Trapping Units and permeable fences at strategic locations behind a migrating mudbank – timing of application is critical (Figure 13).

The MudBank Motor concept must be synchronized with the migration of the mudbanks. Relevant spatial and temporal scales of such interventions and their management therefore amount to tens of kilometres and decades. The temporary realignment concept is best applied in front of an approaching mudbank. From a physical point of view, all other elements can be applied at any time and any place.

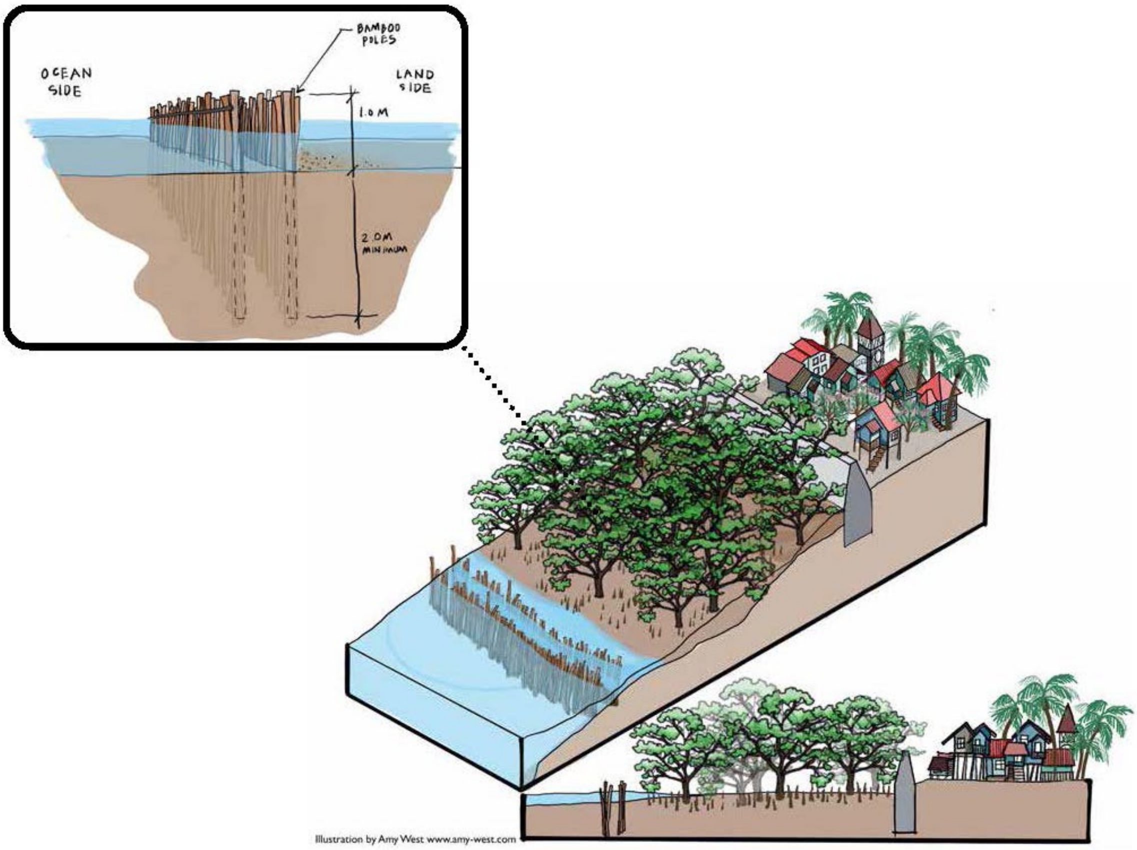



Figure 8. Permeable bamboo fences to dissipate wave energy

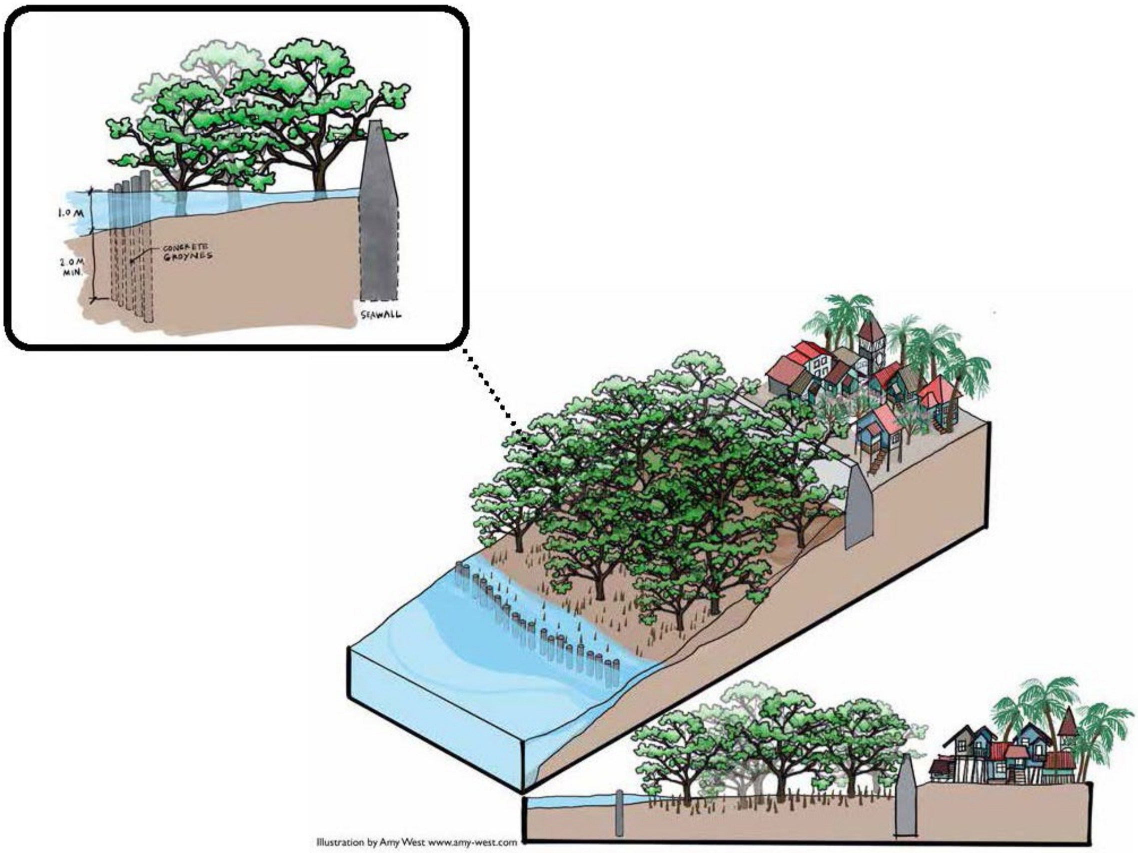



Figure 9. Permeable concrete groynes

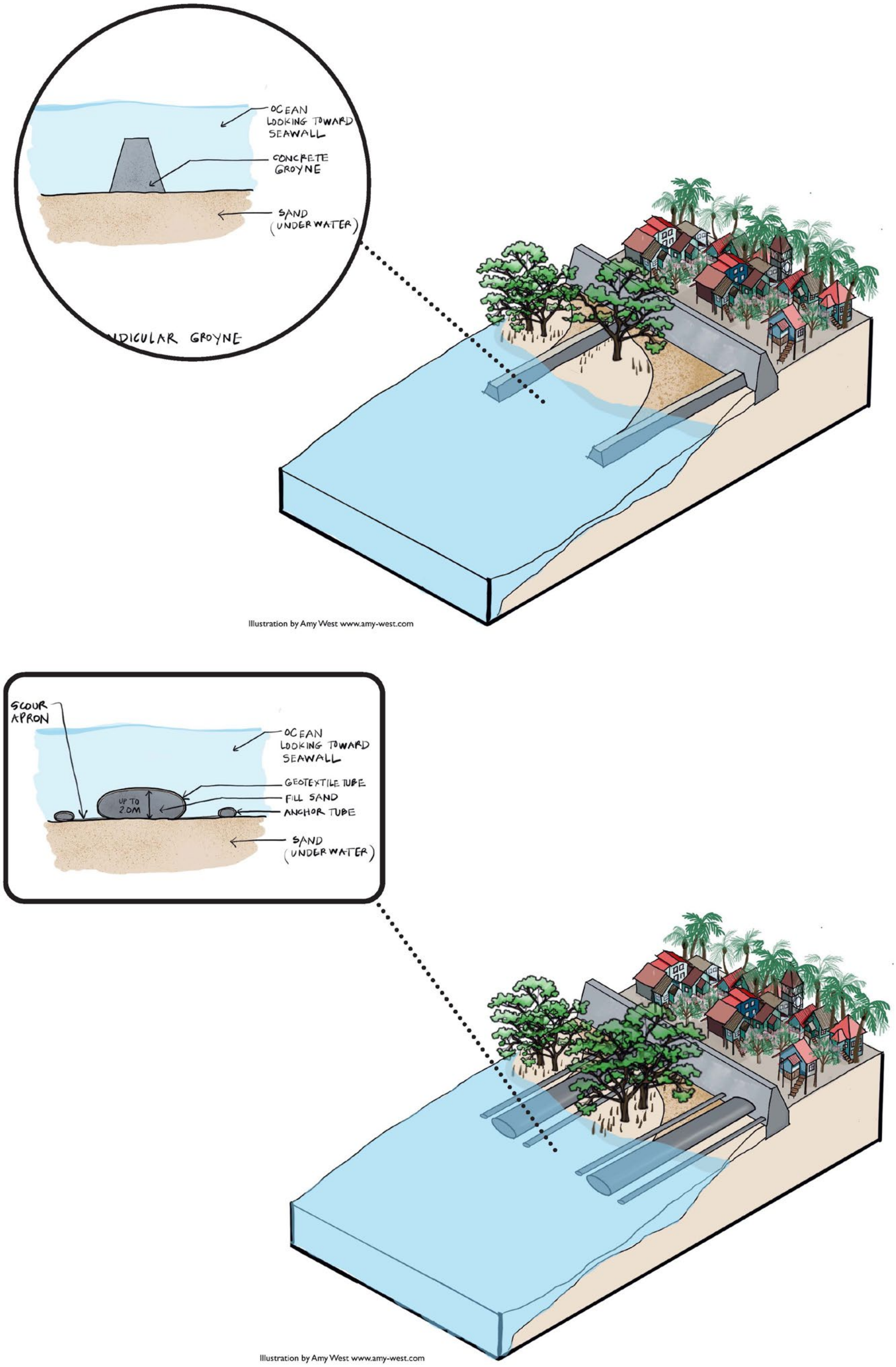



**Figure 10. Coast-perpendicular Groyne**

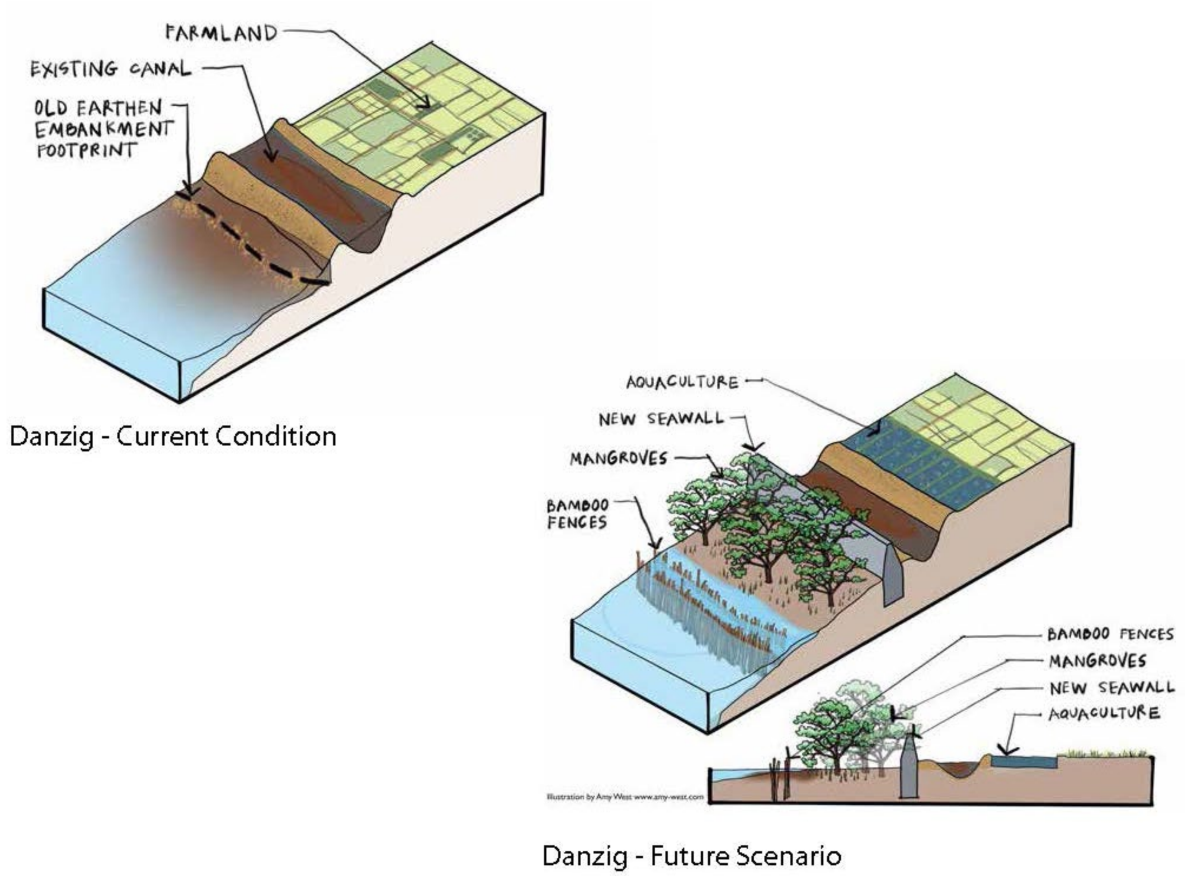



**Figure 11. Schematic of temporary realignment in De Kinderen inundated polder.**

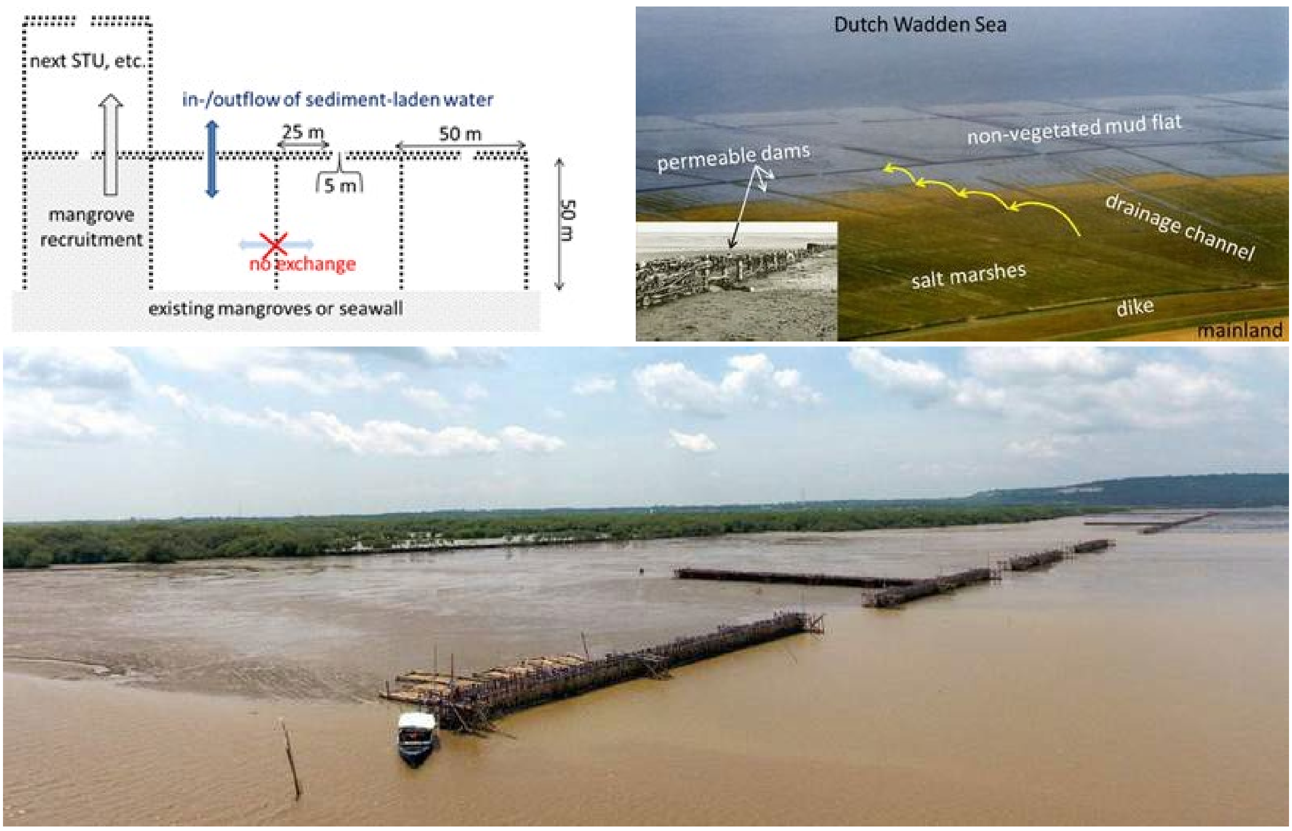



**Figure 12. MudBank Motor concept to accelerate natural mudflat formation behind mudbanks and protect existing mangrove fringes**

**Existing Condition**

**Phase 1**

**Phase 2**

**Figure 13. Schematic of deployment of MudBank Motor concept along Chateau Margot mudbank consisting of Sediment Trapping Units on the intertidal mudflats behind the mudbank and protecting permeable bamboo fences along the tail of the mudbank**

# DESIGN OF CONVENTIONAL COASTAL FLOOD RISK MANAGEMENT STRUCTURES

Flood risk reduction encompasses any measures taken to reduce flooding during extreme water levels. Examples are seawalls, levees, revetments and embankments. These types of structures firstly have a blocking function to prevent direct flooding. Moreover, these structures need to be structurally stable and limit wave overtopping to a maximum tolerable overtopping discharge for structural stability.

Several well-known and commonly used manuals exist for the design of conventional coastal flood risk management structures, such as the US Army Corps of Engineering Shore Protection Manual (ENGINEERS-USACE, 1984), the Rock Manual (CIRIA, 2007) and the EurOtop Overtopping 2007).

Manual (The EurOtop Team, 2007). The existing Coastal Engineering Design Manual for Guyana Sea and River Defenses (Planet, 2016) combines information from these different manuals applicable to Guyana and can thus be used for the engineering design of the seawall, based on wave run- up, wave overtopping and wave reflection (see section 7.4 of Planet (2016)).

Figure 14 provides an overview of the terminology that is used in design of hydraulic structures and schematics of governing processes. The most important design parameter is the crest height of the seawall, which can be determined using the design guidelines based on the tolerable overtopping discharge and on the wave height at the toe of the structure (after transmission through a mangrove greenbelt) during extreme events. Information in this section is largely based on the Rock Manual (CIRIA, 2007).

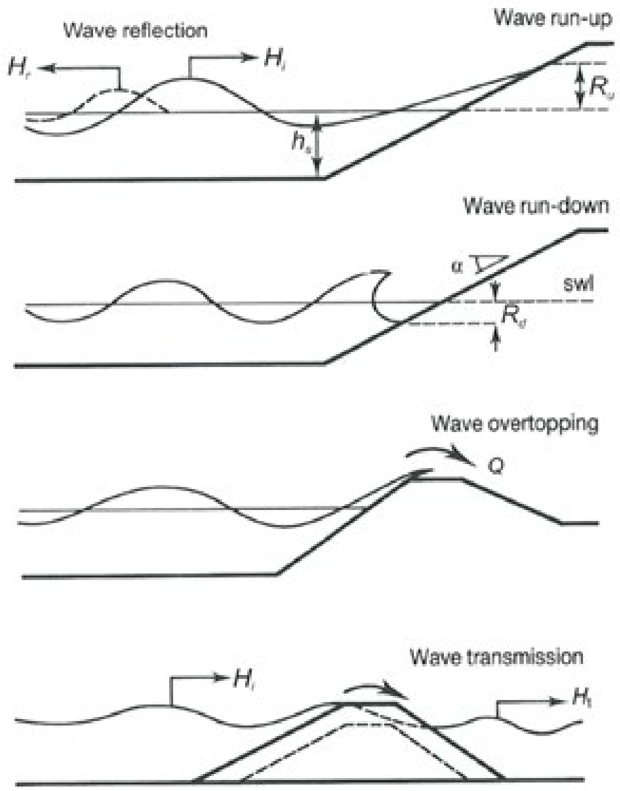



**Figure 14. Hydraulic interactions related to waves and parameters definitions (copied from the Rock Manual (CIRIA, 2007)**

# MANGROVE RESTORATION IN GUYANA

Ecological Mangrove Restoration methods for mangrove restoration and conservation by Lewis (2005), elaborated for the coastal zone of Guyana, include the following.

1. The hydrology of existing mangrove forests should not be disrupted. Currently this does not seem to be a major issue in Guyana, but hydrological aspects should be considered when designing new coastal infrastructure, such as managing drainage water to synchronize with mudflat formation.
2. Before planting, the limiting factors for natural mangrove recruitment should be investigated and manmade causes that limit natural mangrove recruitment modified . A natural factor that may limit natural mangrove recruitment is formed by the migrating mudbanks. During interbank phases, the coastline is more exposed to wave impact, resulting in mangrove mortality and erosion of the mudflat. Moreover, choosing the right location (bed elevation) is very important, as mangroves habitat is typically located at elevations between mean sea level (MSL) and highest astronomical tide (HAT),
3. Correcting the conditions that prevent natural colonization depends on the specific local causes . Important measures include sustainable land use (i.e. assigning designated areas for mangrove restoration), providing favorable hydrological conditions and restoring the sediment balance. If conditions are not able to be corrected to favor mangrove habitats, it may be necessary to select a different site with the right hydrological conditions or bed level elevations.
4. A reference system where natural mangrove recruitment occurs should be selected in the same coastal area. Do not copy solutions from locations across the world, but instead learn from natural success stories in the same coastal system. Investigate the hydrology, topography of the bed, local wave conditions and the sediment balance at the reference site. Monitor and understand the conditions that are favorable for mangrove colonization in your coastal system.
5. Establish a range of favorable conditions at your restoration site for the hydrology, topography of the bed, wave conditions and sediment balance.
6. Possible intervention methods to ameliorate abiotic conditions can consist of creek digging to facilitate flooding, drainage and freshwater supply, sediment nourishment to increase bed levels and stimulate mangrove recruitment, and erecting wave dissipating structures.
7. Learn from previous mangrove restoration projects to evaluate costs of restoration early in project design to make the project as cost-effective as possible.

On top of these principles to enable natural mangrove colonization, some additional measures are suggested specifically for the local conditions in Guyana:

- Protecting mangrove trees from breaking and uprooting by use of cages made from biodegradable materials.
- Protecting mangrove propagules from dislodgement by binding them to small wooden sticks, applying reefballs or using biodegradable fascine mattresses or coconut fiber mattresses.
- Steering the freshwater outflow from the hinterland that is now discharged by sluices towards the mangrove habitat.

# RECOMMENDATIONS FOR GUYANA'S DISTRICTS

The management of the Guyana coastal system is organized through regions and districts, where borders between the districts are defined by rivers: Each district in Guyana may be best suited for a particular type or combination of the recommended green-grey coastal infrastructure strategies, as suggested below and identified in Figure 15.

District 1: In the western part of District 1, a narrow mangrove fringe has developed over the last 30 years, today up to more than 2 km wide. It is recommended not to intervene, though to monitor the development and status of these fringes and of the mudflat in front. If the mangrove fringe begins retreating, the mangrove-mud coast can be stabilized with sediment trapping units (STUs).

The eastern part of District 1 is largely affected by the outflow of the Essequibo River, and coast perpendicular groynes (CPGs) can be deployed, as has been demonstrated in the vicinity of Anna Regina. We recommend erecting more groynes along this part of the coastline, monitoring their efficiency and maintaining them over time. The design of these groynes may be supported/optimized by numerical modelling of the local coastal processes.

District 2 & 3: The available Google Earth images reveal narrow mangrove fringes along the northern coasts of these islands, with a considerable canopy at the eastern tip of district 2 (up to 2 km wide). Mudbank dynamics are likely too far offshore to affect these coastlines. However, suspended particulate matter concentrations in the river mouth are large, and STUs are therefore recommended along almost the entire coastline, building out into the ocean over time.

District 4: The western coast (up to Tuschen) is still under the influence of the Essequibo outflow, and CPGs are likely to be effective, as around Anna Regina, District 1. Similarly, the eastern part (up to Windsor Forest) is affected by outflow of the Demerara River, and also here CPGs are likely to be effective – note that at the beginning of the 21st century, a few 100 m wide mangrove fringes were found along this part of the coast, but now eroded. Further studies are required to make a solid recommendation for interventions along the remainder of the coastline of District 3. For instance, it is not known whether passing mudbanks can induce mudflats along this part of the coast, as these may be too far offshore. If not, STUs may be effective. A pilot project at this location is recommended.

District 5: The very eastern part of the District 5 coastline is affected by the small Mahaica River (not only its outflow, but also its tidal volume), and deployment of CPGs is likely effective. This is also a location where the efficiency of permeable fences may be tested. To the west, in front of Kingston district (Georgetown), the seawall is protected by a 40 – 100 m wide, 1 km long beach, stabilized by four concrete CPGs. We recommend lengthening these groynes, trapping as much of the littoral sand (chenier) transport as possible. It is likely that sand passing Fort Groyne is not deposited along district 4 coastline, thus lost for coastal protection.

The remainder of the coastline is affected by the interplay of the embanked coastline and the migration of mudbanks. Hence the MudBank Motor strategy is required – this strategy is further elaborated below. As these CPGs are small in comparison to the mudbank complex dimensions, these CPGs and MudBank Motors can be deployed jointly.

District 6: The mangrove-mud coastline around the mouth of the Mahaicony River (near Mahaicony village) seems stable since the first satellite images became available, hence no interventions are recommended. A bit further to the west, near De Kinderen, the seawall was breached, likely in response to sand depletion induced by an approaching mudbank, and a polder area of more than 1 km$^2$ is still inundated. This could be a pilot location to test the mangrove accommodation space concept with mangrove catalyst function to initiate further mangrove developments. Along the mouth (left banks) of the Mahaicony and Berbice Rivers, CPGs are likely efficient and are recommended. These CPGs do not have to intervene with an MudBank Motor-strategy along the remainder of the coastline.

District 7 & 8: The east part of District 8 is affected by the Corentyne River, with fringes of mangroves a few 100 meters wide. For the time being no interventions are recommended, but monitoring is mandatory. In case of coastal losses, deployment of CPGs is recommended. Elsewhere along District 7 & 8 coastline the MudBank Motor-strategy is recommended.

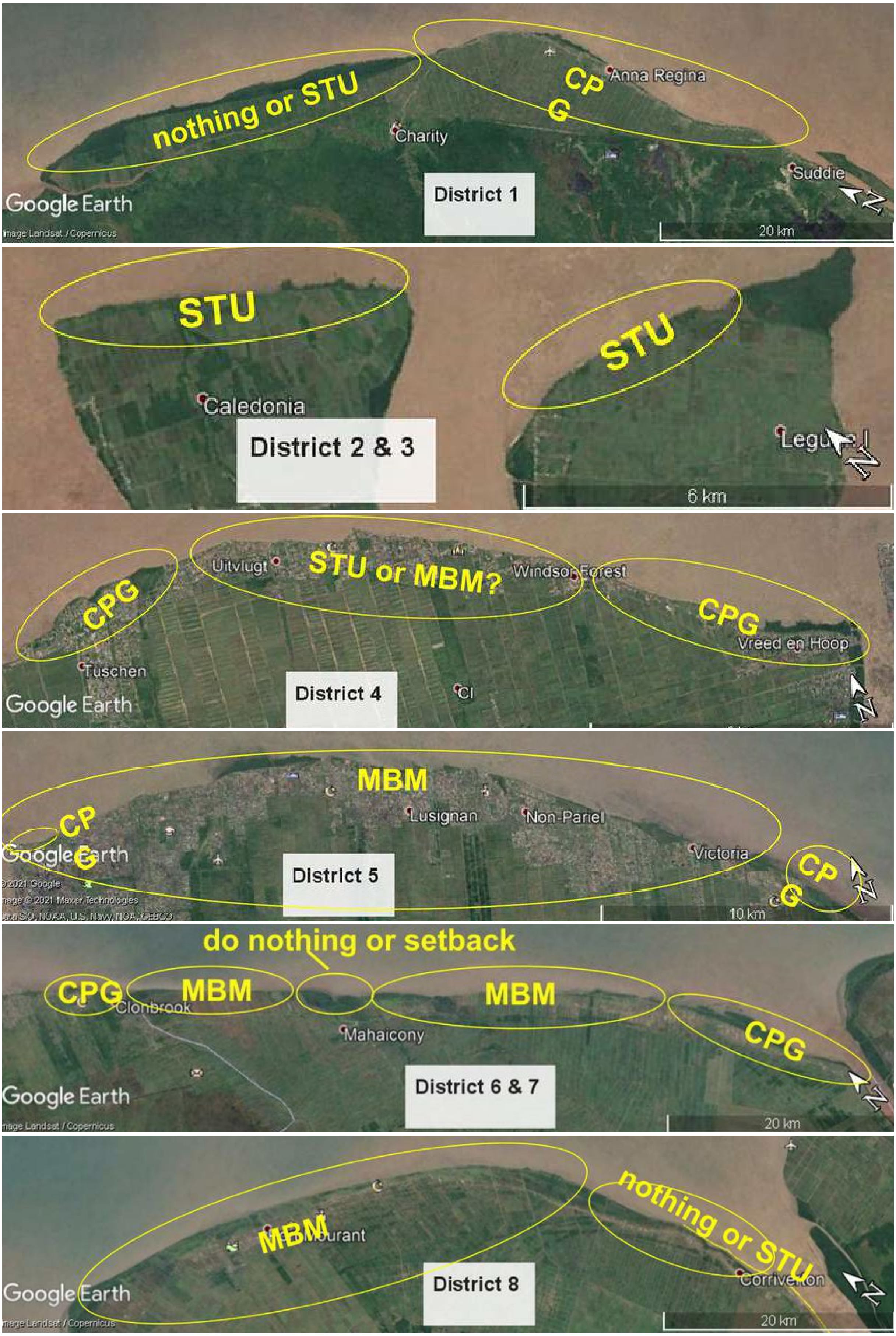



Figure 15. Spatial overview of potential green-grey strategies for each of Guyana's Sea Defense Districts

Coastal protection efforts in Danzig, Mahaicony, while the mudbank advances from the east. © CI/Emily Corwin

# 5. PROJECT COSTS

This chapter provides an overview of the average costs per meter for the green and grey measures implemented along the coast of Guyana. These figures reflect a summation of the costs period from 2013 to 2020, and as such inflation of material prices should be considered for future applications. Further, the costs provided do not include for expenditures such as personnel, transportation, geotechnical and topographic surveys and other secondary inputs.

## COST ESTIMATES

A first cost estimate should include construction costs, personnel, transportation, surveying (geotechnical and topography). Construction costs can be based on a unit cost price (per km / per ha or % of capital cost) and estimated dimensions. NAREI summarized unit cost prices of implemented restoration measures for the following cost categories:

- Mangrove Restoration
- Sediment trapping units
- Structural components (e.g. concrete seawalls, rip rap armored structures, geotube groynes, rubble mound groynes)
- Monitoring
- Maintenance
- Adaptive Management

Indicative construction costs of sediment trapping units or bamboo/brushwood dams amount to 17,000-31,500 USD/100m and mangrove restoration sites cost 4,000-43,000 USD/ha, which is an order of magnitude cheaper than the construction of concrete seawalls (500,000- 600,000 USD/100m). While construction costs are typically low, it is stressed that maintenance costs can become considerable – yet maintenance is crucial for long term success.

Note that the costs of more robust grey see defenses to anticipate sea level rise are disproportionately higher, as the soft soil then demands expensive foundation of the structures. Grey infrastructure may become non-linearly higher with climate change in Guyana as the poor subsoil conditions will need improvements and/or solid foundations to carry larger and heavier seawalls.

By implementing green-grey measures, the design requirements of the seawalls and rip rap armored structures can be reduced. This saves costs for construction and maintenance of these structures. Hence, costs of the green-grey measures can be paid from reduced costs of the seawalls.

# 6. PROJECT APPROVALS

Permits or approvals are given by agencies overseeing the region where a project is located or agencies that regulate the type of proposed project. Typically, the project proponent, or applicant, completes and submits a permit application to the permit approving agency for review and approval.

## PROJECT APPROVALS

Each permit or approval application typically requires a unique set of information, and the amount of time to review and approve the application can vary depending upon the agency, project type, time of year, and quality of information submitted with the application.

In the early stages of a project, the design team, usually the project manager, should consult with local and national jurisdictions to identify the project permits and approvals required before construction can begin. Other approvals that may be needed prior to construction include:

- community organization (formal or informal) and/or land owner approvals;
- construction approvals internal to the implementing organization;
- endorsements from technical advisors;
- financier/investor approvals;
- local municipality and relevant government officials; and
- funder approvals, for example, if contracting with the local community to complete the construction, is outside the normal acquisition policy of the funder.

For some projects, a community-based environmental assessment can facilitate or complement a legally required review of the environmental aspects of a project. Community-based environmental assessments often occur outside of legal frameworks and use participatory methods such as interactive workshops, focus group discussions, community resource mapping, and/or site walks to understand and document environmental challenges and impacts. The outcome of the assessment can inform design development–specifically, selection between alternatives or modifying proposed designs to reduce and/or avoid potential impacts. Possible risks for ecosystems and the community should be monitored proactively throughout the project

# 7. MATERIAL & CONSTRUCTION SPECIFICATIONS

This section contains the lessons-learned on constructing permeable dams in Demak, Indonesia, partly based on the experience gained in Vietnam by GIZ (Von Lieberman, 2012). It is based on the more comprehensive "Technical Guidelines Permeable Structures" (Wilms et al., 2018) developed on the basis of the Building with Nature works in Indonesia. The dams in Indonesia and Vietnam consist of the classical brushwood dams, i.e. horizontally placed brushwood, which mainly damp the waves, and vertical poles to hold the brushwood. However, the issues addressed are directly applicable to the fences proposed for Guyana. The permeable dams need to stay in place long enough for mangroves to take over, which period is determined by the sediment accretion rate (in Guyana estimated at 1 – 3 years) and rate of mangrove recovery (in Guyana estimated at 2 – 4 years). Experience in Guyana suggests lifetime of the bamboo of 3 – 7 years.

## CONSTRUCTION OF PERMEABLE FENCES & GROYNES

We strongly recommend using fences made of vertical (bamboo) poles instead of the classical brushwood dams (where vegetation is placed between two rows or layers of bamboo fences):

1. Fences from vertical poles can be as efficient as brushwood dams with respect to wave damping,
2. The proper placement of brushwood in between supporting vertical poles is difficult, labor-intensive and expensive,
3. Brushwood is lost easily, and its application requires much maintenance,
4. When loose, flow creeps under the brushwood, inducing local scour, further loosening the brushwood bundles.

The fences are constructed of bamboo poles, with diameter of 0.12 – 0.15 m. They are placed on the intertidal, thus totally emerging at least part of the time during low water. The top of the fence is above MHW – some overtopping is no problem.

The fences applied in STU's are mechanically stabilized with a horizontal bar, in particular the frontal fences that are subject to wave loading (wave loading on the "side walls" of the STU's is small).

When deployed as permeable groyne during interbank periods, wave loading can be large and additional mechanical support is recommended as applied in Demak, Indonesia. Note that bars and poles must be connected by wire, nailing damages the bamboo, reducing their lifetime considerably. The use of long wires is convenient, but these are valuable and were frequently stolen in Demak. Therefore, short, less valuable ropes are used, which however imply more construction work, thus higher costs. On the other hand, shorter ropes are easier to re-tighten, thereby lowering maintenance costs.

The bamboo poles are hammered into the soft soil to a depth of about 2m. Experience in Vietnam and Indonesia have proven that a hammer team of about 10 persons can do this efficiently, taking about 10 – 15 minutes per pole. Use of sledgehammers, etc. is not practical and not safe to operate in these shallow waters and may damage the bamboo.

To build ownership, it is recommended to involve local stakeholders in the construction and maintenance of the fences, supervised by experienced staff from the ministries and/or contractors. In Indonesia this was organized through the so-called Bio Rights program, providing funds for local communities in return for construction and maintenance works (van Eijk and Kumar, 2009). This would lead to a construction cycle, as deployed in Indonesia:

1. Based on the Master Plan and Spatial Planning, a spatial design and time schedules are made for the work to be carried out in the next construction cycle.
2. Ongoing stakeholder engagement to explain progress and plans for the rest of the year.
3. Discussions of the plans with local communities to guarantee stakeholder participation. Past experience with previous structures (if any) and physical or social constraints at the proposed locations should be incorporated. Site inspection is a necessity for a detailed design, obtaining up-to- date data on depth, physical obstacles, etc. Markers for the actual construction are set to facilitate the execution of the work.
4. Permits may need to be obtained for construction in the coastal zone – compliance and application of these permits should continuously be checked during the execution of the work.
5. Tender for supervision: prepare documents and allocate budget. When possible, involve the supervisor in the tender for construction.
6. Tender for construction: prepare documents, drawings and allocate budget, also for maintenance. When ordering materials, provisions should be made for losses due to sub- standard quality.
7. Training for construction, maintenance, and monitoring.
8. Construction and supervision accounting for delays and unworkable weather.
9. Monitoring and maintenance start during the construction work and continues.

Bamboo fences and sediment trapping units are made with bamboo, a light bio-degradable material. This can be handled manually by a trained team. Bamboo poles are hammered into the soil by a hammering team to about 2 m depth. Their top is at about mean sea level.

For the placement of permeable groynes and coast-perpendicular groynes, heavy, mechanical equipment is required, and the work must be done by experienced contractors, following common coastal engineering guidelines and safety regulations.

# 8. MONITORING, MAINTENANCE & ADAPTIVE MANAGEMENT

Green-grey infrastructure works in and with living ecosystems, which are adaptive and resilient to external pressures, evolving and performing more strongly with time. Conversely, maintenance requirements for grey only solutions often become more demanding and cumbersome over time, until they reach their 'design life', at which point they are obsolete. Monitoring, maintenance, and adaptive management of both living ecosystems and grey infrastructure are integral to ensure project function and longevity.

- Monitoring should be designed to directly measure and evaluate the project's intended and unintended outcomes;
- Maintenance is critical to the longevity and effective function of a project; and
- Adaptive management iteratively improves the ability of a project to achieve its goals.

This section introduces a multi-step feedback process linking project monitoring and evaluation frameworks, maintenance strategies, and adaptive management.

## WHY IS IT IMPORTANT TO MONITOR GREEN-GREY INFRASTRUCTURE PROJECT OUTCOMES?

Project monitoring is critical to document and understand the strengths and weaknesses of each project, and to inform future green-grey project design and implementation. Monitoring supports essential components of any project: understanding the strengths and weaknesses of project measures, avoiding maladaptation, and ensuring that project outcomes are attained.

With increased uptake of green-grey infrastructure projects globally, understanding the outcomes of interventions, as well as documenting and learning from good practices is more important than ever. Effective monitoring to document the effectiveness of interventions builds the evidence base for green-grey infrastructure, which can catalyze further political and financial investment in green-grey infrastructure and support its broader adoption globally.

Monitoring data will inform (1) recommended design modifications for similar techniques proposed at other sites; and (2) any necessary adjustments at the project site to achieve long-term project outcomes. These are aligned with testing under a designed experiments model as well as optimizing best practices in design guidelines and further implementation at scale.

Compared to conventional grey infrastructure, green-grey infrastructure projects can support a host of co-benefits. For example, design benefits for incorporating natural features include an ecosystem's ability, under the right conditions, to adapt to changing conditions (e.g., such as sea level rise) and rebound after an extreme event. That same ability to adapt and recover introduces uncertainty into the project outcome, when compared to a conventional grey infrastructure project, because ecosystems respond to external pressures and can evolve with time. Employing an adaptive management strategy, with a defined approach to modify the project upon encountering unintended outcomes, is one mechanism to manage this uncertainty.

Four steps for designing and implementing an adaptive management strategy for a green-grey project, which should be considered at the design development stage, are to:

**Step 1:** Develop a monitoring and evaluation framework;
**Step 2:** Define indicators, baselines, and targets;
**Step 3:** Operationalize the monitoring and evaluation framework in a maintenance plan; and
**Step 4:** Use and communicate the results in an iterative process.

See the Guidebook for Monitoring and Evaluating Ecosystem-based Adaptation Interventions[1] for detailed guidance on each of these four steps.

## HOW TO CREATE A MONITORING AND EVALUATION FRAMEWORK?

Monitoring should be designed to directly measure and evaluate the project's intended and unintended outcomes. The project monitoring and evaluation framework is based on the desired project results and should measure the outcomes of the green-grey infrastructure projects. Monitoring and evaluation is often required for climate adaptation projects that require an initial vulnerability assessment and then monitoring, to demonstrate improved resilience.

When designing a project monitoring and evaluation framework:

- Identify objectives and define indicators;
- Collect baseline data that describes conditions prior to project implementation;
- Involve local communities and stakeholders in monitoring to achieve buy-in and enhance local capacity;
- Develop a plan and budget for how the monitoring and evaluation framework will be implemented, potentially well past the time the project ends. Consider:
- How will the information be collected?
- Who will collect the information?
- When will the information be collected and at what time interval?
- Where will the information be collected?
- Create a plan for how monitoring data will be analyzed and how the results will be used to inform adaptive management.
- Who will analyze the information? How and when?
- Will the results be published? How will they be made accessible and communicated to stakeholders (and the wider public, if applicable)?
- How can the results and lessons learned be shared with the wider green-grey community?
- If monitoring reveals an unintended consequence or outcomes that fall short of intermediate goals, the project design team should reconvene to visit the site, evaluate the impact and recommend modifications to the green and/or grey infrastructure elements.

## WHAT INDICATORS CAN BE USED TO EVALUATE GREEN-GREY PROJECT OUTCOMES?

The indicators or criteria selected to evaluate green-grey infrastructure interventions will depend upon the intended results of the project. The project's performance, or ability to deliver these results, should be tracked closely in a project monitoring and evaluation framework and a project maintenance plan.

Of the several benefits accruing to a green-grey project, the following categories are possible to evaluate green-grey project outcomes. This will likely be in addition or complementary to measuring physical performance measures to inform engineering and design decisions, such as material strength, longevity, and integrity.

Climate adaptation and disaster risk reduction benefits – The reduced vulnerability and increased adaptive capacity of people to manage the identified climate and disaster risks are a primary benefit and can be monitored specifically by measuring the ability of people to take advantage of opportunities or to respond to damages associated with climate risks, hazards, changes and uncertainty. This could, for example, include estimating the reduced damage (e.g., fatalities and infrastructure loss) after an extreme weather event compared to a similar event pre-project.

Ecological benefits – The specific ecological benefits that will be monitored depend upon the project design and target ecosystem. For example, metrics to measure ecological benefits of mangrove restoration could include sediment accumulation and sediment stabilization, reduction of wave energy, mangrove seedling survival and growth, and the number of species (increased biodiversity). In this example, ecological monitoring could occur in (1) a control area, with no existing mangroves and outside the influence of the proposed green-grey infrastructure measures, (2) within the project area, and (3) in an existing natural mangrove area.

Social benefits – Social monitoring can provide quantitative and qualitative documentation of the short- and long-term social benefits of green-grey infrastructure projects. Social monitoring can be conducted through focus groups or household surveys. Potential metrics to measure short- and long-term social benefits include:

1 GIZ, UNEP-WCMC and FEBA (2020). Guidebook for Monitoring and Evaluating Ecosystem-based Adaptation Interventions. Bonn, Germany: Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH. 84 pp. https://www.adaptationcommunity.net/download/ME-Guidebook_EbA.pdf. Donatti, C.I., Martinez-Rodrigo, M.R., Fedele, G., Harvey, C.A., Andrade, A., Scorgie, S., Rose, C., and Alam. M. (2019). Guidelines for designing, implementing and monitoring ecosystem-based adaptation intentions. Virginia, USA: Conservation International. 40 pp. https://www.conservation.org/docs/default-source/publication-pdfs/guidelines-for-designing-implementing-and-monitoring-eba.pdf?Status=Master&sfvrsn=bccddc79_3

- Community members' perception of their security or safetyif an extreme weather event were to occur (e.g., perceived risk before and after project);
- Community members' plan of action if notice of an impending extreme weather event were received;
- Community members' sense of well-being;
- Total community income over time as compared to trends in comparable communities; and
- Percent of community income derived from different livelihood types.

Other potential indicators include for project co-benefits include:

- Job creation and support for local livelihoods;
- Gender equality and women's empowerment (e.g., increased salaries, participation in meetings and involvement in decision-making);
- Recreation and human health (e.g., space for people to access and enjoy nature, improve air quality, reduce local temperatures);
- Food security (e.g., drop in income from tourism makes food security provided by "natural systems" critical for resilience);
- Economic benefits (e.g., reduced maintenance cost of infrastructure, reduced damages to assets and
- livelihoods from disasters); and
- Expanded role of marginalized groups (e.g., participation in planning, design, implementation, and
- Monitoring, maintenance, and adaptive management).

Additional resources for identifying key performance indicators, assessment, and measurements methods include:

1. Blue Natural Capital Positive Impacts Management System[2]
2. Use of Natural and Nature-Based Features (NNBF) for Coastal Resilience, Final Report[3]

This includes coastal landscape metrics in Appendix E. Chapter 4 encompasses performance metrics for ecosystem goods and services generated by nature and nature- based features and structural features in the post- hurricane environment.

## WHAT ARE THE ELEMENTS OF A PROJECT MAINTENANCE PLAN?

Project monitoring, maintenance, and adaptive management are connected in a multi-step, feedback process that is outlined in a project maintenance plan. The maintenance plan operationalizes the monitoring and evaluation framework and includes:

1. Defining the "green" ecosystem and grey infrastructure assets to be maintained;
2. Identifying for each asset: (1) guidelines and steps for maintenance (e.g., pruning), (2) indicators to measure (e.g., ecosystem area), and (3) metrics;
3. Detailing the location of each asset, actions to be undertaken, and a maintenance schedule;
4. Applying a cooperative approach to exchange information with stakeholders, and help define and implement maintenance and monitoring practices;
5. Establishing training programs for technical and field staff on the maintenance activities;
6. Monitor performance of the assets, according to the project monitoring and evaluation framework, and report results and findings to the design team and contractors; and
7. Based on the results, modify the management to improve the project function.

Figure 16 provides a visual of the integrated elements of a project maintenance plan.

2 Herr, D., Baldwin, R., and Wilson, S. (2019). BNC+ Framework Blue Natural Capital Positive Impacts Framework Blue Natural Capital Positive Impacts Framework. [Online framework]. Gland, Switzerland and Grand Duchy of Luxembourg: IUCN & The Ministry of Environment, Climate and Sustainable Development. 30 pp.

3 Bridges, T.S., Burks-Copes, K.A., Bates, M.E., Collier, Z., Fischenich, C.J., Piercy, C.D., Russo, E.J., Shafer, D.J., Suedel. B.C., Gailani, J.Z., Rosati, J.D., and Wamsley, T.V., Wagner, P.W., Leuck, L.D., and Vuxton, E.A. (2015). Use of Natural and Nature-Based Features (NNBF) for Coastal Resilience. Washington, DC, USA: Engineer Research and Development Center, U.S. Army Corps of Engineers. xxxi+446 pp. https://usace.contentdm.oclc.org/digital/collection/p266001coll1/id/3442/

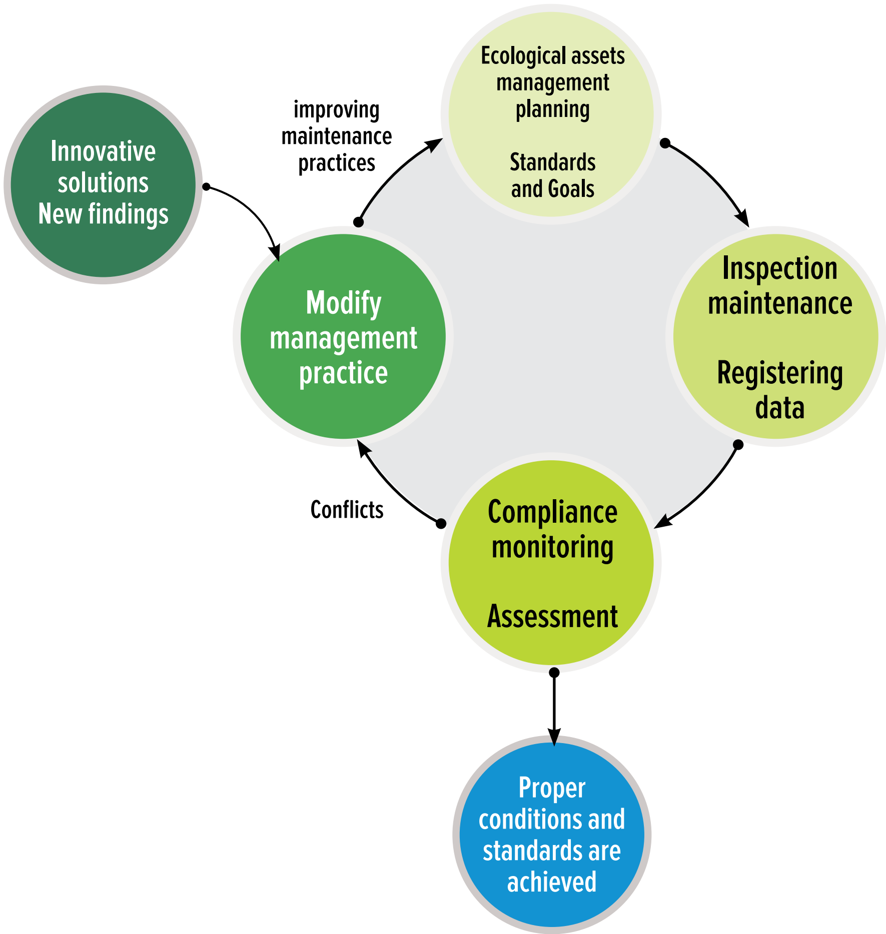



**Figure 16. An iterative approach to adaptive management (source: Iuell et al (2003)[4])**

Conventional infrastructure projects typically transfer to an operational company or organization to conduct maintenance, monitoring, and adaptive management.

The green-grey maintenance, monitoring, and adaptive management plan should be ecologically minded and reflect the long-term conservation and restoration objectives.

# RECOMMENDED ACTIVITIES FOR MANGROVE & SEAWALL GREEN-GREY STRATEGIES

Adopting the green-grey coastal infrastructure concept requires permanent, decades of management and interventions, during which conditions may change, insights and understanding may develop, more data may become available, etc. The information gained from these developments must be archived and accounted for in updates of the Master Plan and the various technical engineering and construction plans. This approach is known as adaptive management and forms a central element in the approach promoted here: working with nature / building with nature to allow nature-based solutions such as the Green-Grey Coastal Infrastructure approach.

Such adaptive management needs to be informed by data, which stem from ongoing monitoring of the effects of the interventions. This requires a monitoring plan, consisting at least of:

1. Ongoing monitoring of the status and integrity of the seawalls (the grey infrastructure),
2. Ongoing monitoring of the natural bathymetry as affected by the migrating mudbanks,
3. Mudbank position and migration,
4. Sedimentation rates in the Sediment Trapping Units and in between the Coast-Perpendicular Groynes,
5. Development of mangrove colonization, and health and biodiversity of the mangrove fringes,
6. Status and integrity of green-grey coastal infrastructure elements, i.e. the fences and groynes, and
7. Debris production.

4 Iuell, B., Bekker, G.J., Cuperus, R., Dufek, J., Fry, G., Hicks, C., Hlavác, V., Keller, V., B., Rosell, C., Sangwine, T., Tørsløv, N., Wandall, B. le Maire (eds.) (2003). Wildlife and Traffic: A European Handbook for Identifying Conflicts and Designing Solutions. Brussels, Belgium: European Co-operation in the Field of Scientific and Technical Research. 21 pp. http://www.iene.info/wp-content/uploads/COST341_Handbook.pdf

A twice per year inspection of the status and integrity interventions is a necessity, and we recommend additional inspections after severe storms. Based on the findings, maintenance works must be planned and executed to be prepared for a next storm season (November – March). It is efficient if local stakeholders can assist in inspection and maintenance, but they must be trained for this.

- The MudBank Motor approach requires considerable monitoring, maintenance, and adaptive management. The migration of mudbanks is key in this concept, and should therefore be monitored, at least once per year. Migration speeds are too erratic to make accurate predictions. Mudflat formation and extent must be monitored frequently as well, preferably twice per year to establish when and where new fences can be placed in front of previous ones. This is easier than the submerged part of the coastal bathymetry, as f.i. airborne lidar can be used at low water. Monitoring of mangrove colonization can partly be done through remote sensing, but visual inspection by biologists/ecologists is necessary to evaluate health and biodiversity of the trees. The various STU's and permeable fences must be inspected frequently on a routine basis, preferably twice per year, and after severe storms. Damage must be restored as soon as possible, and damaged poles must be removed to prevent debris problems.
- Pilot experiments with various STU-dimensions are recommended at specific locations, and their performance must be monitored at an even higher frequency, dictated by wave events. The more important parameter here is the sedimentation rate. This can be established from reading the bed level elevations over time from measuring poles, hammered into the soil, equipped with a measuring scale. Such poles are to be distributed regularly across a STU. Likely, such an array of measuring poles is placed in several STU's, while others are equipped with one reference measuring pole only.
- The eastern edge of the mangrove fringes is vulnerable to erosion when an interbank period approaches. Frequent inspection of the functioning of the permeable groynes placed to protect these mangroves is important.
- Inspection of STU's along the more riverine dominated parts of the coast need to be frequently inspected as well, again preferably twice per year on a routine basis. Sedimentation, i.e. the formation of mangrove habitat within the STU's and subsequent mangrove colonization must be monitored to establish when seaward extension is possible. Likely, wave loading is limited in most cases, as these STU's are located in more sheltered areas.

The permeable groynes to lower wave loading on existing grey infrastructure and reduce wave reflection during interbank periods are likely constructed of durable material (armored concrete). Yearly inspection, in conjunction with the common inspection of the seawalls themselves seems sufficient.

The mechanical stability of the coast-perpendicular groynes (both for sandy and muddy applications) proposed likely requires also once per year inspection, as these are assumed to be solid structures. However, their hydro-sedimentological performance is recommended to be monitored frequently collecting information for better informed designs in the future.

# REFERENCES


Abascal-Zorrilla, N., V. Vantrepotte, N. Huybrechts, Dat Dinh Ngoc, E.J. Anthony and A. Gardel, 2020. Dynamics of the Estuarine Turbidity Maximum Zone from Landsat-8 Data: The Case of the Maroni River Estuary, French Guiana. Remote Sens., 12, 2173; doi:10.3390/rs12132173.

Abernethy, C.L. (1980): Guyana Coast, recommendations for a future sea defense strategy. Report OD 30, Hydraulics Research Station, Wallingford, England, 20 pp.

Adams, J. B., & Human, L. R. D. (2016). Investigation into the mortality of mangroves at St. Lucia Estuary. South African Journal of Botany, 107, 121- 128.

Allison, M. A., Nittrouer, C. A., & Kineke, G. C. (1995). Seasonal sediment storage on mudflats adjacent to the Amazon River. Marine Geology, 125(3-4), 303-328.

Allison, M. A., Lee, M. T., Ogston, A. S., & Aller, R. C. (2000). Origin of Amazon mudbanks along the northeastern coast of South America. Marine Geology, 163(1-4), 241-256.

Allison, M. A., & Lee, M. T. (2004). Sediment exchange between Amazon mudbanks and shore-fringing mangroves in French Guiana. Marine Geology, 208(2-4), 169-190.

Anderson, M.E., J.M. Smith, and S.K. McKay. 2011. Wave Dissipation by Vegetation. Coastal and Hydraulics Engineering Technical Note ERDC/CHL CHETN-I-82.

Vicksburg, MS: U.S. Army Engineer Research and Development Center. http://chl.erdc.usace.army.mil.chetn

Anthony, E.J., A. Gardel, F. Dolique and D. Marin, 2001. The Amazon-influenced mud-bank coast of South America: an overview of short- to long- term morphodynamics of ‘inter-bank’ areas and chenier development. Journal of Coastal Research, SI 64, pp 25 – 29

Anthony, E. J., & Dolique, F. (2004). The influence of Amazon-derived mud banks on the morphology of sandy headland-bound beaches in Cayenne, French Guiana: a short-to long-term perspective. Marine Geology, 208(2-4), 249-264.Anthony, E. J., A. Gardel, N. Gratiot, C. Proisy, M.A.

Allison, F. Dolique and F. Fromard, 2010. The Amazon-influenced muddy coast of South America: A review of mud-bank–shoreline interactions. Earth-Science Reviews 103 (2010) 99–121. doi:10.1016/j.earscirev.2010.09.008

Anthony, E.J., A. Gardel, F. Dolique and D. Marin, 2011. The Amazon-influenced mud-bank coast of South America: an overview of short- to long- term morphodynamics of ‘inter-bank’ areas and chenier development. Journal of Coastal Research, SI 64, pp 25-29, ISSN 0749-0208

Anthony, E. J., Gardel, A., & Gratiot, N. (2014). Fluvial sediment supply, mud banks, cheniers and the morphodynamics of the coast of South America between the Amazon and Orinoco river mouths. Geological Society, London, Special Publications, 388(1), 533-560.

Arnold, B.C. (2011). “Chapter 7: Pareto and Generalized Pareto Distributions”. In Duangkamon Chotikapanich (ed.). Modeling Distributions and Lorenz Curves. New York: Springer. ISBN 9780387727967.

Augustinus, P.G.E.F., 1978. The changing shoreline of Suriname (South America). PhD Thesis, University of Utrecht, Netherlands, 232 pp.

Augustinus, P.G.E.F., Mees, R.P.R. and Alphen Van, J.S.L.J., (1984), “Study of Approach Channels to The Demerara and Berbice Rivers, Guyana”, Report Guychan Project 21-09-1984.

Augustinus, P.G.E.F., 1989. Cheniers and chenier plains: a general introduction. Marine Geology, 90, pp 219-229.

Augustinus, P.G.E.F., 2004. The influence of the trade winds on the coastal development of the Guianas at various scale levels: a synthesis. Mar. Geol. 208, 141–151.

Balke, T., Bouma, T. J., Horstman, E. M., Webb, E. L., Erftemeijer, P. L., & Herman, P. M. (2011). Windows of opportunity: thresholds to mangrove seedling establishment on tidal flats. Marine Ecology Progress Series, 440, 1-9.

Barbier, E.B., Hacker, S.D., Kennedy, C., Koch, E.W., Stier, A.C., Silliman, B.R., (2011). The value of estuarine and coastal ecosystem services. Ecol. Monogr. 81 (2), 169e193.

Beck M (2016) Managing Coasts with Natural Solutions: Guidelines for Measuring and Valuing the Coastal Protection Services of Mangroves and Coral Reefs. (MW Beck & G.-M. Lange, Eds.). Washington DC: The World Bank

Best ÜS (2017) Process-based modelling of the impact of sea level rise on salt marsh & mangrove fringe-mudflat morphodynamics [An assessment of the decadal triggers for morphological evolution and restoration methods]. UNESCO-IHE Bhaskaran PK (2017) Wave attenuation in presence of mangroves: A sensitivity study for varying bottom slopes. The International Journal of Ocean and Climate Systems: 1759313117702919

Bijsterveldt, van, C. E. J., van Wesenbeeck, B. K., van der Wal, D., Afiati, N., Pribadi, R., Brown, B., & Bouma, T. J. (2020). How to restore mangroves for greenbelt creation along eroding coasts with abandoned aquaculture ponds. Estuarine, Coastal and Shelf Science, 235, 106576. https://doi.org/10.1016/j.ecss.2019.106576

Blankespoor B, Dasgupta S, Lange G-M (2017) Mangroves as a protection from storm surges in a changing climate. Ambio 46: 478-491

Brinkman, R. & L.J. Pons 1968 A pedo-geomorphological classification and map of the Holocene sediments in the coastal plain of the three Guianas - Soil Survey Papers 4. Soil Survey Inst., Wageningen, 40 pp.

Brinkman, R.M., Massel, S.R., Ridd, P.V. and Furukawa, K., 1997. Surface wave attenuation in mangrove forests. Proceedings of the Combined Australasian Coastal Engineering and Ports Conference, Christchurch, 941-946.

Brunier, G., E.J. Anthony, N. Gratiot and A. Gardel, 2019. Exceptional rates and mechanisms of muddy shoreline retreat following mangrove removal. Earth Surf. Process. Landforms 44, 1559–1571, DOI: 10.1002/esp.4593.

Bovell O. (2019) Setting the foundations for zero net loss of the mangroves that underpin human wellbeing in the North Brazil Shelf LME: Review of the effectiveness of existing coastal restoration efforts in Guyana. Report by Conservation International and the National Agricultural Research and Extension Institute.

Caires, S. and A. Sterl, 2003, On the estimation of return values of significant wave height data from the reanalysis of the European Centre for Medium-range Weather Forecasts, in Safety and Reliability, eds. T. Bedford and P. H. A. J. M. van Gelder, Lisse Swets and Zeitlinger, pp. 353–361 Caires, S. and A. Sterl, 2005, 100-year return value estimates for ocean wind speeds and significant wave height from the ERA-40 data, J. Climate, 18, 1032–1048

Castillo, E., 1988, Extreme Value Theory in Engineering, Boston, MA, Academic Press, Inc., 389 pp.

Church, J. A., Gregory, J. M., Huybrechts, P., Kuhn, M., Lambeck, K., Nhuan, M. T., Qin, D. and Woodworth, P. L. (2001). “Changes in sea level”. In: J. T. Houghton, Y. Ding, D. J. Griggs et al (Eds.). Third assessment report: climate change 2001, the scientific basis. Cambridge University Press, UK, Intergovernmental Panel on Climate Change: 639-693.

Cintron-Molero, G., 1992. Restoring mangrove systems. In: Thayer, G.W. (Ed.), Restoring the Nation’s Marine Environment. Maryland Seagrant Program, College Park, Maryland, pp. 223–277.

CIRIA, CUR, CETMEF (2007). The Rock Manual. The use of rock in hydraulic engineering (2nd edition). C683, CIRIA, London

Clarke, P.J., 1993. Dispersal of grey mangrove (Avicennia marina) propagules in south-eastern Australia. Aquatic Botany, 45, 195-204. Clough, B. F. (1993). Primary productivity and growth of mangrove forests. Coastal and estuarine studies, 225-225. Coles, S., 2001, An Introduction to Statistical Modeling of Extreme Values, London, Springer-Verlag, 208 pp.

Dalrymple, R. A., Kirby, J. T., & Hwang, P. A. (1984). Wave diffraction due to areas of energy dissipation. Journal of waterway, port, coastal, and ocean engineering, 110(1), 67-79.

Dalrymple, O. K., & Pulwarty, R. S. (2006, June). Sea-level rise implications for the coast of Guyana: Sea walls and muddy coasts. In Breaking Frontiers and Barriers in Engineering: Education, Research and Practice. Fourth LACCEI International Latin American and Caribbean Conference for Engineering and Technology (LACCET 2006) Conference Proceedings (pp. 21-23).

Daniel, J. R. K. (1988). Sea defense strategies and their impact on a coast subject to a cyclic pattern of erosion and accretion. Ocean and Shoreline Management, 11(2), 159-175.

Dasgupta S, Islam M, Huq M, Khan ZH, Hasib M (2017) Mangroves as protection from storm surges in Bangladesh Doody, J.P., 2004. 'Coastal squeeze' - an historical perspective. Journal of Coastal Conservation 10 (1-2), 129-138.

Douglas, B. C., 1995. Global Sea Level Change: determination and interpretation, in: Review of Geophysics, Supplement US National Report to International Union of Geodesy and Geophysics 1991-1994, page 1425-1432

Duarte, C.M., Losada, I.J., Hendriks, I.E., Mazarrasa, I., Marba, N., (2013). The role of coastal plant communities for climate change mitigation and adaptation. Nat. Clim. Change 3 (11), 961e968.

Duivendijk, J. van and J.R. Pieters, 1983. Design and construction of the sea defences of Guyana. In: Proceedings International Symposium 'Polders of the World'. International Institute for Land Reclamation and Improvement, Wageningen, the Netherlands.

Eijk, van, P. and R. Kumar, 2009. Bio-rights in theory and practice A financing mechanism for linking poverty alleviation and environmental conservation. Wetlands International (see also https://www.wetlands.org/publications/biorights-in-theory-and-practice/).

Eisma, D. (1967). Oceanographic observations on the Surinam shelf. Hydr. Newsletter Spec. Publ.5, 21-53.

Eisma, D. and H.W. Van der Marel, 1971. Marine muds along the Guiana coast and their origin from the Amazon Basin. Contributions to Mineralogy and Petrology 31, 321– 334.

Eisma, D., P.G.E.F. Augustinus and C.A. Alexander, 1991. Recent and subrecent changes in the dispersal of Amazon mud. Netherlands Journal of Sea Research 28, 181–192.

Ellison, A.M., 2000. Mangrove restoration: do we know enough? Rest. Ecol. 8 (3), 219–229. ENGINEERS-USACE, U. A. C. O. (1984). Shore protection manual. US Army Corps of Engineers Research and Development Center, Coastal and Hydraulics Laboratory, Vicksburg.Froidefond, J.M., Pujos, M., Andre, X., 1988. Migration of mud- banks and changing coastline in French Guiana. Mar. Geol. 84, 19–30. the EurOtop Team (2007). Eurotop Overtopping manual. FAO (2007) The world's mangroves 1980–2005. FAO Forestry Paper 153, Rome, 89 pp

Feagin RA, Mukherjee N, Shanker K, Baird AH, Cinner J, Kerr AM, Koedam N, Sridhar A, Arthur R, Jayatissa LP (2010) Shelter from the storm? Use and misuse of coastal vegetation bioshields for managing natural disasters. Conservation Letters 3: 1-11

Ferreira, J. A. and C. G. Soares, 1998, An application of the peaks over threshold method to predict extremes of significant wave height, J. Offshore Mechanics and Arctic Engineering, ASME, 120, 165–176

Field, C.D. (Ed.), 1996. Restoration of Mangrove Ecosystems. International Society for Mangrove Ecosystems, Okinawa, Japan. Field, C.D., 1998. Rehabilitation of mangrove ecosystems: an overview. Mar. Pollut. Bull. 37 (8–12), 383–392.

Froidefond, J.M., F. Lahet, C. Hu, D. Doxaran, D. Guiral, M.T. Prost and J.-F. Ternon, 2004. Mudflats and mud suspension observed from satellite data in French Guiana. Marine Geology 208, 153–168.

Gade, H.G., 1958. Effects of a non-rigid, impermeable bottom on plane surface waves in shallow water. Journal of Marine Research 16 (2), 61–82.

Gardel, A., Gratiot, N., 2005. A satellite image-based method for estimating rates of mud bank migration, French Guiana, South America. J. Coast. Res. 21, 720–728.

Gelder, van, P. H. A. J. M. and J. K. Vrijling, 1999, On the distribution function of the maximum wave height in front of reflecting structures, Proc. Conf. Coastal Structures, ed. I. J. Losada, 1, pp. 37–46

Gijón Mancheño, A., W.J. Jansen, J.C. Winterwerp and W.S.J. Uijttewaal, 2021a. Predictive model of bulk drag coefficient for a nature-based structure exposed to currents, Scientific Reports, 11:3517, https://doi.org/10.1038/s41598-021-83035-0

Gijón Mancheño, A., W.J. Jansen, W.S.J. Uijttewaal, A.J.H.M Reniers, A. van Rooijen, T. Suzuki, V. Etminan and J.C. Winterwerp, 2021b. Wave transmission and drag coefficients through dense cylinder arrays: implications for designing nature-based structures, Ecological Engineering, 165:106231, https://doi.org/10.1016/j.ecoleng.2021.106231.

Goda, Y., 1985. Random seas and design of maritime structures. Tokyo: University of Tokyo Press.

Goda, Y., 1992, Uncertainty of design parameters from viewpoint of extreme statistics, J. Offshore Mechanics and Arctic Engineering, ASME, 114, 76–82

Granek EF, Ruttenberg BI (2007) Protective capacity of mangroves during tropical storms: a case study from 'Wilma'and 'Gamma'in Belize. Marine Ecology Progress Series 343: 101-105

Gratiot, N. and E.J. Anthony, 2016. Role of flocculation and settling processes in development of the mangrove-colonized, Amazon-influenced mud-bank coast of South America. Marine Geology 373, 1–10.

Green-Gray Community of Practice. (2020). Practical Guide to Implementing Green-Gray Infrastructure. Gumbel, E. J., 1958, Statistics of Extremes, New York, Columbia University Press, 375 pp.

Hendry, M. (1993). "Sea-level movements and shoreline changes". In: G. A. Maul (Ed.). Climate Change in the Intra-Americas Sea. Arnold, London.: 115-161

Hogarth, P. J. (2015). The biology of mangroves and seagrasses. Oxford University Press. Holthuijsen, L. (2007). Waves in oceanic and coastal waters. Cambridge University Press. Horstman E, Dohmen-Janssen CM, Narra P, Van den Berg N, Siemerink M, Hulscher SJ (2014) Wave attenuation in mangroves: A quantitative approach to field observations. Coastal engineering 94: 47-62

Horstman, E.M., 2014. The mangrove tangle – short-term bio-physical interactions in coastal mangroves, PhD-thesis, University of Twente, The Netherlands.

Hossain, M. D., & Nuruddin, A. A. (2016). Soil and mangrove: a review. Journal of Environmental Science and Technology, 9(2), 198-207.

Hughes SA (2008) Estimation of combined wave and storm surge overtopping at earthen levees. Coastal and Hydraulics Engineering Technical Note ERDC/CHL CHETN-III-78. Vicksburg, MS: U.S. Army Engineer Research and Development Center (ICBA), I. C. B. A. (2006). Guyana Sea Defenses, Bridging Programme Progress Report Block 5 Coastal Processes. G. S. D. Government of Republic of Guyana.

Jeuken, M.C.J.L., Z.B. Wang and D. Keiller, 2008. Impact of setbacks on the estuarine morphology, In Dohmen-Jansen, C.M. and S.J.M.H. Hulscher (eds.), River, Coastal and Estuarine Morphodynamics, RCEM2007, Taylor & Francis, 2008, London, pp1125-1134.

Kamali, B., & Hashim, R. (2011). Mangrove restoration without planting. Ecological Engineering, 37(2), 387–391.

Kineke, G. C., & Sternberg, R. W. (1995). Distribution of fluid muds on the Amazon continental shelf. Marine Geology, 125(3-4), 193-233

Kineke, G. C., Sternberg, R. W., Trowbridge, J. H., & Geyer, W. R. (1996). Fluid-mud processes on the Amazon continental shelf. Continental shelf research, 16(5-6), 667-696.

Kirwan M.L., Megonigal J.P. (2013) Tidal wetland stability in the face of human impacts and sea-level rise. Nature 504(7478):53–60

Kit LW (2016) Wave attenuation function of mangroves along Singapore's northern coast. Kobayashi N, Raichle AW, Asano T (1993) Wave attenuation by vegetation. Journal of waterway, port, coastal, and ocean engineering 119: 30-48

Lambs, L., Muller, E., & Fromard, F. (2008). Mangrove trees growing in a very saline condition but not using seawater. Rapid Communications in Mass Spectrometry, 22(18), 2835-2843.

Lees, D., Wernerus, F.M.J., Simpson, M.C., 2009. Strategic environmental assessment of the sea defenses sector policy in Guyana, letter of contract no. 2008/150593.

Lehman, S. M. (2004). Distribution and diversity of primates in Guyana: species-area relationships and riverine barriers. International Journal of Primatology, 25(1), 73-95.

Lewis, R.R., 1977. Impacts of dredging in the Tampa Bay estuary 1876–1976. In: Pruitt, E.L. (Ed.), Proceedings of the Second Annual Conference of the Coastal Society—Time-stressed Environments: Assessment and Future Actions. The Coastal Society, Arlington, Virginia, pp. 31–55.

Lewis, R.R., 1982. Mangrove forests. In: Lewis, R.R. (Ed.), Creation and Restoration of Coastal Plant Communities. CRC Press, Boca Raton, Florida, pp. 153–172.

Lewis, R.R., 1994. Enhancement, restoration and creation of coastal wetlands. In: Kent, D.M. (Ed.), Applied Wetlands Science and Technology. Lewis Publishers, Inc., Boca Raton, Florida, pp. 167–191.

Lewis, R. R., Streever, W., 2000. Restoration of Mangrove Habitat. Tech Note ERDC TN-WRP-VN-RS-3. US Army, Corps of Engineers, Waterways Experiment Station, Vicksburg, Mississippi.

Lewis, Roy R. (2001). Mangrove Restoration - Costs and Benefits of Successful Ecological Restoration. Mangrove Valuation Workshoop, 4–8. Retrieved from http://www.fao.org/forestry/10560-0fe87b-898806287615fceb95a76f613cf.pdf

Lewis III, R. R. (2005). Ecological engineering for successful management and restoration of mangrove forests. Ecological engineering, 24(4), 403-418.

Lewis, Roy R. & Gilmore, R.G. (2007). Important considerations to achieve successful mangrove forest restoration with optimum fish habitat. Lieberman, Von, 2012. Management of Natural Resources in the Coastal Zone of Soc Trang Province, Vietnam, Von Lieberman, Hamburg, project report 13775-01.

Marchand M (2009) Modelling coastal vulnerability: design and evaluation of a vulnerability model for tropical storms and floods IOS Press

Martin, L., Dominguez, J. and Bittencourt, A. (2003). "Fluctuating Holocene sea levels in eastern and southern Brazil: evidence from multiple fossil and geometric indicators". Journal of Coastal Research9(1): 101-124.

Massel S, Furukawa K, Brinkman R (1999) Surface wave propagation in mangrove forests. Fluid Dynamics Research 24: 219-249

MacDonald, M., 2006. Feasibility Study for the Sea Defences Programme financed under the 9th EDF for "The Co-operative Republic of Guyana", Feasibility Report, Croydon, 220 pages.

Maza M, Lara JL, Losada IJ (2015) Tsunami wave interaction with mangrove forests: A 3-D numerical approach. Coastal Engineering 98: 33-54

Mazda Y, Magi M, Ikeda Y, Kurokawa T, Asano T (2006) Wave reduction in a mangrove forest dominated by Sonneratia sp. Wetlands Ecology and Management 14: 365-378

McDonald, T., Jonson, J., & Dixon, K. (2016). National standards for the practice of ecological restoration in Australia (vol 24, pg S1, 2016). Restoration Ecology, 24(5), 705-705.

McIvor, A.L., Möller, I., Spencer, T., Spalding, M., 2012a. Reduction of wind and swell waves by mangroves, Natural Coastal Protection Series: Report 1. Cambridge Coastal Research Unit, Cambridge ISSN 2050-7941.

McIvor A, Spencer T, Möller I, Spalding M (2012b) Storm surge reduction by mangroves The Nature Conservancy and Wetlands International. McIvor, A.L., Möller, I., Spencer, T., Spalding, M., 2013. Mangroves as a sustainable coastal defense, Proceedings of the 7th International Conference on Asian and Pacific Coasts (APAC 2013) Bali. Indonesia, September 24-26, 2013.

McKee, K.L., 1993. Soil physiochemical patterns and mangrove species distribution-reciprocal effects? J. Ecol. 81, 477–487.

McKee, K.L., 1995a. Seedling recruitment patterns in a Belizean mangrove forest: effects of establishment ability and physiochemical factors. Oecologia 101, 448–460.

McKee, K.L., Faulkner, P.L., 2000a. Restoration of biogeochemical function in mangrove forests. Rest. Ecol. 8 (3), 247–259.

McLachlan, R. L., Ogston, A. S., Asp, N. E., Fricke, A. T., Nittrouer, C. A., & Gomes, V. J. C. (2020). Impacts of tidal-channel connectivity on transport asymmetry and sediment exchange with mangrove forests. Estuarine, Coastal and Shelf Science, 233, 106524.

Melcher, P. J., Goldstein, G., Meinzer, F. C., Yount, D. E., Jones, T. J., Holbrook, N. M., & Huang, C. X. (2001). Water relations of coastal and estuarine Rhizophora mangle: xylem pressure potential and dynamics of embolism formation and repair. Oecologia, 126(2), 182-192.

NEDECO, 1972, Report on sea defense studies, NEDECO, The Hague, The Netherlands. Nickerson, N.H., Thibodeau, F.R., 1985. Associations between pore water sulfide  mangroves. Biogeochemistry 1, 183–192.

Pachauri, R. K., Allen, M. R., Barros, V. R., Broome, J., Cramer, W., Christ, R., ... & van Ypserle, J. P. (2014). Climate change 2014: synthesis report. Contribution of Working Groups I, II and III to the fifth assessment report of the Intergovernmental Panel on Climate Change (p. 151). Ipcc.

Parizek, B. R. and Alley, R. B. R. B. (2004). "Implications of increased Greenland surface melt under global-warming scenarios: ice-sheet simulations". Quaternary Science Reviews 23(9-10): 1013-1027.

Planet, 2016. Coastal engineering design manual for Guyana sea and river defenses. FWC BENEFICIARIES 2013 EuropeAid/132633/C/SER/multi, LOT 2: Transport and Infrastructure, Contract No. 2015/362251.

Plaziat, J.-Cl. and P. G.E.F. Augustinus, 2004. Evolution of progradation/ erosion along the French Guiana mangrove coast: a comparison of mapped shorelines since the 18th century with Holocene data. Marine Geology 208, 127– 143

Primavera, J. H., & Esteban, J. M. A. (2008). A review of mangrove rehabilitation in the Philippines: successes, failures and future prospects. Wetlands Ecology and Management, 16(5), 345-358.

Raper, S. C. B. and Braithwaite, R. J. (2006). "Low sea level rise projections from mountain glaciers and icecaps under global warming". Nature439(7074): 311.

Repko, A., P. H. A. J. M. van Gelder, H. G. Voortman and J. K. Vrijling, 2000, Bivariate statistical analysis of wave climates, Proc. 27th Int. Conf. Coastal Engineering (Sydney), Reston, VA, ASCE, pp. 583–596

Rull, V., Vegad-Vilarrubia, T. and De Pernia, N. E. (1999). "Palynological Record of an Early-Mid Holocene Mangrove in Eastern Venezuela. Implications for Sea-Level Rise and Disturbance History". Journal of Coastal Research15(2): 496-504.

Rupprecht, F., Möller, I., Evans, B., Spencer, T. & Jensen, K. 2015. Biophysical properties of salt marsh canopies – Quantifying plant stem flexibility and above ground biomass. Coastal Engineering 100:48–57.

Saenger, P., 2002. Mangrove Ecology. In: Silviculture and Conservation. Kluwer Academic Publishers, Dordrecht, The Netherlands. Sandilyan S, Kathiresan K (2015) Mangroves as bioshield: an undisputable fact. Ocean & Coastal Management 103: 94-96 Schiereck, G. J. (2012). Introduction to bed, bank and shore protection. VSSD, Delft.

Smith, D.E. et al., 1999. Relative sea level rise during the Main Postglacial Transgression in NE Scotland, UK Transactions of the Royal Society of Edinburgh: Earth Sciences 90, page 1-27

Spalding MD, McIvor AL, Beck MW et al (2014) Coastal ecosystems: a critical element of risk reduction. Conserv Lett 7(3):293–301

Stevenson, N.J., Lewis, R.R., Burbridge, P.R., 1999. Disused shrimp ponds and mangrove rehabilitation. In: Streever, W.J. (Ed.), An International Perspective on Wetland Rehabilitation. Kluwer Academic Publishers, The Netherlands, pp. 277–297.

Stocken, Van der, T., J. López-Portillob, N. Koedam, 2017. Seasonal release of propagules in mangroves – Assessment of current data. Aquatic Botany 138,92–99. http://dx.doi.org/10.1016/j.aquabot.2017.02.001.

Sutton-Grier, A. E., Wowk, K., & Bamford, H. (2015). Future of our coasts: The potential for natural and hybrid infrastructure to enhance the resilience of our coastal communities, economies and ecosystems. Environmental Science & Policy, 51, 137-148

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Front and back cover photo: Chateau Margot coast with mangrove fringe. © CI/John Greene

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# Guyana Green-Grey Coastal Infrastructure Engineering Guidelines

## Technical Reference Manual

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**Guyana Green-Grey Coastal Infrastructure Engineering Guidelines**
Technical Reference Manual

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# Contents

# 1 Introduction

This Technical Reference Manual provides the scientific and engineering background upon which the Guidelines for mangrove-seawall engineering are based. It summarizes the information, data and knowledge available at the time of writing this report. As it is anticipated that more data will become available, and more knowledge will be developed, this report should be updated frequently, in other words, the present report should be a living document.

In the next chapter, the concept of Green-Grey Coastal Infrastructure is introduced with focus on its application in the (Guyana) coastal zone. The Guidelines provide a general introduction on the best way to combine mangrove restoration and seawalls for coastal protection in Guyana. Mangroves can only flourish when conditions are suitable on the upper reaches of intertidal mudflats. Generally, mangrove habitat is found from around mean sea level (MSL) to high-high water spring (HHWS), but when wave conditions are unfavourable, the lower edge mangrove habitat is found around mean high water (MHW). Therefore, to design a successful mangrove restoration project ample attention must be paid to the sediment dynamics in the coastal zone, as these govern the formation and fate of intertidal mudflats. Proper understanding of these natural processes, the interaction between natural processes and hard reflective structures like seawalls, and the relevant time scales is key for successful application of the Green-Grey Coastal Infrastructure approach.

One role of a mangrove greenbelt in front of a Grey structure (i.e. the existing seawalls and dikes) is to lower wave stresses and runup, which reduces the required size of the Grey structure, and therefore decreases construction and maintenance costs. However, in Guyana it is not only for financial reasons that this approach is beneficial: the subsoil of the Guyana coastal zone is too soft to support the weight of huge seawalls. The dissipation of wave energy expected in a mangrove greenbelt can be used in the design of the greenbelt width and associated seawall.

A second role of a mangrove greenbelt is to increase the resilience of the coast against external stresses, such as sea level rise and storms, as a greenbelt can auto-repair damage. This resilience is one of the ecosystem services provided by the mangroves, together with carbon sequestration, water purification, fish habitat, etc.

Implementation of the Green-Grey Coastal Infrastructure approach requires a thorough understanding of all aspects of the natural system, which subject of the Chapters 3 – 6 of this Reference Manual. The central element in this understanding is the dynamics of the fine, muddy and course, sandy sediment in the coastal waters, as these form the habitat of the mangroves. Mangroves are so-called eco-engineers, as they engineer their own habitat by trapping sediment and dissipating waves, creating calm hydrodynamic conditions for expansion. The natural mangrove-mud coasts along the Guianas respond to the passage of large mudbanks, accreting when present and retreating in interbank periods.

These natural dynamics are disturbed by the erection of seawalls/dikes too close to the waterline. The restoration of these natural dynamics is therefore key in applying a Green-Grey Coastal Infrastructure policy in Guyana. This can be achieved with methods borrowed from the Building with Nature concept, the elements of which are introduced in the Chapters 7 – 9. These elements consist of green engineering infrastructure, such as permeable dams, of management interventions, such as (temporal) realignment and of actively stimulating mangrove recruitment.

It is stressed that before any interventions are designed, a Master Plan must be drafted, setting short- and long-term targets, while placing the interventions in a wider perspective of the socio-economic developments of the country. Because of the time scales of the natural system, a Master Plan should cover many decades. Also this must be a living document, accommodating the lessons learned from earlier interventions, new insights in the functioning of the coastal system, and last but not least of new socio-economic developments.

The conceptual design of Green-Grey Coastal Infrastructure interventions is discussed in the Chapters 11 – 16 with an overview of the locations along the Guyana coast where the various types of interventions are expected to be applicable. At some locations, timing is not crucial, at other locations interventions are only possible when synchronized with natural processes, e.g. the passage of mudbanks, and timing is critical.

The interventions proposed are no-regret scenarios, i.e. they are flexible and adaptive. This implies however that monitoring is a must, and lessons learned need to be analysed and documented, together with gaps in knowledge and data, as discussed in Chapter 17. Chapter 18 provides some estimates of costs involved. Finally, in Chapter 19 the gaps, identified during the writing of the current Guidelines, and the work to be carried out to fill these are collected.

# 2 Green-Grey Coastal Infrastructure: Combined Vegetation-Seawall Systems

## 2.1 Key Messages

- A sufficiently wide mangrove greenbelt in front of a seawall reduces incoming wave heights at its toe. Reduced wave impact on a seawall reduces the required crest height and mean loads, thereby reducing construction and maintenance cost.
- The design of Green-Grey Coastal Infrastructure should be informed by a thorough understanding of the natural system at all spatial and temporal scales.
- The amount of wave reduction strongly depends on vegetation characteristics, such as vegetation height, density and stem diameter, as well as on the elevation and slope of the foreshore and wave height and period.
- Wave reflection against a seawall can hamper the (re-)establishment and growth of mangroves.

## 2.2 Green-Grey Coastal Infrastructure for Coastal Flood Risk Management in Guyana

Green infrastructure such as wetlands and forests can provide nature-based adaptative solutions for flood control and water security, alongside a host of co-benefits to biodiversity, livelihoods, and more. However, for communities exposed to extreme climate and disaster risks, green infrastructure alone may not provide adequate protection. Conventional grey infrastructure, in the form of seawalls and dams, can provide immediate protection but is often prohibitively expensive to build, maintain, and replace, and can create unintended and unforeseen unfavorable impacts. By blending “green” conservation with “grey” engineering techniques, communities can incorporate the benefits of both approaches, while minimizing the limitations of using either green or grey infrastructure individually.

Green-Grey Infrastructure combines conservation and/ or restoration of ecosystems with the selective use of conventional engineering approaches to provide people with solutions that deliver climate change resilience and adaptation benefits. This Green-Grey Infrastructure design approach can apply in coastal, freshwater, and terrestrial settings and accomplish a variety of project goals.

An example of Green-Grey Coastal Infrastructure is where natural coastal ecosystems – such as mangroves, salt marshes, inter-tidal flats, seagrasses and coral reefs – are combined with grey infrastructure such as seawalls, to combine the values of wave attenuation and flood control of natural ecosystems with the benefits of engineered structures. In addition, the conservation and restoration of natural coastal ecosystems can extend the lifespan of grey infrastructure, while also supporting fisheries, regulating water quality, and sequestering carbon. The combined solution can therefore be more comprehensive, robust, and cost-effective than either solution alone.

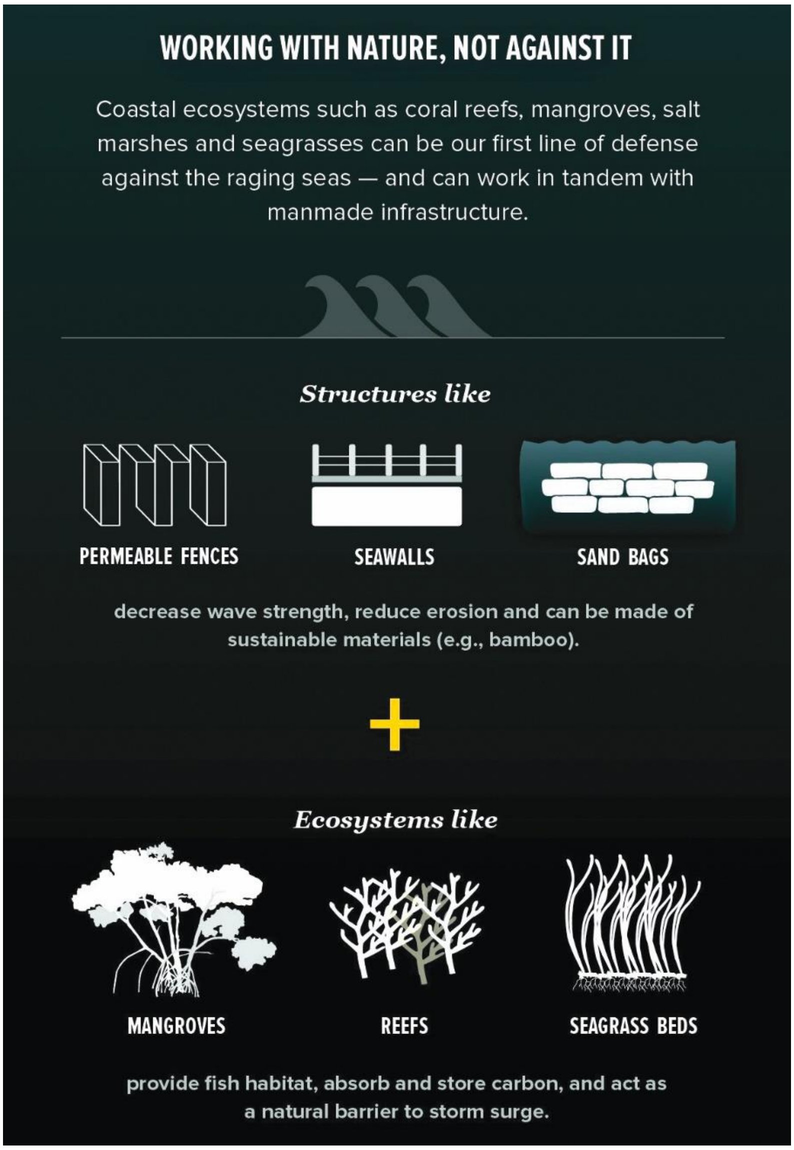


*Figure 2.1 Visualization of the Green-Gray approach (Green-Grey Community of Practice, 2020).*

Green-Grey Coastal Infrastructure solutions are emerging, but not yet in common use globally. This chapter outlines how Green-Grey infrastructure solutions can be applied for coastal flood risk management in Guyana.

Mangroves in front of a seawall (see Figure 2.2) offer excellent opportunities for adaptive and robust flood risk reduction schemes (Sutton-Grier et al, 2015; Van Wesenbeeck et al, 2017). A sufficiently broad mangrove greenbelt can considerably decrease wave height at the toe of a seawall (Brinkman et al., 1997; McIvor et al., 2012, 2013) and consequently wave impact, thereby reducing the required seawall crest height and material costs. This capacity makes the Green-Gray Coastal Infrastructure approach very efficient to manage the effects of changing external conditions, such as increasing wave heights and sea level rise.

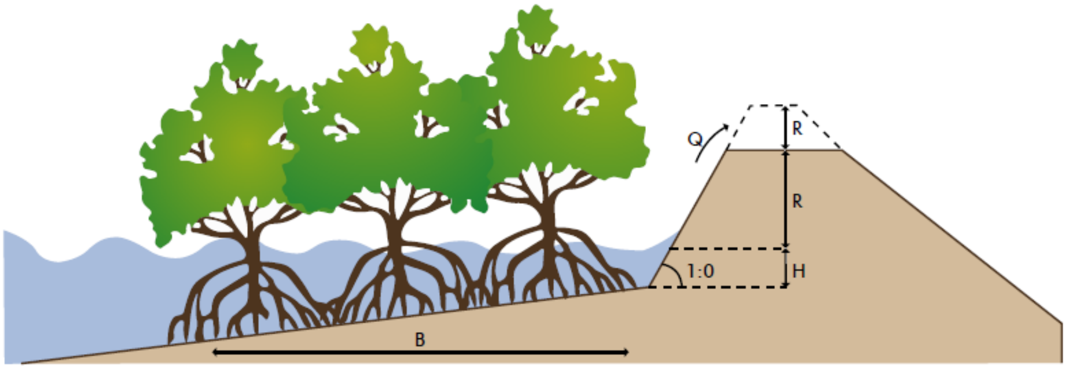


*Figure 2.2 Combination of mangroves with a seawall or levee and the parameters influenced by the presence of mangroves (World Bank, 2017)*

Nature-based solutions and coastal zone management should start with master planning and a detailed analysis of the natural system at all temporal and spatial scales (Van Wesenbeeck et al., 2021a), see chapter 10, i.e. a thorough system understanding. These solutions should be designed and managed as dynamic interventions, in which the width of the mangrove greenbelt may vary over time, and not as a static approach. The minimum width of a greenbelt should be such that the design criteria are met under extreme conditions.

## 2.3 Conventional Grey Coastal Infrastructure

This section summarizes the functional properties, design criteria and parameters for conventional 'grey' coastal defense structures (e.g. seawalls).

***Functional Design***

It is important to make a distinction in flood risk management and sediment management. Flood risk management encompasses any measures taken to reduce flood risk during extreme conditions. Conventional flood risk management measures are for example seawalls, levees and dikes. These types of structures primarily have a blocking function to prevent flooding. Moreover, they need to limit wave overtopping to a maximum tolerable overtopping discharge with respect to structural stability. Sediment management measures aim for a stable coastline and to reduce coastal erosion. Examples of typical measures are groynes, breakwaters and sediment nourishments. The focus of this chapter is on flood risk management measures. Sediment management measures to e.g. trap sediment trapping and stimulate mangrove growth are presented in chapter 7. Chapter 9 describes methods for mangrove conservation and restoration.

***Structural Design***

Several well-known and commonly used manuals exist for the design of conventional coastal protection structures, such as the US Army Corps of Engineering Shore Protection Manual (ENGINEERS-USACE, 1984), the Rock Manual (CIRIA, 2007) and the Eurotop Overtopping Manual (The EurOtop Team, 2007). The existing Coastal Engineering Design Manual (CEDM) for Guyana Sea and River Defenses combines information from these different manuals applicable to Guyana and can thus be used for the engineering design of seawalls, based on wave run-up, wave overtopping and wave reflection (CEDM section 7.4). In this guideline the most important design criteria and parameters are summarized. Furthermore, section 2.5 elaborates on additional considerations when a seawall is applied in combination with fronting vegetation.

Figure 2.3 provides an overview of the terminology that is used in the design of hydraulic structures and a schematization of governing processes. The most important design parameter is the crest height of the (vertical) seawall, which can be determined using the design guidelines based on the tolerable overtopping discharge and on the wave height and period at the toe of a structure (possibly after transmission through a mangrove greenbelt) during extreme events. Information in this section is largely based on the Rock Manual (CIRIA, 2007).

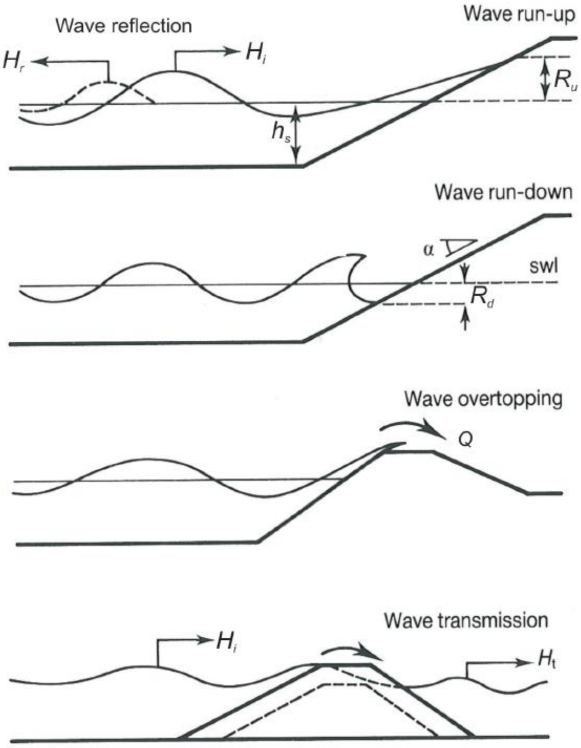


*Figure 2.3 Hydraulic interactions related to waves and parameters definitions (copied from the Rock Manual (CIRIA, 2007))*

*Wave run-up*

Wave action on a sloping structure propels seawater up and down over a vertical range. The highest level possible is referred to as the wave run-up ($R_u$), whereas the lowest level is referred to as wave run-down ($R_d$), both relative to the still water level (SWL). The run-up level is used to determine the necessary crest height of a structure, or as an indicator for overtopping. The run-down level can be used to determine the lower extent of an armour layer. The run-up and run-down levels can be computed using formulations provided in the Rock Manual (CIRIA, 2007). Important parameters governing the run-up level are the slope, roughness and permeability of the structure. Rough and/or permeable slopes (e.g. with rock armor) dissipate wave energy and thereby reduce the run-up. The effect of the shallow foreshore, which is typically the case in the Guyana coastal system, should also be considered.

*Wave reflection*

Part of the incident wave energy is reflected by coastal structures. For traditional 'hard' structures this is most of the wave energy, whereas for 'soft' solutions (i.e. a dissipating slope, a natural beach or a permeable dam) less energy is reflected. Commonly used design manuals, such as the Rock Manual (CIRIA, 2007), recommend reducing wave reflection to prevent local scour in front of structures. For the current grey-green infrastructure, wave reflection should be reduced as well to limit stresses on the vegetation, see section 2.5. A standard way to limit wave reflection is by placing dissipating materials (e.g. rubble stones or concrete blocks) in front of a structure. Chapter 0 suggests that permeable structures in front of a seawall may also reduce wave reflection.

In Coastal Engineering practice the reflection is estimated based on a reflection coefficient $K_R$, which is expressed in terms of the incident and reflected wave heights: $K_R = H_R/H_i$. Values for the reflection coefficients can be estimated based on structural types from Table 2.1 (Goda, 1985).

*Table 2.1 Estimation of reflection coefficient ($K_R$) based on structure type (Goda, 1985)*

| **Structure type** | **Reflection coefficient ($K_R$)** |
|---|---|
| Vertical wall, crown above water | ~0.7-1.0 |
| Vertical wall, submerged crown | ~0.5-0.7 |
| Revetment consisting of rubble stones | ~0.3-0.6 |
| Revetment consisting of energy dissipating concrete blocks | ~0.3-0.5 |
| Permeable (energy dissipating) vertical structure | ~0.3-0.8 |
| Natural beach | ~0.05-0.2 |

*Wave overtopping*
If run-up- levels exceed the crest height of a structure, wave overtopping will occur. Low overtopping rates may be accepted without severe consequences to the structure or the protected area. Therefore, a maximum tolerable overtopping discharge is used as design criterion. The Eurotop Overtopping Manual (The EurOtop Team, 2007) provides a sound, commonly used design guideline for overtopping discharge and elaborates further on different settings. Suitable tolerable overtopping discharges are provided for structural design, operation, damage to protected property and infrastructure, and hazard for people and vehicles. Based on these maximum tolerable overtopping discharges a suitable design criterion can be selected.

Once the maximum tolerable overtopping discharge has been selected, the design conditions are computed based on the formulations provided in the Overtopping Manual. Assuming a plain vertical wall and non-impulsive conditions, eq. 7.4 from the Overtopping Manual applies, which is valid for $0.1 < \frac{R_c}{H_{m0}} < 3.5$. This equation provides an exponential expression for the dimensionless overtopping discharge ($\frac{q}{\sqrt{gH_{m0}^3}}$) as a function of the relative crest freeboard ($\frac{R_c}{H_{m0}}$):

$$\frac{q}{\sqrt{gH_{m0}^3}} = a * \exp\left(-b\frac{R_c}{H_{m0}}\right)$$

where $q$ is the mean overtopping discharge in m³/m/s, $H_{m0}$ is the significant wave height at the toe of the seawall in m, $R_c$ is the crest freeboard in m and *a* and *b* are experimental coefficients (in case of deterministic design a = 0.04 and b = 1.8).

Similar as for wave run-up, rough and/or permeable slopes and a shallow foreshore may reduce the wave overtopping (through dissipation of wave energy) and should be considered in the design of conventional Flood Risk Management structures.

*Failure mechanisms*
The relevant failure mechanisms for revetments, as depicted in Figure 2.4, are instability of protection, wave overtopping, toe erosion, instability of slope, collision/aggression and

subsidence. More information on failure mechanisms is provided in the various manuals referenced above.

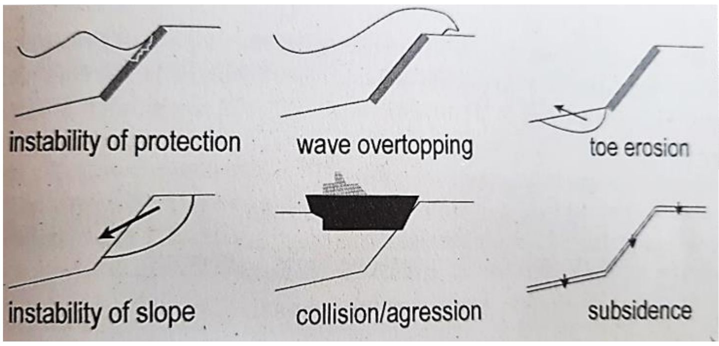


*Figure 2.4 Failure mechanisms for seawalls, levees and revetments (Schiereck, 2012)*

## 2.4 Green Coastal Infrastructure: Mangrove Greenbelt

The functional properties and design criteria and parameters for 'green' or nature-based solutions are summarized in this section.

***Functional Design***

A mangrove greenbelt in front of a seawall can provide multiple functions (also referred to as ecosystem services; Barbier et al., 2011). On top of its intrinsic ecologic value and the capacity to capture and sequestrate carbon, the most important functional properties of mangrove greenbelt for flood risk mitigation are (Duarte et al., 2013):

- The mangrove greenbelt traps sediment, allowing for the bed level to grow vertically (Figure 2.5, panel a), potentially keeping pace with rising sea level (Kirwan & Megonigal, 2013).
- After small disturbance events, a vegetated mudflat is able to recover, which makes them more resilient than traditional measures (Spalding et al, 2014; panel b).
- Mangroves attenuate incoming waves (panel c). A healthy mangrove forest may reduce wave heights by 0.2 – 1% per m vegetation (Brinkman et al., 1997; McIvor et al., 2012a, 2013; Horstman, 2014). The amount of wave reduction strongly depends on specific vegetation characteristics, such as vegetation height, density and stem diameter (Anderson et al., 2011) – see chapter 6.

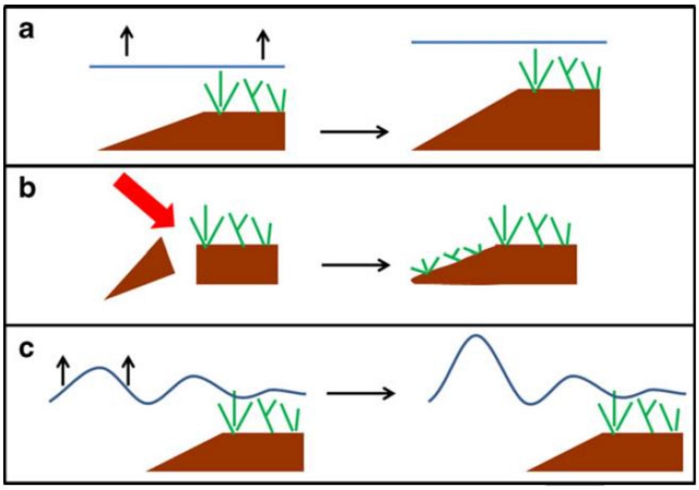


*Figure 2.5 Schematization of three adaptive features of ecosystems that can contribute to flood risk mitigation (from Van Wesenbeeck, et al (2017)). a) Accretion with rising water levels; b) Self-repair (resilience) after small disturbance events; c) Reduction of waves with different heights to almost similar height.*

***Structural Design***

The design of a mangrove greenbelt should aim to lower the wave height to an acceptable level, such that the hinterland is protected to the required safety level, depending on local conditions and combinations with conventional structures. An important design parameter is the water level (or surge level) during storm conditions, as high water levels cause flooding. These levels should be evaluated in combination with wave setup and wave heights for overtopping computations.

The bed level and slope of the foreshore are important parameters that influence wave dissipation. In the nearshore area interactions of the waves with the seabed cause shoaling and wave dissipation. For steeper bed slopes high wave dissipation and shoaling rates occur, whereas for mild slopes the wave dissipation rate is lower. Typically, mangrove-mud coasts have a mild slope (about 1:1000) owing to the characteristics of the muddy substrate, which is also reflected in the wave conditions (less energetic than on sandy or gravel coasts). Therefore, wave breaking does not play a major role along these mangrove-mud coasts. Starting offshore, the incoming waves are influenced by the muddy foreshore (the subtidal area) and part of the incoming wave energy dissipates. Note that due to internal friction, wave dissipation over soft, muddy substrates is larger than by bed friction alone. The wave dissipation caused by bed level and slope of the muddy foreshore should be included in the design of green solutions.

Wave attenuation by vegetation has been quantified in many studies, based on field and laboratory measurements (see Vuik et al. (2016) for an overview) or numerical models (Suzuki et al., 2012; Tang et al., 2015). The wave dissipation mainly depends on hydrodynamic parameters, such as the water depth (Paquier et al., 2016) and the height (Anderson et al., 2011) and period (Jadhav et al., 2013) of the incoming waves, as well as on the vegetation characteristics. The main vegetation parameters affecting the wave attenuation capacity of vegetation are the above-ground biomass (Marsooli and Wu, 2014) and the flexibility of the vegetation (Luhar and Nepf, 2016; Paul et al., 2016), as well as its governing failure mechanisms. The vegetation stems are the most important contributors to wave attenuation, for which the above-ground biomass is determined by the stem height (m), stem diameter (m), stem density (stems/$m^2$) and the mass density of the stems (kg/$m^3$). The turbulence induced by the vegetation dissipates wave energy. The flexibility of the plants determines how plant motion and wave motion interact and determines the magnitude of the drag forces (Bouma et al., 2005; Dijkstra and Uittenbogaard, 2010; Mullarney and Henderson, 2010; Rupprecht et al., 2015). Section 6 elaborates further on the wave attenuation of mangrove-mud coasts.

Failure mechanisms for vegetation under wave forcing are important to consider, as these may cause significant loss of above-ground biomass. Vuik et al (2018) presented a model which determines the wave load that plant stems can withstand before they break or fold, applicable for salt marsh vegetation. For mangrove vegetation similar research is currently ongoing.

## 2.5 Interaction Between Mangroves and Structures

*Wave reflection*

Flood risk management structures prevent waves from penetrating the hinterland, but in doing so they induce wave reflection (Figure 2.6), as explained in section 2.3. In case of a vertical impermeable structure (e.g. a seawall) full reflection occurs, consequently a standing wave is generated with twice the amplitude of the incoming wave. Bed shear stresses close to the structure, scaling with the square of the wave height, then increase by a factor four with high risks of local scour at the foot of the seawall. This may in turn result in structural failure of the seawall, if the bed is not sufficiently protected (e.g. by a scour protection).

Then mangroves may also be attacked by waves from the back. Fully grown mangrove trees can withstand quite large shear stresses, but young mangrove seedlings can be eroded. If wave reflection damages the forest, killing individual trees, wave damping further reduces, and wave attenuation increases further, etc. This sets a minimum greenbelt width of several 100 m, depending on the rate of wave dissipation by the mangrove vegetation for fully reflecting sea defenses. This is one reason that it is very difficult to rehabilitate mangrove habitat along solid levees or seawalls, as in some parts of the Guyana coast. Adding features on such levees or seawalls to reduce wave reflection may thus increase the success of mangrove rehabilitation in these environments.

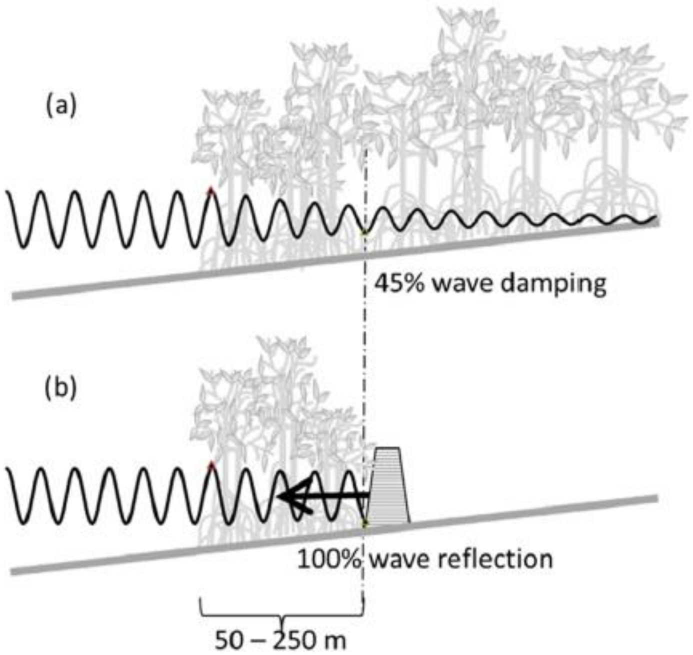


*Figure 2.6 Schematic of wave amplification by reflection against seawall, a) "pristine" and b) with seawall (from Winterwerp et al, 2020)*

*Wave run-up*
Wave run-up does not play a major rule in the interaction between mangroves and structures. However, there is a trade-off between wave run-up and wave reflection: any wave energy that is not dissipated will be conserved and therefore results in either reflection or run-up. Any measure that reduces wave reflection will, without additional dissipation of wave energy, lead to increased wave run-up.

*Wave overtopping*
When a conventional coastal defense structure (e.g. seawall) is used in combination with a fronting mangrove greenbelt, the significant wave height at the toe of the structure ($H_{m0}$) will be smaller due to dissipation of wave energy by the mangroves. This way, the mangrove vegetation can provide a significant portion of the reduction of wave overtopping that is traditionally provided by extra crest height. Consequently, a smaller crest height and width are required for the seawall. The seawall design criteria are thus relieved to the minimum necessary to prevent flooding during extreme water levels and structural (macro-stability) failure, potentially saving (substantial) construction costs.

Another implication is that the design lifetime of the seawall can be extended, as the upper range of wave heights at the toe of the structure are limited by applying the fronting vegetation (Hughes, 2008). Thus, a structure designed for a certain standard of protection can provide this functionality for a longer period, which may help saving substantial costs associated with upgrading the seawall along parts of the coastline where the structural condition of the seawall allows for this.

*Disconnected hydrology*
A common reason for mangrove degradation is disruption of the hydrology of the mangrove forest. The hydrodynamics by tides (saline water) and rivers (fresh water) determine the hydrological conditions, as well as inundation periods, which are essential for the health of a forest (Lewis, 2005). The construction of structures along the coast, rivers and creeks may block the influx of freshwater from the hinterland. Therefore, any engineering works constructed near mangrove forests must be designed to allow for sufficient exchanges with tides and riverine outflows.

# 3 Phenomenological Description of the Guyana Coastal System

This chapter provides an overview of the processes governing the historical morphological development and the hydrodynamics, as well as the land use and coastal protection measures implemented along the Guyana coastline to protect the hinterland. Seasonal variations in the wave climate and its impact on the mangrove establishment and growth are also expounded on, with a consideration of possible sea level rise scenarios. Guyana's poor sub-surface soil along the coast makes this zone prone to settlement. This exacerbates the relative sea level rise and increases the design height of the structures needed to protect the coastal hinterland.

## 3.1 Large Scale Dynamics of the Guyana Coastal System

The coast of Guyana is part of the 1600 km stretch of coastline between the Amazon and the Orinoco Rivers and has similar geographical attributes as the coasts of Suriname and French Guiana – we refer to the Guianas coastal system. This system has its primary sediment supply from the Amazon River. Figure 3.1 provides a summary of the sediment fluxes along the Guianas coastline. A portion of this sediment (52%), as indicated in Figure 3.1, is transported westward (alongshore) by a combination of currents and waves. The coastal area was shaped during four depositional phases separated by erosion cycles. The first phase is the Mara deposit phase and is older than 6000 years. It is followed by the Wanica phase which lasted from about 6000 to 3000 years B.P, the Moleson phase which extended from about 2500 years B.P. to 1300 B.P. and the Comowine phase which started between 2000 to 1300 years B.P. and is still ongoing. During the latter phase, the majority of these sediments were deposited at or near the mean sea level in intertidal, subtidal and occasionally supratidal environments, which provided space for the establishment of intertidal vegetation (Ginsburg & Missimer, 1976).

The westward alongshore transport from the Amazon occurs in a pattern of large wave-like mudbanks and in suspension the total transport of sediments is in the order of 150 - 200 Mton/yr (more details in Chapter 5). It is estimated that 50 - 100 Mton/yr is transported within a migrating mudbank, while the remainder can travel over distances further that a singular mudbank.

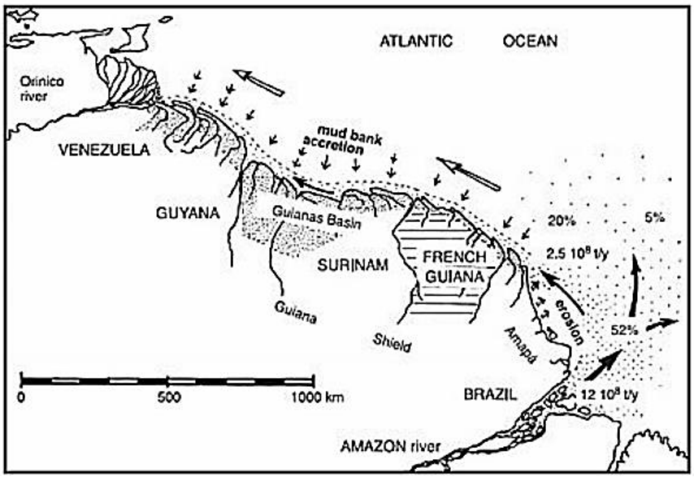


*Figure 3.1 Sketch of the Sediment Fluxes along the Guiana System (Parizanganeh, et al., 2008).*

The wavelength of these mudbanks varies from 25 - 50 km, with an approximate average of 40 km (Allison et al.,1995; Eisma et al., 1971). The shoreline and nearshore subtidal areas undergo rapid changes because the deposition along the Guiana Coast is cyclic, with the cycles averaging about 30 years. The period of erosion occurs during the inter-bank phase. These mudbanks travel along the coast at a rate of about 1 - 3 km per year. The passage of a mudbank is reflected by accretion, whereas between the mudbanks, the inter-bank phase, there is erosion.

## 3.2 Long-Term Behavior of the Guyana Coastline and the Mudbanks Along the Guyana Coastline

The (pristine) foreshore of Guyana consists of a shallow, intertidal area, covered with cohesive sediment (mud) and mangroves. The fertile coastal plain of Guyana is a comparatively narrow, low-lying area which consists of soft clayey soils, which very gently slopes down to the sea. It is below the level of the high-water (HWL). In addition to the soft clays, there are silts with some ridges of sand and shells. The oceanic coast is subject to the direct influence of the Atlantic Ocean and shows a pattern of cyclic erosion and accretion.

*Figure 3.2 Guyana's foreshore consisting of its shallow foreshore, intertidal area, covered with cohesive sediment (mud) and colonized by mangrove and salt marsh vegetation.*

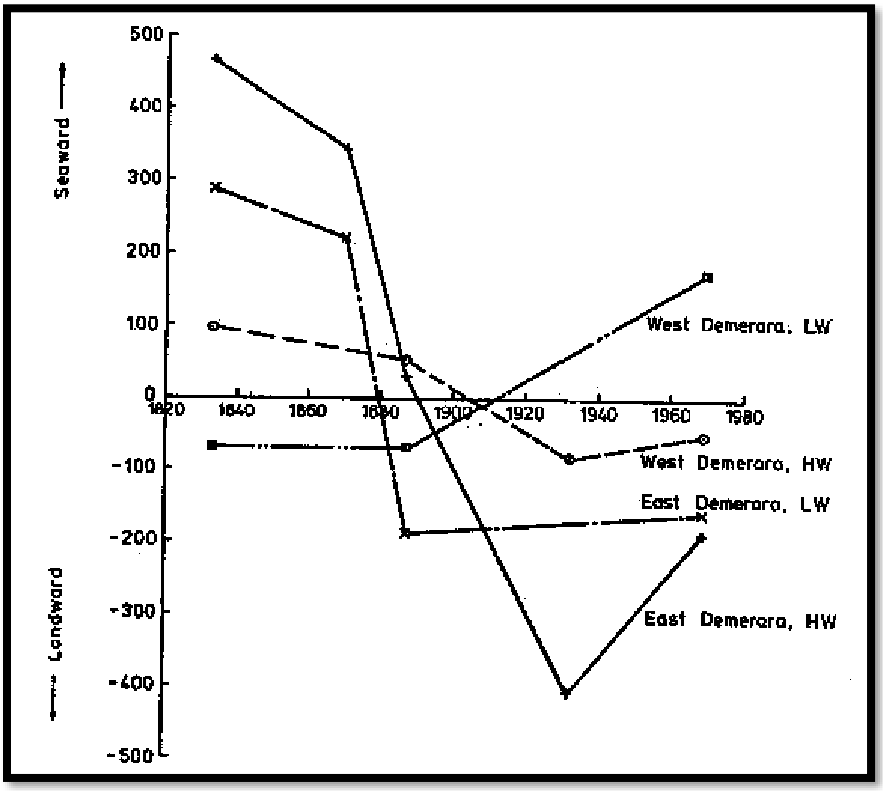


*Figure 3.3 Comparison of maps of West and East Demerara coasts of Guyana from 1833, 1870, 1870, 1890, 1932 and 1969. This summarizes the movement of the high and low water lines, where the x-axis shows the time and the y-axis shows the cross-shore movement (Abernethy, 1980).*

The NEDECO (1972) analysis concluded that during the past two centuries, there was a general regression of the Demerara East Coast at an approximate rate of 3.5 - 6 m/year. However, the research of Abernethy (1980) as shown in Figure 3.3, showed a rapidly evolving coast with no obvious trend in coastline retreat or advance. Between 1935 - 1940, historical records indicate that sea defences were constructed for the first time. The need for this venture was reflected in the extensive erosion along both the West and East coasts of Demerara starting around the end of the 19th century. We can conclude from Figure 3.3, that the structures were able to stop the rapid coastline loss, but periods of erosion continued, and were exacerbated during inter-bank periods. This suggests a relationship between the existence of the grey defences and the observed morphodynamic behaviour.

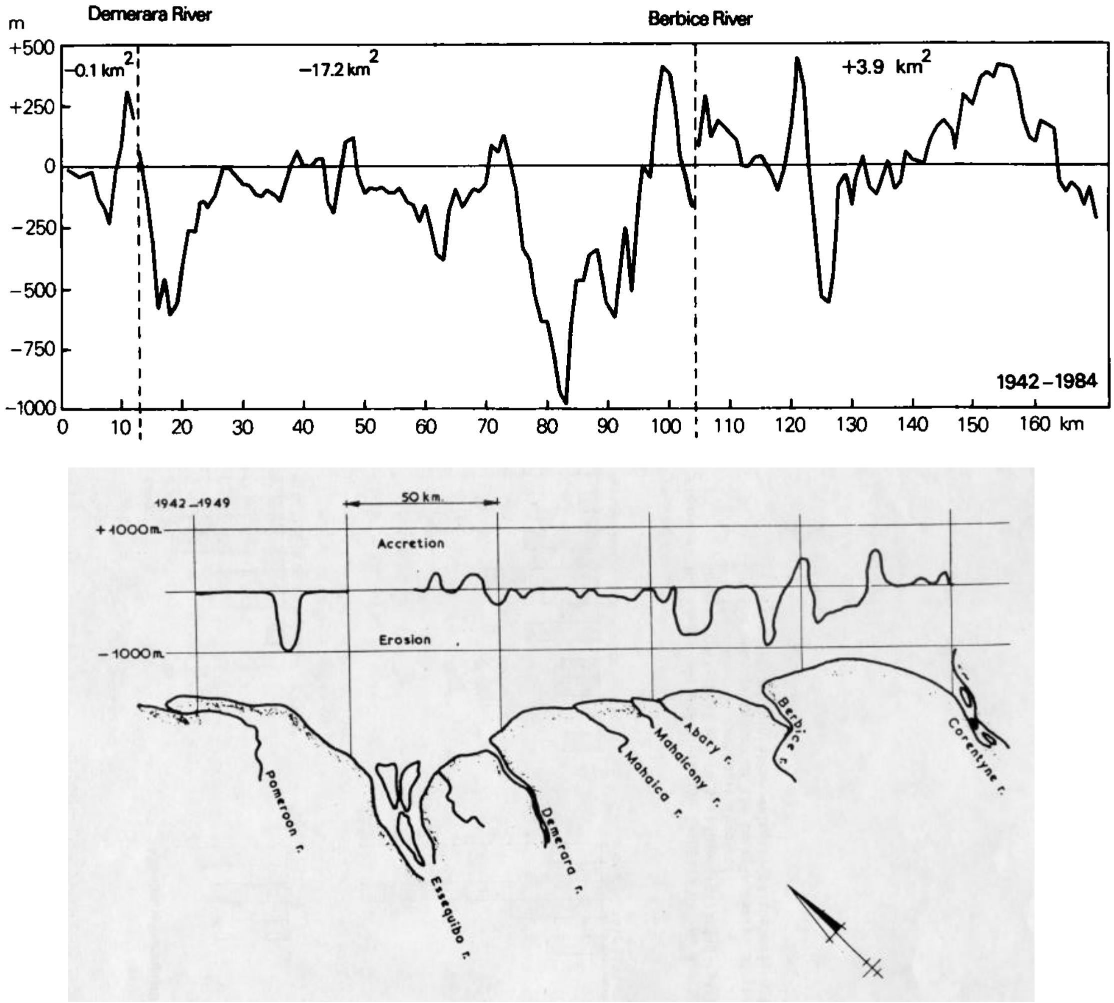


*Figure 3.4 The erosion-accretion balance for the Guyana coastline: (a) computed from aerial photographs from 1942- 1984 (Augustinus, et al., 1984)), (b) from NEDCO, 1972 analysis of the aerial photographs of 1942-1949.*

In Figure 3.4, the balance of accretion and erosion is given for the period 1942 - 1984 for the stretch between the Demerara River and the Berbice - Corentyne area. The largest displacements were seen along the eastern part of the coast (Demerara-Berbice) and this coastal stretch appears to be more dynamic than the western sections. This may be attributed to the transition from an oceanic coast to an estuarine coast at the mouth of the Essequibo River. However, no further explanation for this irregular behavior can be given at present and requires additional monitoring of the sedimentation patterns. Though the NEDECO (1972) report concluded on a regressive trend, we can see from Figure 3.4, that the local variations may be substantial, resulting in deviating rates of regression.

Coastline accretion occurs when a mudbank is located in front of a coastal section due to its sheltering and the damping effect of waves by soft mud. As a result of the moderate hydrodynamic conditions, a mangrove system is able to generate between a mudbank and the coast. Erosion of the coast occurs when a mudbank is not present in front of a coastal section and waves attack the coastline. Figure 3.5, shows the position of the emerging parts of the mudbanks for the respective years indicated. In this figure, the coastline is shifted perpendicular to the shore to facilitate visualization the measured migration speeds. The distance between the respective lines is proportional to the time elapsed. Over the period between 1942 - 1984, the five mudbanks which were observed consistently moved westward along the coast. There is much variability in the mudbank lengths ranging between 4.5 – 41 km with an average of 20 km. This impacts the sediment volume which is transported to the intertidal areas behind the mudbanks. Additionally, there is also variation in the migration rates ranging between 2.28 km/yr to -0.08 km/yr (moves in the eastward direction). However, for both the migration rate and the length, no obvious trends are observed for a certain period or types of coast (oceanic, transitional and estuarine). These variables are important for the sediment budget analysis of the system. For additional details on the considerations needed for the sediment budget, see Chapter 5.

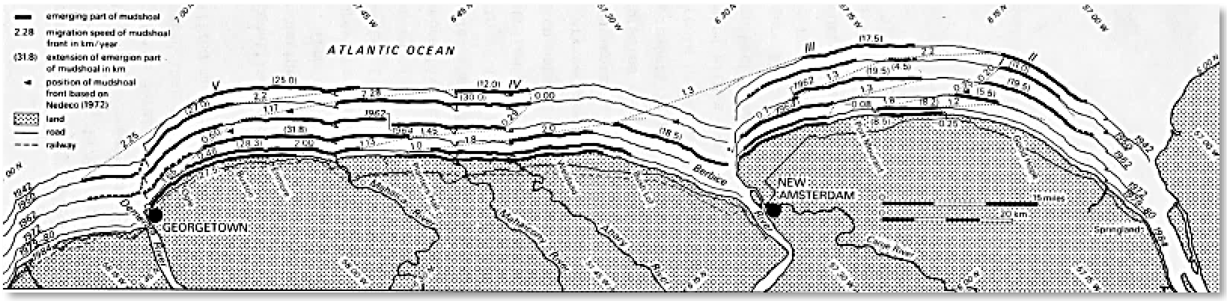


*Figure 3.5 Historical Mapping for the emerging parts of the mud-bank: locations, lengths and their migration speeds in 1942, 1950, 1962/1964, 1972/1975, 1979/1980 and 1984 (Augustinus et al 1984).*

## 3.3 Local Dynamics of the Nearshore Zones and Governing Processes

The Guyana coastal system contains large amounts of cohesive sediments, or mud. Suspended sediment concentrations in the coastal waters amount to a few 100 mg/l (NEDECO, 1972), which can be regarded as a high-concentration suspension close to capacity conditions, given the hydrodynamic conditions (Winterwerp and Van Kesteren, 2004). This implies strong vertical concentration gradients and a significant interaction between the suspended sediment and turbulence mixing, see Chapter 4. The sediment suspension is kept close to the coast by gravitational circulation in combination with the Trade Winds.

There are large tracts of mangrove vegetation along the Guyana coastal system, namely the *Rhizophora mangal* (red mangroves) which occupies soft, muddy soils especially near riverbanks (Parizanganeh, et al. 2008). *Avecennia germinans* (black mangrove) and *Laguncularia racemose* (white mangrove) are dominant along the coastal areas not affected by erosion and they border mangrove swamps along the coast. Figure 3.6 shows the spatial distribution of the vegetation species along the Chateau Margot area. *Avecennia germinans* has can rapidly colonize accreting shores.

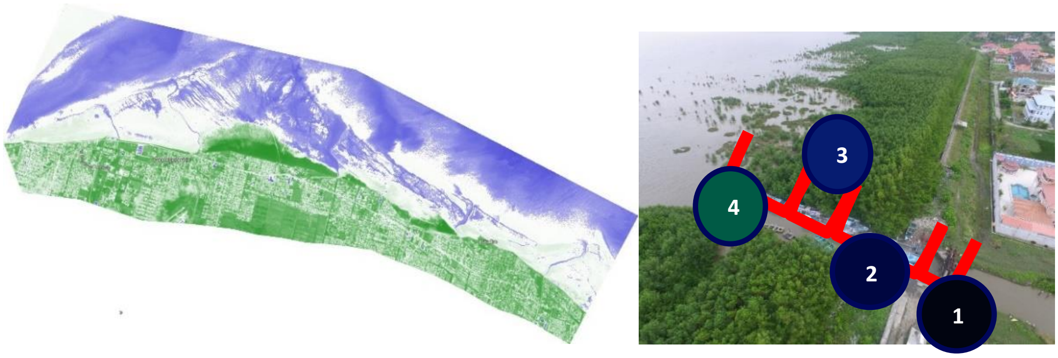


*Figure 3.6 Characteristic mangrove growth and species diversity along the Guyana coastline where, 1: Laguncularia racemose, 2: Rhizophora mangal, 3: Avicennia germinans, 4: Spartina alterniflora*

*Water levels*

The tide is mainly semi-diurnal with an average tidal range between 1.17 m during an average neap tide and 2.5 m during an average spring. Mean water levels along the coast show little variation. The difference between extreme water levels on the Essequibo West Coast and those on the Corentyne Coast (see Figure 3.12 for the locations) has never been higher than 0.46 m. The Guyana Coast is influenced by the Trade Winds; strong winds do not often occur and there are no tropical storms in the area. Therefore, deviations from the astronomical tide are small; the extreme water levels differ only between 0.15 m and 0.30 m from the astronomical extremes.

*Table 3.1 The amplitude for the main astronomical constituents for the tide station in Georgetown ICBA (2006)*

| Constituent | Amplitude (m) |
|---|---|
| $O_1$ | 0.09 |
| $K_1$ | 0.12 |
| $N_2$ | 0.18 |
| $M_2$ | 0.89 |
| $S_2$ | 0.29 |

The amplitude of the five main tidal constituents for Georgetown are given in Table 3.1. Figure 3.7 shows a prediction of the tidal water levels at Georgetown for a half-year period as well as the variation in the current direction with the water level over two weeks.

The propagation speed of the tidal wave is large in the deep Atlantic Ocean. As a result, tidal filling and emptying of the Guyana coastal system occurs more or less perpendicularly to the coast and the tide does hardly generate longshore currents. These cross-shore currents measure typically a few dm/s.

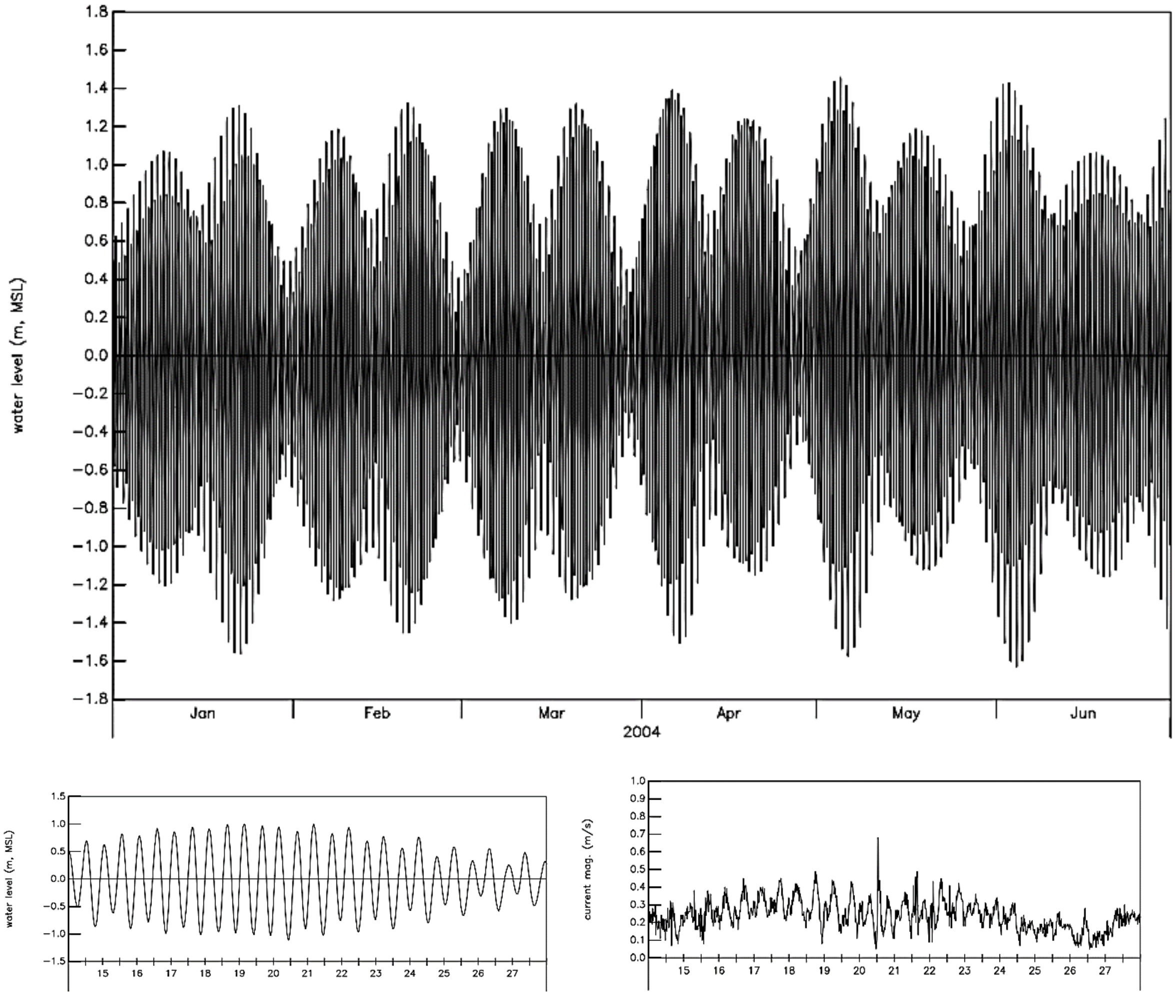


*Figure 3.7 The hydrodynamic conditions along the Guyana coastline where (top and bottom left) the variability in the water levels and (bottom right) currents are integral in the transport of sediments ((ICBA) 2006)*

*Currents*

The currents in the Guyana coastal system are driven by the tide, Trade Wind and to a lesser extent by waves. The alongshore currents induced by the Trade Winds are known as the Guiana Current, which can be regarded as a continuation of the South Equatorial Drift.

Figure 3.8 shows characteristic flow patterns of the Guyana Current. The measured currents have a magnitude between 0.1 and 0.5 m/s and a direction varying between 240 °N and 360 °N. With the tidal current and the Guyana Current having the same order of magnitude at these water depths (approximately 5 – 50 m), water particles (and consequently suspended sediment) follow a zig-zag pattern along the coast towards the North-west.

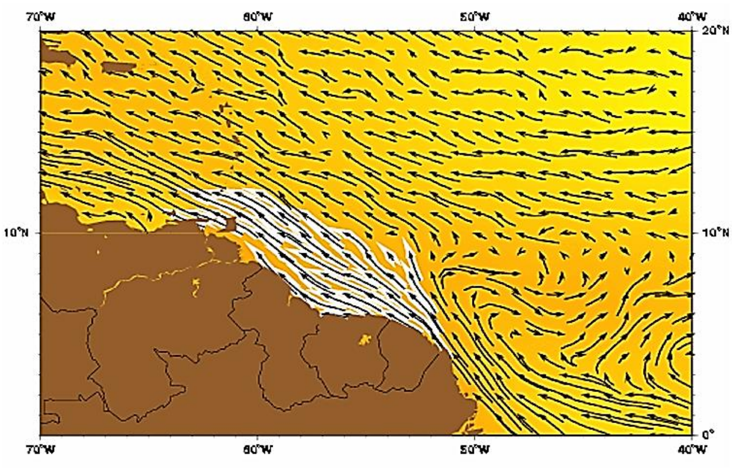


*Figure 3.8 Characteristic flow patterns of the Guyana Current (NEDECO 1972, Kjerve (http://oceancurrents.rsmas.miami.edu))*

*Wind*

During the wet season (June to August), temperatures are lower and temperature gradients are smaller, thus wind strength decreases. Hence, strongest winds occur in the period December – March/April between 3 - 8 m/s in a predominant northeast direction (this is depicted in Figure 3.9). Closer to the coast, sea-land breeze may generate some additional short waves close to the coast.

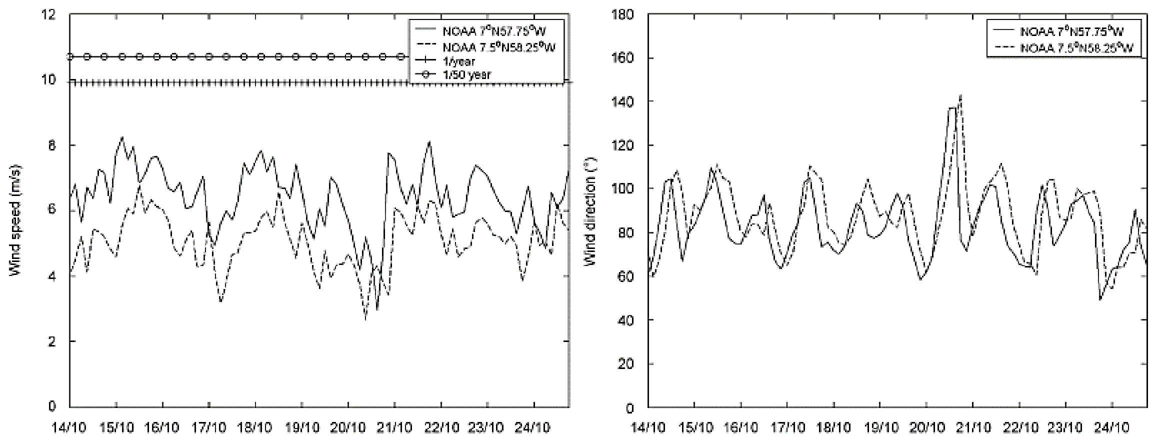


*Figure 3.9 Wind Speed and Direction over the month of October 2005 (NEDECO 1972).*

*Waves*

The offshore wave climate in Guyana is mainly determined by swell originating from storms in the Atlantic Ocean. Offshore, the contribution of the wind-generated waves is insignificant compared to the swell component. In the area of the mudbanks and in river mouths wind generated waves are dominant. The intensity of the wave action is highest from December to February and lowest around August and September and synchronizes with the Trade Winds (NEDECO, 1972). The waves are attenuated as they proceed to the coast; in inter-bank periods wave action on the coast can be fairly strong. The NEDECO (1972) report indicated that typical wave periods amount to about 8 seconds, yielding wave lengths in the order of 100 m. These values are typical for swell, e. the longer waves are not generated locally, but in the Atlantic Ocean. The observed average and maximum wave heights given in NEDECO (1972) are summarized in **Error! Reference source not found.** below.

*Table 3.2* Historical Wave Data presented at four locations along the coastal area of Guyana recorded between the years 1969 – 1971 (NEDECO 1972).

| **Data Location** | **Significant Wave Height (m)** | |
|---|---|---|
| | **Average** | **Maximum** |
| ***Offshore* (Ship observations, water depth = 25- 45m)** | 1.3 | 4.0 |
| ***Buxton* (Water Depth = 11m)** | 0.6 | 2.0 |
| ***Demerara Beacon* (Water Depth = 6.5m)** | 0.5 | 1.3 |
| ***Kitty Groyne* (Water Depth = 0.7m)** | 0.3 | 1.2 |

Close to the coast, the sea-land breeze may locally generate waves. Since these waves are not high (0.2 - 0.4 m) and develop into offshore direction, they do not have a significant effect on the stability of the mangrove-mud system. For additional information on the wave dampening capacity of mangroves, see Chapter 6.

The datasets presented here contain three types of wave data: data from measurements (OSSI, see its location in Figure 5.6 and the values in Figure 6.9), data from ERA5 reanalysis data (see Figure 3.11) and from NOAA Wave Models (Global and WNA). The NOAA wave data was validated against offshore AWAC measurements in 2004 by Royal Haskoning (2004a). It was concluded that the NOAA wave model provided a reliable source of offshore wave data. In Figure 3.10, the NOAA (point 8°N, 57.5°W) wave data for each available year (1998 -2002) is presented. Both figures show the seasonal variation of the wave height and period. Figure 3.11, shows the timeseries (yearly, 1980 – 2020) of the significant wave height and the significant wave period for three offshore locations (P1, P2 and P3) along the Guyana coastline.

From Figure 3.10, it can be concluded that the:
- Average offshore significant wave height varies between 1.25 m in July/August to about 2.0 – 2.25 m in December/January;
- Historical maximum offshore significant wave height is 4 m and occurred in December 1998.
- Overall mean significant wave height varies by +/-0.5 m during July/ August and increases to +/-1 m during the months of December to January.
- Average peak wave period varies between 6 s – 10 s with an average of 7.5 s.
- Peak wave period is fairly constant during July to August; but during September to April the offshore peak period can increase to 16 s. This was observed 3 – 5 times per year and may be attributed to tropical storms or hurricanes in the Atlantic Ocean or Caribbean Sea.
- Wave direction offshore varies between 45°N and 75 °N. During the months of May to August the wave direction is fairly constant with a shift from 75°N to about 45 °N;
- Wave direction originates from the North - North-easterly sector.

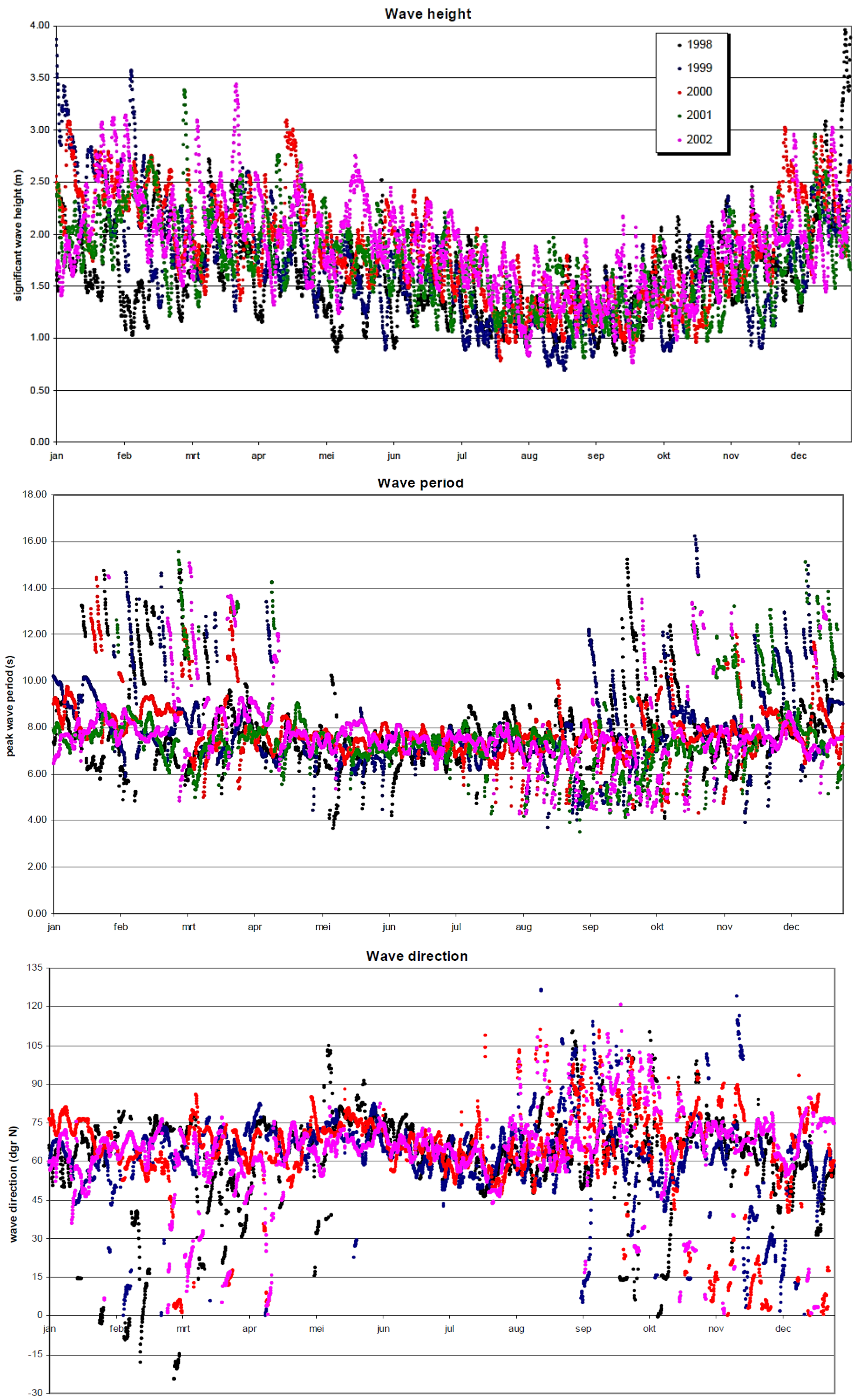


*Figure 3.10 Seasonal variation of NOAA (8°N, 57.5°W) wave height, period and direction during the years 1998 to 2002.*

*River discharge*
The Guianas coastal system is largely affected by the input of fresh water, which occurs at two scales. At the larger scale, the effects of the Amazon are important. Its freshwater discharge is so large that it affects almost the entire northern coast of South America. The freshwater plume is carried by the South Equatorial Drift and Guyana Current and kept close to the coast by the Trade Winds. The salinity within this plume in the Guyana coastal system varies from about 15 ppt close to the coast to about 20 ppt, 7 km offshore. As salinities further offshore attain oceanic levels, a pronounced cross-shore salinity gradient exists with dito gravitational circulation, which drives an offshore near-bed current, keeping fine suspended sediment close to the coast.

At a smaller scale, the sediment dynamics and coastal stability around the west-Demerara Guyana coast are affected by the outflow of the Essequibo, and to a lesser extent by the outflow of the Demerara. The east-Demerara Guyana coast is influenced to some extent by the Corentyne River and the Berbice River. See chapter 5 for additional details on the sediment load of the main rivers in Guyana. The combined annual average freshwater discharge of the upper Essequibo, the Mazaruni and Cuyuni Rivers (all flowing through the mouth of the Essequibo) is about 4100 $m^3/s$, with the largest monthly-averaged discharges in June and July (wet season) of 8700 $m^3/s$, and the lowest in November (dry season) of 1850 $m^3/s$ (Hydromet Office in Guyana (1965 - 1998)).

The Demerara River freshwater discharges are lower, with an annual average of about 75 $m^3/s$, a maximum monthly-averaged discharge in July of about 160 $m^3/s$ and minimum in November - March and particularly in December at about 35 $m^3/s$. For the Berbice River the same pattern is seen with an annual average of about 45 $m^3/s$. Both the Demerara and Berbice Rivers are characterised by a large variation in discharge throughout the year (see Table 3.3). The difference in discharge characteristics affects the salinity intrusion in the respective estuary/river systems.

The salinity front in the rives moves with the ebb- and flood tidal currents; its location and degree of stratification depend on the tidal phase (neap – spring) as well as the river discharge. Where fresh and saline water meet, an estuarine turbidity maximum is found. The estuarine turbidity maximum of the Essequibo River is found well off the Guyana coastline as a result of its large discharges. At sea, the water column is likely rather salinity stratified, owning to small flow velocities.

*Table 3.3 Fresh water discharges of main rivers in Guyana*

| River/estuary | Annual average discharge ($m^3/s$) | Monthly-averaged discharge | |
|---|---|---|---|
| | | Wet season ($m^3/s$) | Dry season ($m^3/s$) |
| **Essequibo** | 4100 +/- 1000 | 8700 +/- 2400 | 1850 +/- 750 |
| **Demerara** | 75 +/- 25 | 160 +/- 60 | 35 +/- 15 |
| **Berbice** | 45 +/- 40 | 125 +/- 115 | 15 +/- 10 |

## 3.4 Sediment Source and Composition

The Guyana coast is a low-lying coastal plain of marshes and ridges and is below sea level during high tide. A concise overview of the history and geological setting of the Guianas coastal system can be found in e.g. Nedeco (1972); Augustinus et al. (1989); Plaziat and Augustinus (2004). The coastal plain consists of residues of deeply weathered Precambrian rocks, while within the coastal plain there are four principal outcrops of sediments, as depicted in Figure 3.12:

- Berbice sediments of terrestrial origin deposited in the Pliocene epoch (>10 million years ago),
- Corpina sediments of marine origin, deposited during the Pleistocene epoch (>1 million years ago),
- Demerara sediments of marine origin, deposited during the Holocene epoch (<12,000 years ago),
- Pegassee or peat sediments that have been deposited in the transitional zone between the Demerara and Corpina sediments (6,300 – 8,700 years ago).

Deposits of fine sediment have a thickness ranging between 300 m west of the Essequibo River up to 1800 m near New Amsterdam. These sediments consist of fine colloidal clays ("Demerara clay") with sand and sand/clay strata.

Recent (Holocene) deposits consist of several tens of metres low- to well-consolidated mud, both in the coastal plain and in the coastal region. Moreover, due to drainage and natural consolidation processes, the coastal plain is expected to subside (note that drainage works were initiated by the first settlers in the 17$^{th}$ century).

Most of the fine cohesive sediment (mud) in the Guianas coastal system originates from the Amazon River. There are two indications for this:
- The Guianas rivers carry little fine sediment as their catchment consists of very old pre-Cambrium structures which hardly erode (Allison and Lee, 2004 report suspended fine sediment values in the Guiana Rivers of 1 – 10 mg/L),
- The composition of the sediment in the Guyana coastal area matches very well with the composition of Amazon sediments. These clay fractions consist mainly of illite (30 – 55%), kaolinite (20 – 25%) and some chlorite (10 – 15%), e.g. Nedeco (1972). The fine sands have a chemical fingerprint of Amazon sediments also (Augustinus, 1978).

As such, the Guyana coastal system can be regarded as part of the larger Amazon delta with extensive old and recent fine sediment deposits, as elaborated by Plaziat and Augustinus (2004). More recent publications (Martinez et al., 2009) estimate the mean total annual fine sediment supply by the Amazon River at about $8{\cdot}10^8$ ton/year, about 20% of which would be deflected to the North, entering the Guianas coastal system (Plaziat and Augustinus, 2004). About 40% of that load is stored in the migrating mudbanks (Eisma et al., 1971, 1991), hence about 100 Mton should be transported in suspension along the coast. Though these numbers have not been updated recently, and may be off considerably, they imply that large amounts of fines are likely to be transported in suspension along the coast (see also Chapter 5).

Along the whole coast the subsoil consists of soft clay layers resting on a stiff, over-consolidated substrate known as the coropina clay. The thickness of the soft clay layer varies, but is mostly over 9 m. Locally some layers, lenses or inclusions of sand occur, and at a few places some organic matter, known as Pegasse peat, is found. In the soft layers a cohesion value of 34 kPa and an angle of internal friction of 13.5° has been found. In the sandy layers the angle of internal friction was generally a little over 30°. These soil characteristics prohibit the construction of very high embankments. Because of the possible scour in front of a sea-wall, the high-water levels and the strong wave action which may occur, stability requirements should be carefully related to hydraulic requirements. Allowance must be made for the settlement of the seawall which will occur in the course of time (See section 3.5 for sea level rise implications).

Though the wave climate in the Guyana coastal zone is moderate, the waves are long and have a considerable effect on the sediment dynamics. The waves prevent sediments to settle and remobilise deposits that are formed under quiet conditions. During the rising tide, flood currents carry fine sediment towards the coast, feeding the mangrove coastal system. Distinction should be made between the longer waves, which are generated away from Guyana coastal system (swell) and shorter, locally generated waves. Both may reach and subsequently attack and damage the (mangrove) coastline. Both, however, will also mobilise fine sediment from the seabed located offshore from the mangrove forests, which then becomes available to supplement the mangrove-mud coastal system.

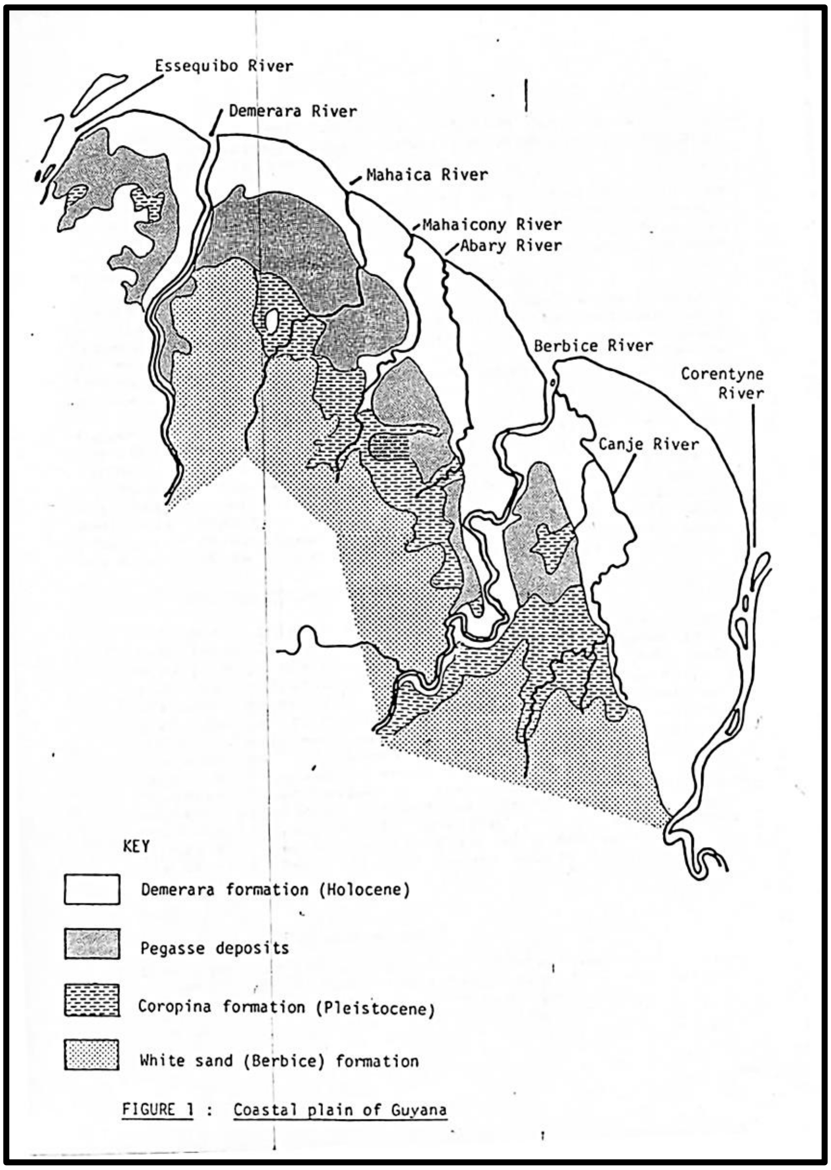


*Figure 3.11 The sediment variation along the coastal plain of Guyana (Augustinus, 1978).*

Sandy material is rather rare in this mud dominated environment. Locally small quantities are delivered by some large rivers, such as the Corentyne River and the Essequibo River. In addition, some dark coloured very fine sand originating from the Amazon River may be dispersed along the coast (Augustinus, 1978). As a result of the erosion of mudflats it is "washed out" of the muddy sediments.

At locations, cheniers are found along the coastline, in particular along the east coasts of French Guiana, Suriname and Guyana. Cheniers are sand lenses atop an otherwise muddy substrate (see below). This sand is mainly carried by local rivers, e.g. the Oyapock, Approuague and Sinamary Rivers in French Guiana, the Marowijne or Maroni/Mana River along the border between French Guiana and Suriname, the Corantijne or Courantyne along the border between Suriname and Guyana, and the Essequibo River in Guyana. Sand is also carried with the Amazon plume, washed out along its trajectory, but volumes are small, and that sand is very fine.

Because of the north-western transport of sediments along the coast, there are three distinct landscapes which develop: mud accretionary coasts, sand accretionary coasts and erosional coasts. The mud accretionary and the erosional coasts are more common in Guyana due to the limited amount of sand and shell available, which are currently only transported by the Berbice and Essequibo rivers. The coastal accretion and retreat provide an important temporary source/sink of fine sediment, as is elaborated in Section 4.3 and Chapter 5.

## 3.5 Sea Level Rise

The existing vulnerability of this coast is further exacerbated when the projections of future sea-level rise are considered (Warrick et al., 1996; Church et al., 2001). Historic relative sea-level rise at the coastline was determined at 5.1 mm/yr, based on linear extrapolation of sea-level data available from 1960-1981. This value is comparable to those determined from previous studies and, corresponds somewhat to the regional sea-level rise of approximately 3 mm/yr (Hendry,1993; Rull et al., 1999; Martin et al., 2003).

Tide-gauge records for the period 1951 to 1979 indicate a mean sea level rise in Guyana in excess of 10 mm/ yr. This rate of increase is approximately 2 to 5 times faster than the estimated global average of 2 to 4 mm/yr. (Douglas, 1995 and Smith et al., 1999). This suggests that an additional factor maybe operating on Guyana’s coast, e.  not only is the sea level rising but also the land level is sinking. One hypothesis (World Bank, 2007) is that the mainland, e.  the Guyana Shield, is affected by subsidence. Due to this subsidence, sea level rise values differ quite strongly from the average global estimates of 2 to 4 mm/yr in the first half of the 21st century, and of 3 to 6 mm/yr in the second half. With the exemption of mild approximation used by Dalrymple et al., (2006) of 2.1 mm/yr, studies with definite values on the rate of subsidence could not be ascertained during this project.

Modelling conducted to predict climate change for Guyana’s initial National Communication in response to its commitments to the UNFCCC (2000) and National Vulnerability Assessment to Sea Level Rise (2002) established the net change in sea level from 1951 to 2005 at approximately 55 cm and corresponds to the 10 mm/y. estimate from the tide gauges. Sea level is projected to rise in Guyana by about another 40 – 60 cm by the end of the twenty-first century.
Further, the projections from the Intergovernmental Panel on Climate Change (IPCC) indicates an increase ranging from 0.6 m – 1.0 m in the mean global sea level by the year 2100. Global sea level rise projections as well as the projected increase in sea level for the three scenarios (with a 1990 baseline) are shown in Table 3.4.

These values provide preliminary guidance on the likelihood and impact of overtopping of seawalls, flood frequency and inundation extent, coastal vegetation losses and the degree of erosion.

*Table 3.4 Projections of sea-level rise for study areas (2021-2065), (Dalrymple et al., 2006; Pachauri et al., 2014)*

| Global absolute Sea Level Projection - IPCC (mm/yr) | Relative Sea Level Increase since 1990 in Guyana (mm) |
|---|---|
| 2.8 | 348 |
| 4.0 | 400 |
| 5.0 | 444 |
| 6.3 | 502 |

Regular measurements and monitoring are required to properly establish the baseline for sea level rise in Guyana. Sea level rise baseline data collection should be a priority in terms of impact mitigation. Particularly relevant to Guyana is the possible effect on sea level rise related to the subsidence of the Guyana Shield.

Guyana's poor sub-surface soil (e.g. compressive strength and bearing capacity) along the coast makes this zone further prone to settlement. This exacerbates the relative sea level rise, thus increasing the design height of the structures needed to protect the coastal hinterland. The poor soil bearing capacity also dictates that there is a limitation on the type of structures that can be built and their design dimensions.

Furthermore, existing mangrove fringes along the coast are also at risk from sea-level rise. In their natural state, most halophytic (salt-tolerant) coastal vegetation such as mangroves are anticipated to move landward following a zonation pattern based on the salinity gradient in response to a sea-level rise (Sieh and Lee, 1990). However, the presence of permanent protection measures anchors the landward edge of the mangroves and has deprived the mangroves of this possibility of migration. Moreover, the mangrove clearance for human settlements exacerbates the problem. In the event of a rising sea level, there will be increasing pressures on the mangrove buffer.

# 4 Mud Banks: Migration and Sediment Dynamics

## 4.1 Key Messages

Sediment Dynamics in the Guyana coastal system:

- The Guyana coastal system is part of the larger Amazon delta, from Cabo Cassipore (Brazil) and the Orinoco River (Venezuela), a stretch of about 1500 km. We refer to the Guianas coastal system, sub-divided in French Guiana, Suriname and Guyana.
- The sediment in the Guianas coastal waters consists mainly of silt and clay. The majority stems from the Amazon River and is carried in suspension and in the form of migrating mudbanks along the coastline.
- The suspended sediment concentration typically measures a few 100 mg/L, though locally much larger, and sediments are carried by the tidal flow, the Guiana Current and fresh water induced gravitational circulation in a zig-zag path from Southeast to Northwest. This suspension provides the background fine sediment load in the coastal waters. Local rivers do not add many fines to the Amazon load.

Characterization of mud banks:

- The mud banks are large, with lengths of several 10 kilometer, about 5 – 10 m thick stretching out to the 10 – 12, or even 20 m isobath, hence are some 10 – 20 km wide.
- At any time, there are 15 – 25 mudbanks along the Guianas coast. In between the banks, one refers to interbank areas. Over a year, the banks migrate about 1 – 3 km during episodic events – migrations speeds are fairly irregular, though. The cyclicity of the mudbanks is therefore several decades – this is the time scale of the natural processes.
- The windward (southeastern) side of a bank is eroded by large waves, and the eroded sediment, mixed with the background sediment load may form fluid mud layers at the banks leeward (northwestern) side. These layers are pushed to the coast by streaming induced by the waves dissipating over the fluid mud.
- Thus, large volumes of soft mud are deposited against the shoreline during such events. The streaming component in the water column may also bring large volumes of sediment-laden water to the shore, depositing at the foot and behind the mudbanks. When high and stiff enough, these deposits may be colonized rapidly by mangroves, in case of an abundancy of propagules. During its presence, the coastline may prograde by hundreds of meters to about a kilometer behind a mudbank.

Coastal response to mudbank migration:

- Wave conditions behind the mudbanks are fairly mild, creating calm water habitat for mangroves.
- The interbank area is characterized by a cross-shore concave-up bed profile and ocean waves can penetrate towards the shoreline. The interbank areas are therefore erosive, and pristine mangrove forest may retreat by many 100 m up to a kilometer.
- Flood defenses, such as embankments and seawalls will of course prevent such retreat. However, such embankments create unfavorable conditions for the restoration of mangrove habitat owing to the reflection of the incoming waves.
- Mangrove recruitment behind mudbanks in front of reflective embankments is therefore rare; the current large mudbank (Chateau Margot mudbank) with massive mangrove recruitment close to Georgetown is exceptional, likely formed during exceptional hydro-sedimentological conditions.

The role of cheniers:

- The coastline at some inter-bank areas contains cheniers, thin lenses of sand atop an otherwise muddy substrate. These cheniers migrate to the West by classical wave-driven alongshore sand transport.
- Some very fine sand is carried with the Amazon sediment load. However, the majority of sand stems from some local rivers.
- In pristine areas, these cheniers play an important role in the coastal dynamics because of their stabilizing role.

## 4.2 Suspended Sediment Load

The Guianas coastal system is extremely turbid. As mentioned in section 3.4, the responsible fines originate from the Amazon River. However, on their path along the coast, a large quantity of these fines is temporarily stored in mudbanks and through coastal accretion (Section 4.3). During migration and erosion of the coastline, large quantities of fines are released again – note that these may have been stored for any time between a few hours and many hundreds of years. As a result, the suspended fine sediment concentrations in the Guianas coastal zone exhibit large variations, both spatially and over time. However, all literature reports suspended fine sediment concentrations up to a few 100 mg/L, e.g. Nedeco (1972): several 100 mg/L; Allison and Lee (2004): 100 – 300 mg/L; Froidefond et al. (2004): < 300 mg/L, while Abascal-Zorilla (2020) measured suspended fine sediment concentration in the vicinity or the Marowijne/Maroni River and its estuarine turbidity maximum of 50 – 500 mg/L. Lacking sufficient data, in the following we presume a background suspended fine sediment concentration of 50 – 100 mg/L, e. a mean concentration of fines in the Guianas coastal zone, which is supposed to be always present. Though rather speculative, the exact value of this background concentration is not critical for the reasoning below.

The maximum suspended fine sediment concentration in the Guianas coastal waters is limited by the so-called carrying capacity of the turbulent water flow (e.g. Winterwerp, 2001; Winterwerp et al., 2021). This carrying capacity can be characterized by the so-called saturation concentration $C_S$, which is a function of the settling velocity of the mud flocs in the water column, and of water depth and flow velocity:

$$C_s = K_s \frac{\rho_w}{\Delta} \frac{U^3}{g h w_s} \tag{4.1}$$

where $\rho_w$ and $\rho_s$ are densities of water and sediment, $\Delta$ is the relative sediment density ($\Delta = (\rho_s - \rho_w)/\rho_w$), $U$ is the characteristic flow velocity, $g$ is the acceleration of gravity, $h$ is the water depth, $w_s$ is the settling velocity of sediment particles, and $K_s$ is an empirical coefficient ($K_s \approx 1.4 \cdot 10^{-4}$, see Winterwerp, 2001; 2006). For water depths between 2 and 10 m, settling velocities are between 0.2 and 0.5 mm/s (Gratiot and Anthony, 2016 report values $w_s < 0.2$ mm/s), and a characteristic flow velocity of 0.5 m/s, we find $C_s$ = 200 – 500 mg/L. This implies that if the suspended fine sediment concentration would increase by e.g. wave-induced erosion, the turbulent flow can no longer mix the sediment over the vertical, the sediment settles out fast, and fluid mud is formed (a process referred to as auto-saturation in Winterwerp, 2001 and Winterwerp et al., 2021). This has important consequences for the sediment dynamics in the Guianas coastal zone, as discussed below.

Sediment particles in suspension follow a zig-zag path, as sketched in Figure 4.7. This path is driven by three agents: the coast-perpendicular tidal velocities, the alongshore Guiana Current and gravitational circulation induced by the cross-shore salinity gradients, as explained in Chapter 3.

## 4.3 Phenomenological Description of Mudbanks

The seabed between Cabo Cassipore (Brazil) and the Orinoco River (Venezuela), a stretch of about 1500 km, consists of a large series of mudbanks (Figure 4.1a). At any time, some 15 – 25 larger and smaller mudbanks can be found (Anthony et al., 2010). These were first studied by Delft Hydraulics Laboratory (1962); their behaviour has been analysed in detail by e.g. Nedeco (1972); Augustinus (1978); Allison and Lee (2004); and Anthony et al. (2010). The mudbanks have typical longshore dimensions of several 10s of kilometres, from about 30 km some six decades back, to up to 60 km in Suriname at the end of the 20th century, while reducing since then again (Augustinus, 2004). They stretch out to the 10 – 12 m isobath (Anthony et al. 2010) to the 20 m isobath in Suriname and Guyana (Augustinus (1978) and Nedeco (1972)), and thus are 10 – 20 km wide. The banks may have a thickness of 5 – 10 m. The volume of each mud bank can contain the equivalent of the annual mud supply of the Amazon River (i.e., 750 to 800×$10^6$ tons; Anthony et al., 2010). The mudbanks, e. their crests, are more or less orientated towards the direction of the Trade Winds, thus more or less NE, and therefore their orientation w.r.t. the shoreline varies along the Guianas. This implies that the apparent length of the mudbanks along the shoreline varies as well.

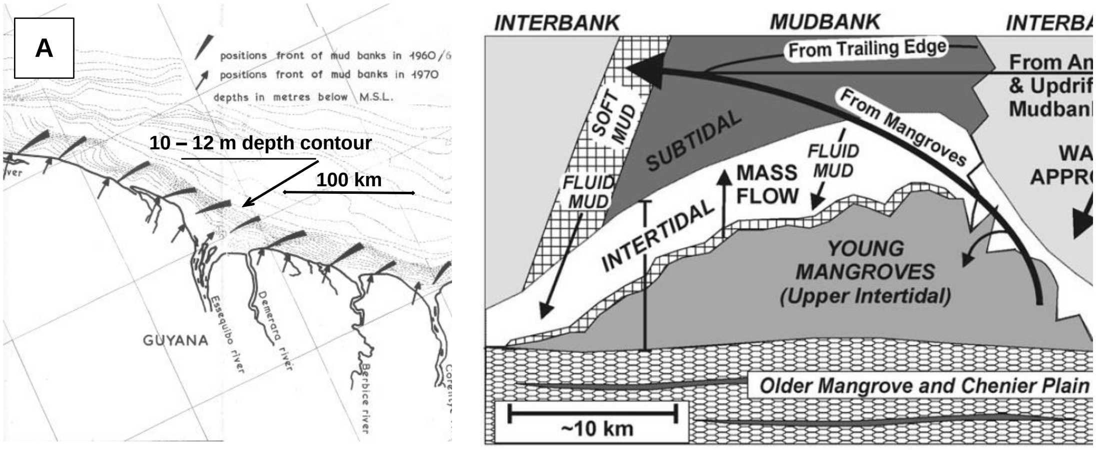


*Figure 4.1 Location of mudbanks in 1960; arrows indicate their location in 1972 (panel A, Nedeco, 1972), and schematic of mudbank composition (panel B, after Allison and Lee, 2004).*

Figure 4.1b presents a schematic of the inner part of a mudbank, as proposed by Allison and Lee (2004), which picture is generally accepted today. The mudbank is disconnected from the shore and sediment reaches the upper intertidal zone (thereby leading to shoreline accretion) as (fluid) muds transported onshore during periods of coastal setup and flood tide. Some of this sediment may be transported back offshore during falling tide and/or as mass flows. Arrows reflect the relative magnitude of sediment supply to the leading-edge deposition on the inner mudbank. The largest quantity is derived from erosion of the trailing edge mangrove fringe, with additional material coming from erosion of the trailing edge mudflat and interbank intertidal–subtidal surface, and from updrift mudbanks and the Amazon River. An important aspect of the latter picture is the proposition that the mud banks are not shore-attached. Between the mudbanks and the shore, pools of soft/fluid mud can be formed, as depicted in Figure 4.1 (right panel) and 4.3.

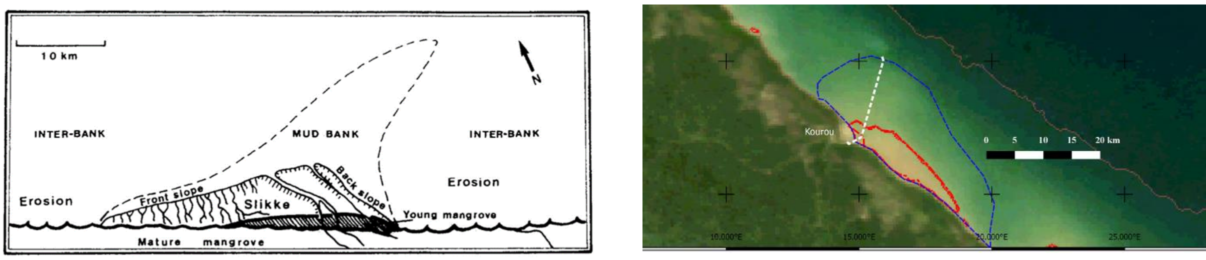


*Figure 4.2 left panel: Schematic diagram of subtidal and intertidal mudbank, and coastal accretion with mangrov colonization (Froidefont et al., 1988); right panel: satellite image near Kourou (French Guiana) with visible mudflat (red linec and estimated extension of entire mudbank complex.*

The aerial photograph of Figure 4.3 shows part of an emerging mudbank along the Guyana coast, clearly detached from the coast itself.

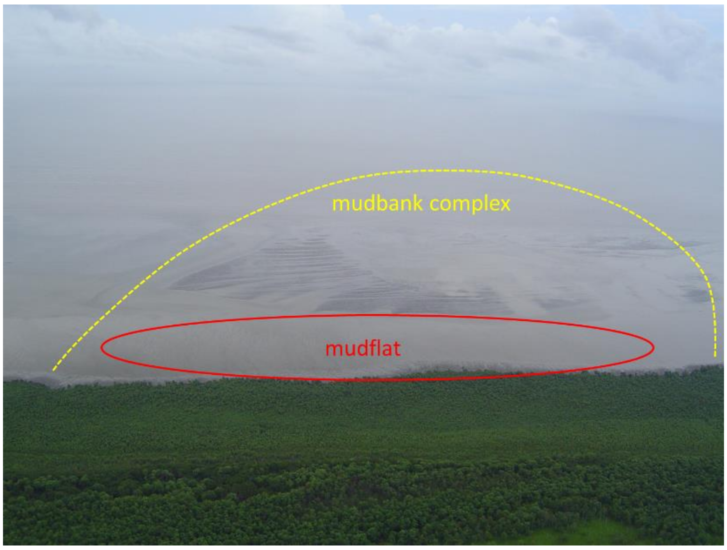


*Figure 4.3 Aerial photograph of mudbank in Guyana coastal system with detached mudbank and mudflat, e. the soft (fluid) mud in between the bank and shore (photo 2004).*

These observations are important for the current guidelines and arguments in this chapter, and we therefore introduce a distinction between mudbanks and mudflats, as illustrated in Figure 4.3:

| | |
|---|---|
| mudbank complex | generic term of entire mudbank complex, e. mudbank + mudflat |
| mudflat | visible, intertidal part of the mudbank complex, formed from fluid mud (see below), providing habitat for mangroves |
| mudbank | detached and submerged, mainly non-visible part of the mudbank complex. |

The area in between two mudbanks is referred to as the interbank area. Behind a mudbank, the hydrodynamic conditions (waves!) are mild, and the coastline can accrete, whilst the coastline of the interbank area is exposed directly to ocean waves – pristine coastlines then erode. This is illustrated in Figure 4.4 by Augustinus, showing pro- and degrading stretches of the coastline of Suriname by several hundred meters, up to one kilometer. In general, the Suriname coastline exhibits net accretion over longer periods, but alternated with periods of erosion/retreat. However, near Coronie and Paramaribo (at the mouth of the Suriname River), the coastline does not recover after a period of erosion. These stretches are characterized by anthropogenic interventions (polders with hard, reflective embankments) too close to shoreline.

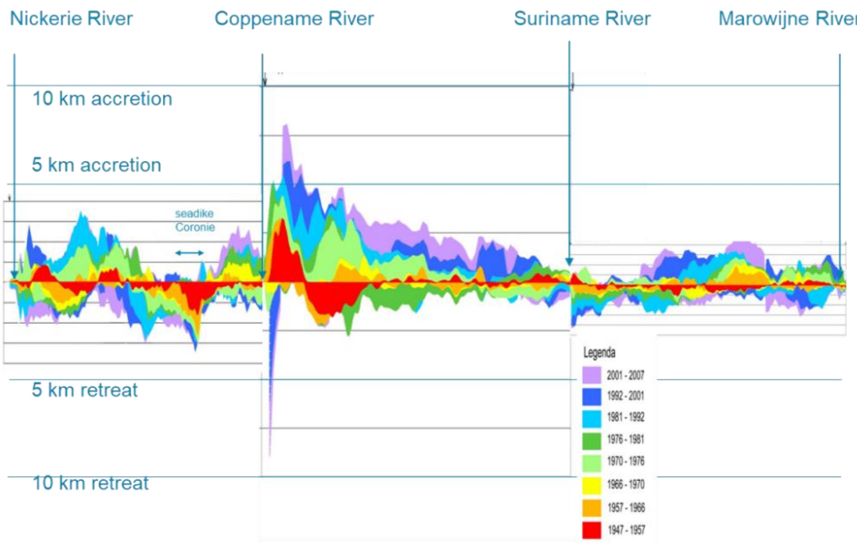


*Figure 4.4 Prograding and degrading of the Suriname coastline over eight periods of about 10 year each since 1947 – note spatial and temporal alterations (courtesy P. Augustinus).*

This is further illustrated in Figure 4.5 showing how the removal of mangroves and the construction of a seawall to protect the polder behind the coastline has disrupted the natural cycle of pro- and degrading of the coastline just east of the Marowijne/Maroni River (French Guiana, Brunier et al., 2019). Peak erosion rates up to 200 m/year were reported.

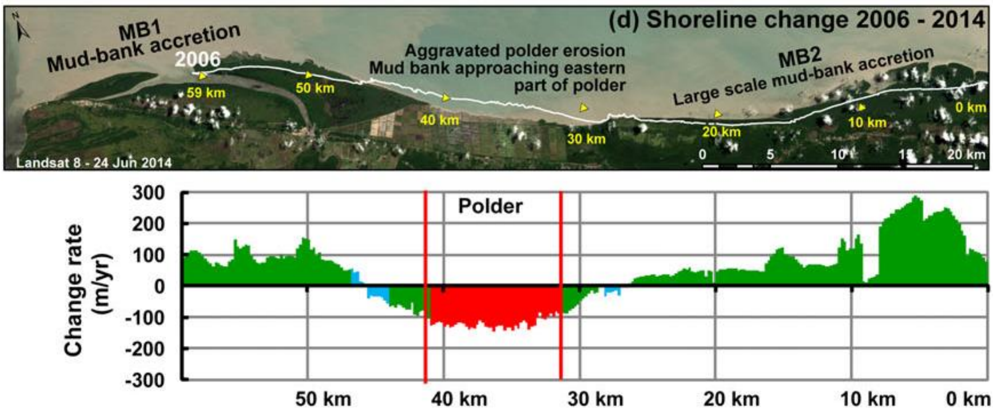


*Figure 4.5 Prograding and degrading coastal stretch in French Guiana (from Brunier et al. (2019).*

## 4.4 Migration of Mudbanks

There exists no mechanistic explanation for the generation of the mudbanks, nor for the processes which maintain their shape while eroding and migrating. However, there is no doubt that the mudbanks migrate, with observations as early as the 17th century. Though the migration velocities may vary (see below), migration speeds have been overall fairly constant, as shown in Figure 4.6, depicting data by Nedeco (1972). However, migration speeds are becoming more and more irregular, though the physics behind are not understood.

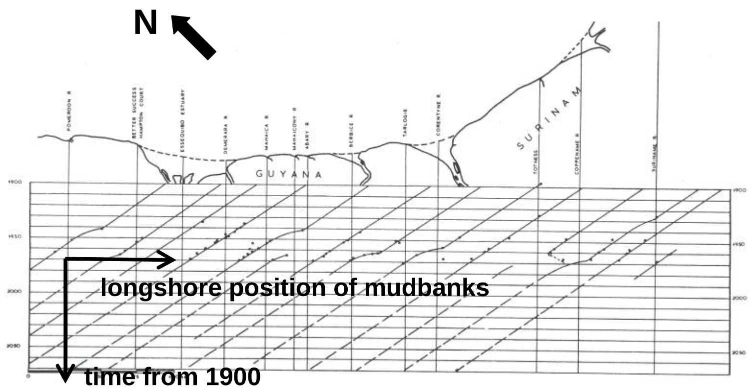


*Figure 4.6 x-t diagram of mudbank position along the Guyana and Suriname coastline between 1900 and 1970 (from Nedeco, 1972).*

Figure 4.5 suggests a yearly migration distance of about 1 – 3 km (periodicity of about 30 years). Augustinus (1978) observed that migration is correlated to stormy conditions, e. a few times per year, in particular in the period December – March. Hence, migration is event-driven. Augustinus (2004) found that during more easterly winds (i.e. ENE), migration speeds of the Suriname mudbanks increase, and banks become larger. This was the case in the 1950s – 1980s, with increasing wind speeds as well, whereas in the 1990s, NNE winds were more frequent, with smaller wind speeds. Similarly, Gardel and Gratiot (2005) found migration velocities of banks along the French Guiana coast of about 0.2 – 1.8 km/yr in the 1980s increasing to 1.8 – 3.0 km/yr in the period 1990 – 2005. Migration velocities increase with speed and more easterly direction of the wind. However, the wave climate is generally milder for more easterly winds.

Figure 4.7 presents a schematic diagram explaining the processes driving mudbank migration. This picture cannot be complete as it fails to explain how shape and volume of the mudbanks are maintained during migration. However, it provides the necessary background to elaborate on the local sediment dynamics in a qualitive way.

The main driver of mudbank migration is the waves. Generated by the Trade Winds, swell and sea waves both come from the NEN-ENE quadrant (Chapter 3) with offshore heights of 1 – 2 m and periods of 7 – 9 s, with the lower, shorter waves in May – September, and the higher and longer ones in November – February. Approaching the mudbanks, the waves are refracted towards the crest of the banks, which may explain their orientation. Applying Snell's law, refraction angles of a few 10 degrees at most are expected, as the mudbank slopes are very gentle. When energetic enough, these waves erode the mudbanks, certainly their windward side, and possibly also parts of their leeward side.

Sediments eroded at the windward side are carried in suspension by the zigzag currents, accelerating towards the crest of the mudbank, mixed with the background suspended fine sediment. During rising tide, suspended sediment is carried towards the coast by flow-induced advection. Beyond the mudbank crest, fines possibly eroded from the leeside contribute to this suspension. Beyond the crest of the mudbank, the flow decelerates, the suspension becomes stratified, forming a so-called High-Concentrated Mud Suspension (HCMS), which is characterized by a reduction by the suspended sediment in vertical turbulent mixing (e.g. Winterwerp, 2001; Winterwerp et al., 2021). HCMS is still a Newtonian fluid (no strength resulting from high suspended fine sediment concentrations) and can be transported by the turbulent flow. If suspended fine sediment concentrations become large enough, the HCMS can no longer be carried by the turbulent flow and fluid mud is formed (capacity conditions – see above). Such layers of fluid mud damp the incoming waves by viscous dissipation within the viscous fluid mud, as has been measured frequently (e.g. Wells and Kemp, 1986; Winterwerp et al., 2007).

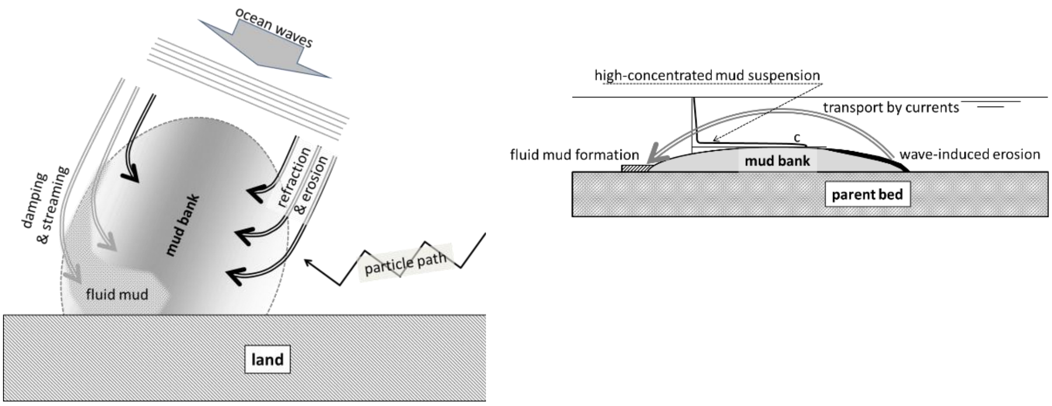


*Figure 4.7 Schematic of flows and waves around a mudbank and fine sediment transport (G. current = Guiana current; grav.circ. = gravitational circulation.*

In the direction of damping, the waves induce a stress on the mud, the so-called radiation stress, which induces a force in the direction of the waves. This process is known as “streaming”. It can be shown that the stresses induced by streaming in the water column are an order of magnitude larger than those in the fluid mud layer (e.g. Gade, 1958 and Winterwerp et al., 2021). The latter may become several 0.1 Pa, while those in the water column may reach several Pa. The stresses in the water column would induce a setup, which cannot be maintained though because of the lateral confinement of the fluid mud layers. Therefore, water flows off laterally in front of the shore, which is compensated by a coast-directed current of sediment-laden water. Thus, horizontal circulation cells are induced, similar to the well-known rip currents along sandy beaches. This is an efficient process, bringing large quantities of fines towards the coast, forming the soft/fluid mud layers found behind the mudbanks, as sketched in Figure 4.8. When damping rates are large, this onshore sediment flux may even exceed offshore directed currents during falling tide (Winterwerp et al., 2021).

The fluid mud layer itself is also pushed towards the coast. Though the streaming-induced stresses and subsequent transport velocities may be an order of magnitude smaller than those in the water column, the sediment flux itself may be large, owing to the large amounts of sediment in a fluid mud layer. Though the radiation stresses induce a body force, the fluid mud is sheared over its depth because of bottom friction. Pores in the mud are torn open, and pore water can escape. Hence during streaming, the fluid mud densifies, and may even become over-consolidated. When the radiation stresses become too small and/or the fluid mud to densified, the soft mud becomes stagnant.

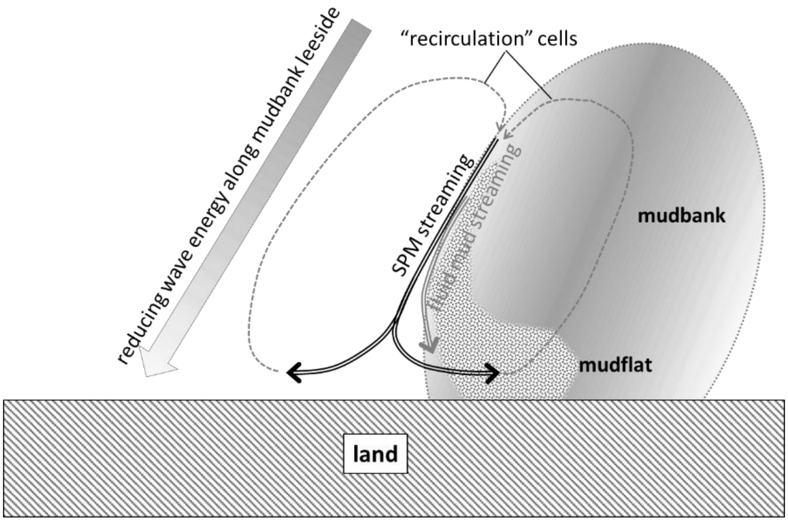


*Figure 4.8 Schematic of recirculation cells induced by wave-damping-induced streaming and resulting onshore flux of suspended fine sediment (SPM).*

In case waves do not erode enough sediment from the banks to form a saturated HCMS, fluid mud is not formed. However, waves are still damped, but at a smaller rate, and streaming-induced onshore sediment transports are small. In this case, advective transport by the rising tide is likely the dominant mechanism. In other words, during moderate wave conditions, when mudbank sediments are eroded, mudflats are built up, but at a smaller rate than during more extreme storm conditions.

The process of mudbank migration and subsequent formation of intertidal mudflats is therefore event-driven, and during one event large quantities of mud can be deposited on the shore. When these deposits are stiff and high enough, the mudflats colonized rapidly by mangroves (see below), though at some locations, colonization may take several years until habitat conditions are optimal. With respect to the design of Green-Grey Coastal Infrastructure, this implies that no interventions, such as sediment trapping structures, should be deployed at the leeward side of the mudbanks, as this would unfavorably affect the coast-building streaming processes.

*Table 4.1 Coastal response to wave regimes in the Guianas coastal waters.*

| | mild waves | moderate waves | strong waves |
|---|---|---|---|
| elevated sediment concentration | + | ++ | +++ |
| mud bank migration | | + | ++ |
| mudflat formation | | + | ++ |
| coastal erosion | + | ++ | +++ |

As the fine sediments are very soft, the interbank coastline is likely to be eroded by all waves, small to large. Hence it is likely that three wave regimes can be identified, as in Table 4.1. The transition between these regimes is not known quantitatively and is expected to vary with the tidal phase.

## 4.5 Response of Embanked Coasts to Mudbank Migration

As discussed above, the coastline behind a migrating mudbank can grow rapidly during storm events, forming mudflats. In the inter-bank areas, the same storm is likely to erode the coast. Smaller waves would also erode the coastline, as mud deposits are soft. Hence smaller waves only “take”, while the larger waves “give and take” (i.e. drive the formation of the mudflats), as identified in Table 4.1.

When conditions are favorable, i.e. the proper height and consistency of the mudflats, and availability of abundant seedlings, mangrove colonization can be fast (see Chapter 9). A deposited fluid mud resulting from streaming is already densified by shearing, and mangrove-favorable habitat may be available almost directly after a storm. However, when a fluid mud is formed from deposition by suspended fine sediment, sediments first need to consolidate which may take longer, but not longer than a few weeks before the mudbank surface is stiff enough to carry and anchor the mangrove juveniles.

To formulate the guidelines for Green-Grey Coastal Infrastructure, the question has to be addressed why land-use in general, and the erection of seawalls in particular do frustrate coastal accretion, as historically observed. This can be understood by comparing the wave dynamics along a pristine mangrove coastline and along an embanked coastline. Waves attacking a pristine mangrove coastline will be dissipated entirely within the forest, possibly partly eroding the coastline, resulting in its degradation (setback), as observed in the inter-bank areas in French Guiana and Suriname. This is sketched in Figure 4.9a. Such coastline erosion induces a concave-up bed profile, known from eroding intertidal areas, consistent with observations, theoretical analyses and numerical modeling.

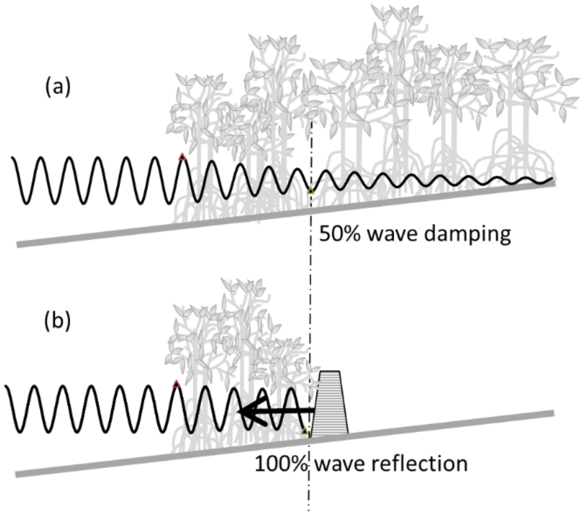


*Figure 4.9 Schematic of wave dissipation within mangrove forest (a) and after erection of an embankment within the forest, some distance from the shoreline (b) (Winterwerp et al., 2020).*

To elaborate on the illustration of section 2.5, suppose that at some distance from the shoreline an embankment is erected in the mangrove greenbelt, for instance to protect a polder behind (Figure 4.9b). Incoming waves are then reflected against this embankment. If this embankment would be set at a location where the mangrove were to dampen 50% of the incoming wave energy, and the reflection coefficient were 100%, incoming and reflecting wave together would form wave conditions identical to the undisturbed incoming wave. If the embankment were to be placed even closer to the original shoreline, wave heights within the forest would even be amplified with respect to the undisturbed incoming wave. Under those conditions wave-induced erosion rates will be larger in the back of mangrove forest than at the open waterfront.

This is further illustrated in the schematic of Figure 4.10, a coast without mangrove forest. Full reflection is then to be expected, forming a standing wave, doubling the wave height in case of 100% reflection. As the erosive stresses (bed shear stress $\tau_b$) scale with the wave height $H_s$ squared ($\tau_b \propto {H_s}^2$), these stresses would increase by a factor four. The result is massive erosion and deepening of the seabed in front of the embankment, as sketched in Figure 4.10. These erosion rates are much larger than in case of a pristine mangrove-mud coasts during interbank periods, yielding much larger depths. The larger depths allow further penetration of larger waves, initiating unfavorable feed-back between wave reflection, wave amplification, bed erosion and reduction of wave dissipation by bed friction.

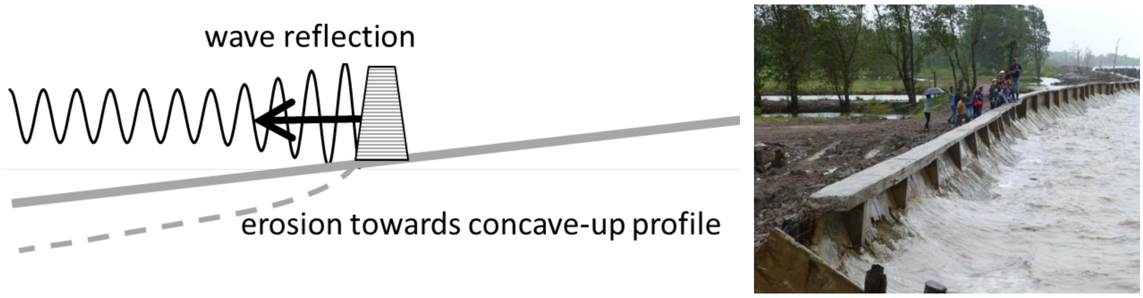


*Figure 4.10 Wave amplification by reflection, left panel: schematic, right panel photo in Suriname (Weg aan Zee, courtesy P. Augustinus).*

Wave amplification in from of the seawall influences transport from the mudbank to the coast in three ways:

1. Because of larger depths, larger quantities of sediment (fluid mud) are required to attain favorable heights of the mudflats for mangrove colonization (the mangrove habitat),
2. If fluid mud were to be transported to the foreshore, also the reflecting wave is damped by viscous dissipation. The resulting streaming, however, is now directed offshore, preventing transport of the fluid mud to the shore,
3. Sand is mobilized in front of the embankments by the larger waves, dispersed offshore, covering mudbanks (Augustinus, 2021 – personal communication).

We conclude that seawalls along the coast hamper the formation of mudflats, though the submerged, detached part of the mudbank complex, e. the mudbank, is still present, and migrate to the West at a distance of many 100 m from the coastline. In contrast, in the past, arrival of a mudbank always induced mudflat formation with local shoreline accretion with massive mangrove recruitment. In the case of Figure 4.9 conditions, only very large mud banks under very dynamic conditions will generate mudflats, inducing favorable habitat conditions for mangrove recruitment. Such conditions become exceptional i.e. infrequent. However, this is currently the case along the east coast of Guyana with a huge mudbank east of Georgetown. This is fortunate, and authorities should profit from this opportunity.

## 4.6 The Role of Cheniers

Cheniers are sand lenses atop an otherwise muddy substrate. In the Guianas coastal system, the sands mainly originate from local rivers, though some fine sand stems from sorting of Amazon derived sediment. The cheniers are formed along the coastline during interbank periods and migrate westwards by “classical littoral transport”, i.e. driven by the residuals of the wave forcing (Augustinus, 1989; Anthony et al., 2011). In the interbank areas, these cheniers form natural sea defenses, slowing down coastal erosion, while dissipating incoming wave energy largely.

Part of a chenier may be covered by fluid mud deposits during episodic events. The remaining downdrift chenier is then cut off from sand supply, thins and may breach, as in Figure 4.11. This process can only take place if large amounts of mud are deposited on the shore in short times, thus an indication for the event-driven migration of the mudbanks. Hence, a bit counter intuitive, breaching and inundations take place ahead of the migrating mudbank, and not behind.

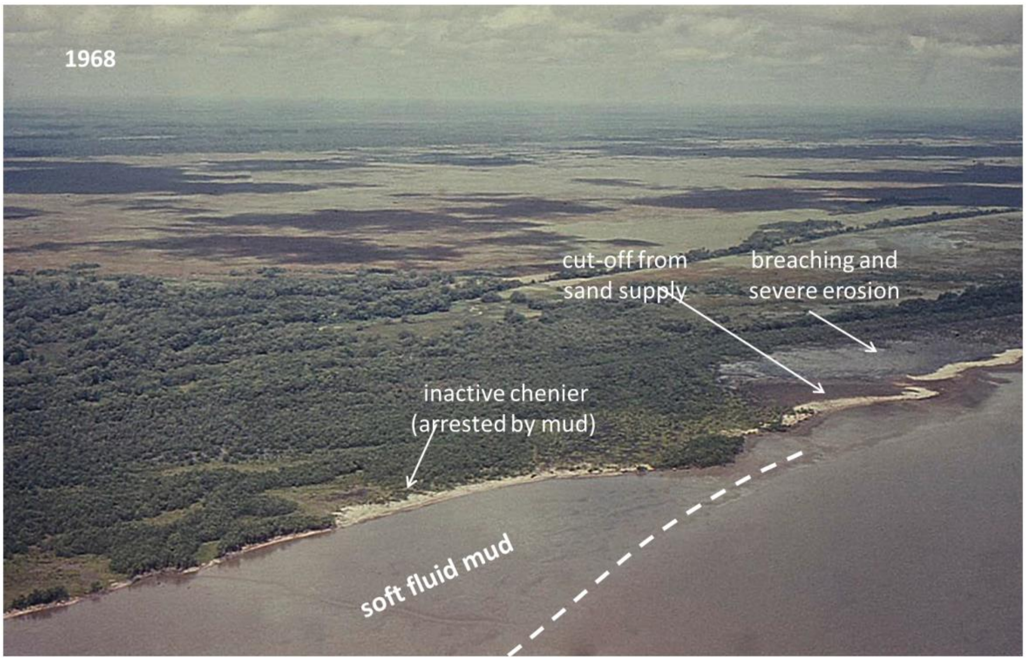


*Figure 4.11 Overtaken chenier, with subsequent breaching (courtesy P. Augustinus).*

The role of cheniers on coastal stability is further illustrated in Figure 4.12, showing the migration of a mudbank along the coast near De Kinderen, as indicated by the presence of breaking waves.

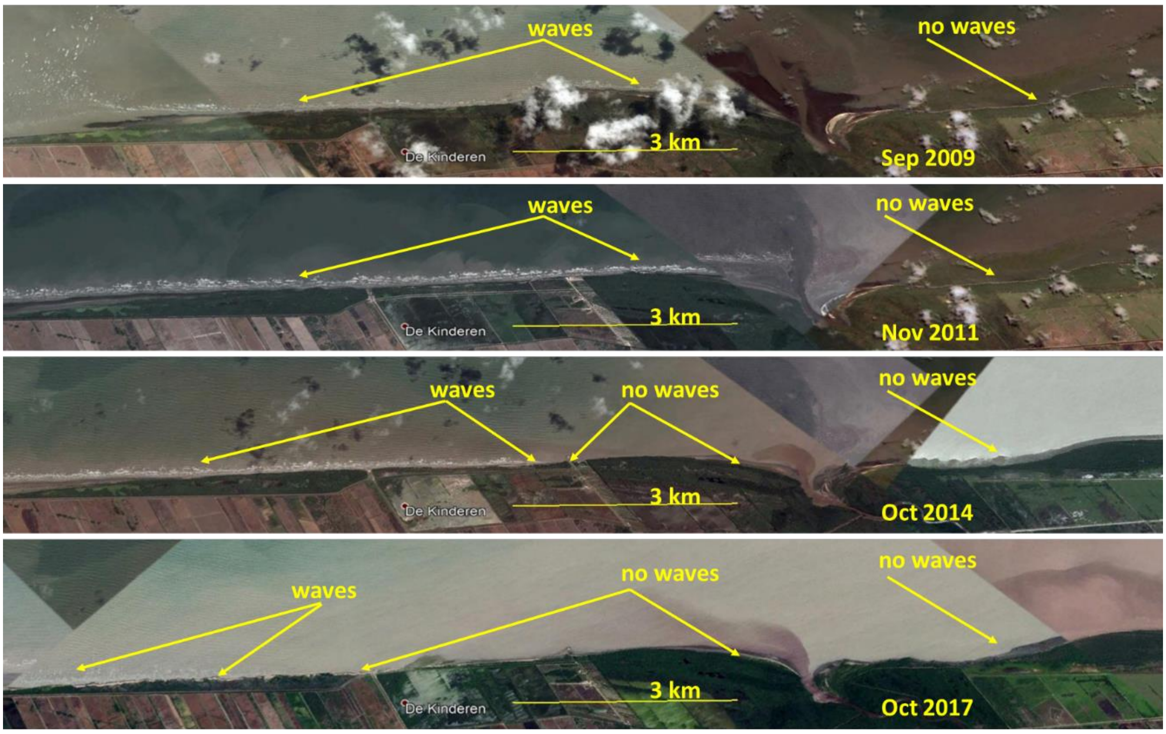


*Figure 4.12 Wave dynamics as an indication of mudbank migration near De Kinderen breach (Google Earth).*

In the interbank areas, waves can penetrate far onto the foreshore, and break on non-vegetated coastlines. Hence, breaking waves are a proxy for the migration of mudbanks. The remote sensing images of Figure 4.12 suggests that somewhere between 2014 and 2017, a mudbank arrived near De Kinderen, arresting the chenier sands present. Thus, west of this mudbank, the migrating cheniers are depleted of sand, and thin. Likely the breach near De

Kinderen is the result of this thinning, weakening the local seawall, as in the case of Suriname (Figure 4.11). Possibly the seawall further west of De Kinderen is also at risk.

The conditions of Figure 4.10 also complicate the formation of cheniers in front of embankments: likely the water depth is too large for the sand lenses to emerge. It is likely that in front of embankments with the deeper foreshore, the chenier-forming sands are still preset, but cannot emerge. In contrast they may be dispersed and deposited on mudflats further downdrift.

## 4.7 Mudbank Migration Predictions

Figure 4.13 presents a series of Landsat satellite images of the position of the mudbank complex east of Georgetown (Chateau Margot mudbank), mainly indicated by its visible part, e. the mudflat. Though difficult to distinguish, its migration speed is quite small, about 500 m/yr compared to historic speeds. Its extension along the coastline is estimated at about 25 km, see Figure 4.14.

This would imply that the current mudbank complex remains in front of greater Georgetown for a few decades. However, historic migration speeds have always been observed to be a few factors larger (1 – 3 km/yr), hence this estimate of a few decades is highly uncertain. In other words, frequent monitoring is a necessity. This anomaly might explain why the mudflats became high enough for mangrove colonization – however this is speculation and would require dedicated research to support this suggestion. Note that around the turn of the century, mudflats developed in front of Georgetown as well (Figure 7.7), but apparently did not become high enough to enable mangrove colonization.

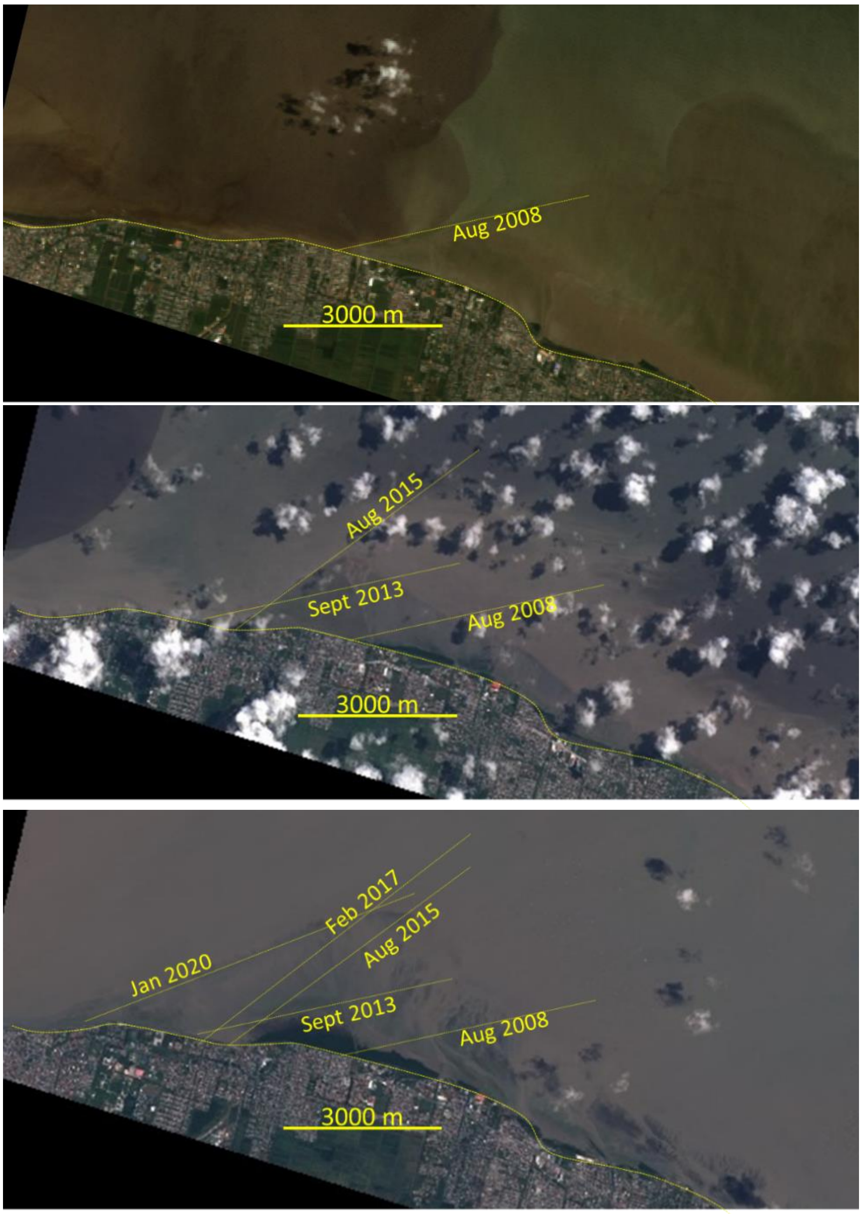

*Figure 4.13 Landsat satellite images of mudbank complex near Georgetown between 2008 and 2020.*


*Figure 4.4 Landsat satellite images of mudbank complex near Georgetown and indication of its alongshore extension.*

# 5 Sediment Dynamics along the Guyana Coastline

This chapter describes the sediment balance and the morphological development of the Guyana coastline at three spatial scales. The first explores the large-scale system dynamics of the Guianas coastline, followed by a description of the key processes governing the Guyana coastal sediment balance and lastly, a local approach exploring the sediment balance at a mudflat scale along the Guyana coast during mudbank and inter-bank periods.

## 5.1 Large Scale System Dynamics: Amazon Borne Suspended Sediment

The 1600-km-long South American coast between the Amazon and the Orinoco Deltas is a prograding muddy shoreline with sandy cheniers. It comprises mangrove-colonized tidal flats and bare mudflats several hundreds of meters to several kilometers wide. These muddy deposits locally isolate cheniers. Further, seismic studies of the shelf deposits show that the inner mud shelf overlies sandy deposits of presumably fluvial origin that crop out on the mid-shelf at depths beyond 20 m (Bouysse et al., 1977; Pujos et al., 1990).

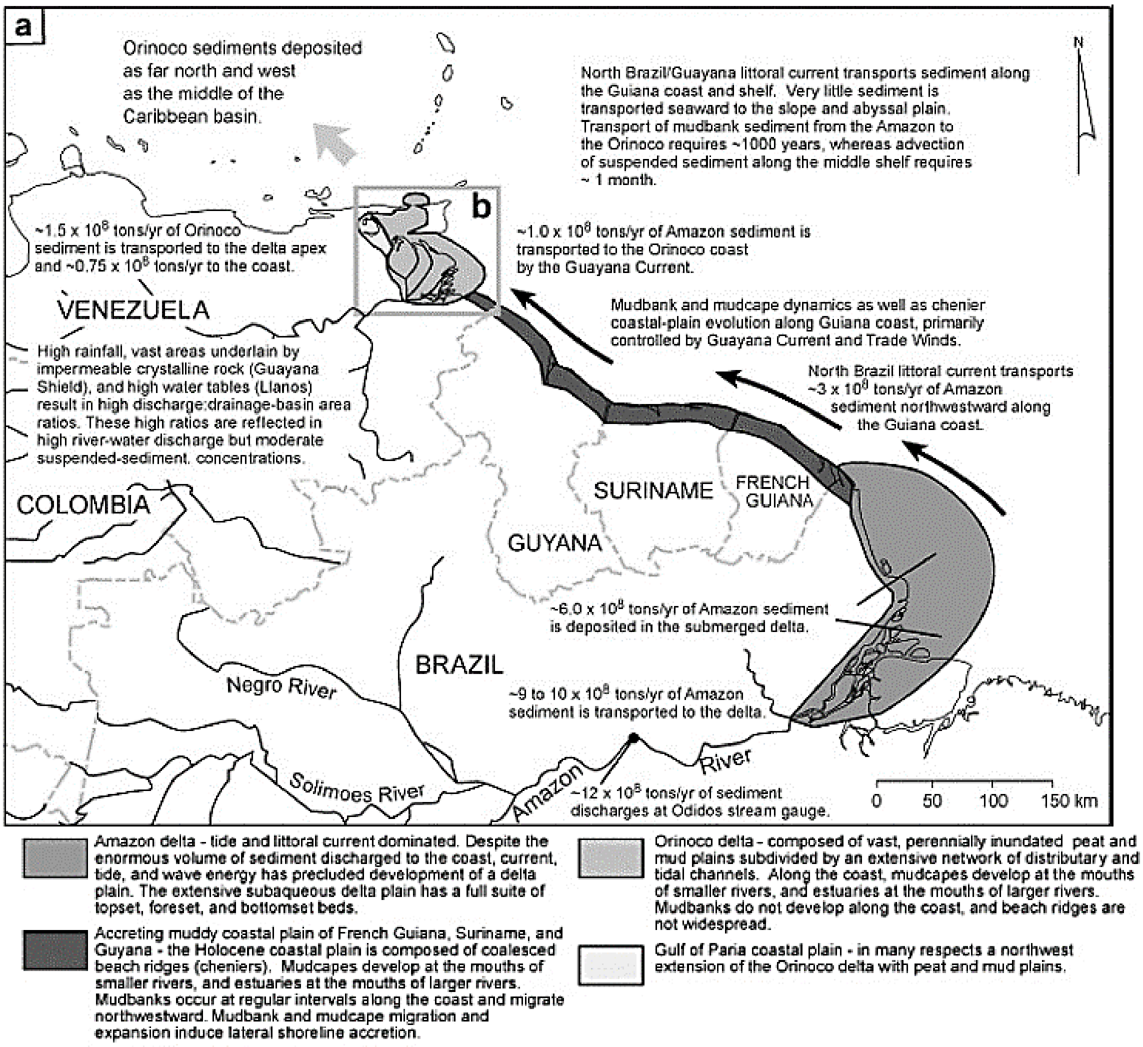


*Figure 5.1 The large-scale system dynamics along the Amazon Delta, Guiana Shield, Orinoco Delta and Gulf of Paria (Warne et. al 2002).*

The role of the sandy deposits is of secondary importance (Section 5.2) w.r.t the sediment budget, as the mud fluxes from the Amazon delta is the driving input. Figure 5.1 provides a schematic of the large-scale sediment transport between the Amazon delta, the Guiana Shield, the Orinoco delta and the Gulf of Paria. The sediment transport consists of sand and fine, cohesive sediment. The Amazon River yearly supplies an estimated 1100 – 1300 Mton of silt and clay and 30 - 80 Mton of sand and fines, where the latter accounts for approximately 5% of the total load (Meade et al., 1985; Eisma et al. 1991; Martinez et al. 2009). As discussed in Chapter 3, from the Amazon River mouth the sediment load is dispersed under the influence of (Eisma et al 1991):

- tides, which reach a range of 6 to 10 m in the Amazon River mouth, with current velocities up to 2 m/s;
- waves which come from the NE and reach heights of 5 m in the Amazon area;
- the North Brazil and Guiana Currents which flow along the shelf to the NW at velocities reaching 1 m/s; and
- estuarine circulation that develops on the inner shelf under influence of the river outflow.

Most of the supplied mud stays on the shelf, predominantly on the inner shelf, and is either deposited there or transported to the north-west (NW), extending as far as the eastern Caribbean (see Figures 5.2 and 5.4). Yearly 630 ± 200 Mton is deposited on the shelf adjacent to the Amazon River mouth (Kuehl et al., 1986), which is 52 % ± 16 % of the supply from the Amazon River.

As discussed in Chapters 3 and 4, part of the sediment is transported in the form of mudbanks, which are on the average 20 to 35 km long, and move along the coast at a velocity of less than 1 to more than 5 km/yr, with a spacing of 15 to 25 km. The mud moving along the coast of the Guianas is amounts to approximately 20% of the total Amazon supply (220 – 260 Mton/yr). This is an average value, while Figure 5.2 shows the variation in the Amazon-borne sediment supply. Along the coasts of the Guianas, an average of 150 Mton is yearly transported in northwest direction in suspension and about l00 Mton is transported in the form of large migrating mudbanks.

| **Fate of the Amazon- driven Suspended Sediment** | |
|---|---|
| **Deposition Amazon Shelf** | 36 – 68 % |
| **North Western Transport** | |
| **Near-shore suspension** | 12 -14 % |
| **In Mudbanks** | 7 – 8.5 % |
| **Offshore** | < 5 % |
| **Deposition Cayenne-Suriname- Guyana coast** | < 1 % |
| **Loss of Particulate Organic Matter (POM)** | 4 – 6 % |
| | **65 – 103 % (Avg. 84 %)** |

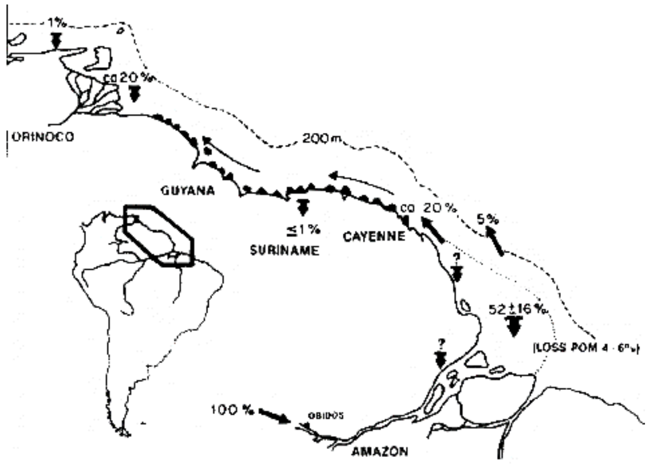


*Figure 5.2 The Dynamics of the Sediment Budget for the Guiana Shield with proportions of the sediment load from the Amazon Delta (Warne et. al 2002).*

Between 0.4 - 0.5% (Figure 5.2 sums this as less than 1%) of the Amazon supply is deposited on the French Guiana-Suriname-Guyana coast, while the remainder reaches the Orinoco delta,


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where 50 to 66% of the fine-grained sediment in the delta consists of Amazon mud (Eisma & Van Der Marel, 1971; Eisma et al., 1978) (see Figure 5.1). Data indicates that during the period of the 1940s to the 1970s, the average net deposition on the coast of the Guianas was about 5 – 6 Mton/yr (Eisma et al. 1991). Warne et al. (2002) observed that approximately 100 Mton/yr of the sediment which is transported by the Guyana Current enters the Orinoco coastal system. A small amount is deposited on the north Venezuelan shelf (about 1% of the Amazon supply; Milliman et al., 1982). Less than 5% of the Amazon supply is transported off the shelf into the ocean (Kuehl et al., 1986) (Figure 5.2). So, this implies that 220 - 260 Mton/yr passes the Guyana coastal system.

Augustinus et al. (1984) observed that the direction and migration velocity of the mudbanks depend on the orientation of the coastline w.r.t the prevailing angle of the incoming waves. Eisma et al. (1991) also noted a relationship with the deposited volumes along the three coastlines, where the deposition along the Suriname coast was much larger than along the Guyana coast.

## 5.2 Large-scale System Dynamics: Sandy Cheniers and Sand-Shell Lenses

As mentioned in Section 3.4, sandy material is rare in this mud dominated environment. Locally small quantities are delivered by some large rivers, like the Corentyne River and the Essequibo River. In addition, some dark colored very fine sand originating from the Amazon River may be found along the coast (Augustinus, 1978). See Chapter 3 for additional details.

Figure 5.3 shows the sediment distribution along the Brazilian-Guianas coastal system. Cheniers are sand lenses atop an otherwise muddy substrate. Relict cheniers form sand ridges in the landscape, which occupy a 5 - 12 km wide belt between the Corentyne and Pomeroon Rivers. The highest concentration of cheniers occurs between the Corentyne and Berbice Rivers. They are easily identified from aerial photographs and satellite imagery because of their lighter tone (caused by the well-drained sandy soils), in contrast to the poorly drained clayey soils of the surrounding areas. They are more numerous to the west of large river mouths.

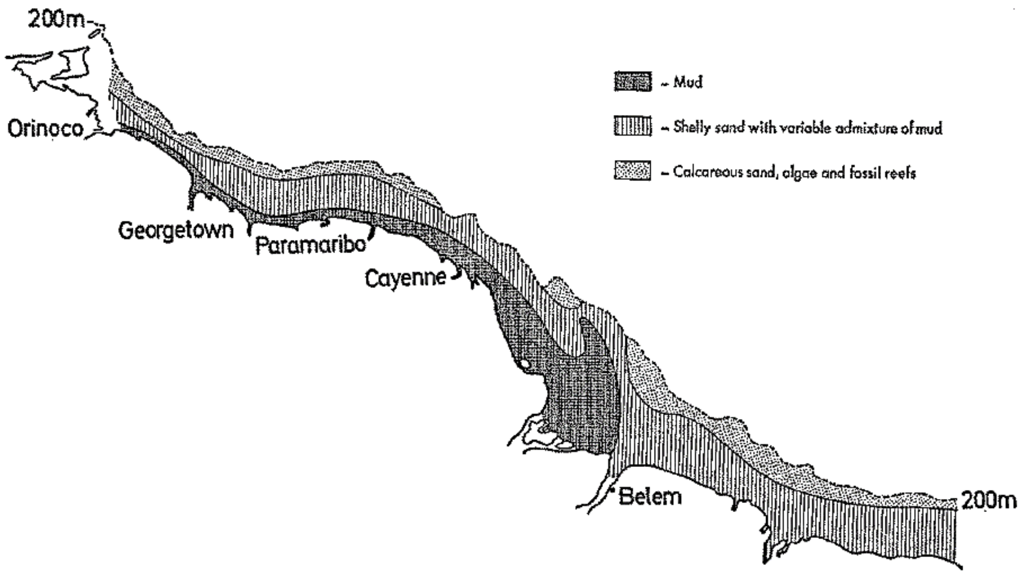


*Figure 5.3 General Distribution of bottom sediment types on the continental shelf along the north coast of South America (Eisma et al 1971)*

Cheniers are still found in the foreshore of the Guianas, where the majority of sand stems from local rivers, while the Amazon sands are fine and not abundant. As mentioned in Section 3.4, cheniers become immobile and often covered with mud deposits, when sheltered from waves by mudbanks. The sandy deposits which are exposed during inter-bank phases and subsequently transported north westward contribute to the various morphological features. During inter-bank periods, they (Figure 5.3) provide (some) natural protection for parts of the coastal plain against wave attack.

## 5.3 Sediment Balance along the Guyana Coastal System

As mentioned in Section 5.1, less than 1% of the sediment supplied from the Amazon River is deposited along the coast of the Guianas. Due to the limited data, we assume that about 220 – 260 Mton/yr enters the Guyana coastal system sediment – the estimated volume of deposits is well below this gross flux. The total amount of sediment by the Guyanese rivers debouched into the coastal system is in the order of 6 -10 Mton/yr (see Table 5.1). In the mouth of the Essequibo River only about 5 - 10% of the coastal mud is of Guyanese origin, indicating that most of the mud stems from the Amazon.

*Table 5.1 Catchment area, discharge and sediment load of the Amazon and the main Guyanese rivers (Eisma et al 1971)*

| | **Suriname** | | | **Main Rivers in Guyana** | | | | **Venezuela** |
|---|---|---|---|---|---|---|---|---|
| | **Saramacca** | **Coppename** | **Nickerie** | **Corentyne** | **Berbice** | **Demerara** | **Essequibo** | **Orinoco** |
| **Catchment Area ($km^2$ x $10^3$)** | 12 | 20 | 10 | 69 | 11 | 5 | 164 | 950 |
| **Discharge ($m^3$/ year x $10^8$)** | 8 | 14 | 6 | 47 | 11 | 7 | 178 | 946 |
| **Sediment Load (tons/year x $10^6$)** | 0.2 | 0.4 | 0.2 | 1.4 | 0.2 | 0.1 | 4.5 | 86 |

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Mud is transported along the Guyana coast in suspension or temporarily deposited in large mudbanks. If remaining in suspension, it would take mud particles roughly one month to cover the distance of about 1400 km between the Amazon estuary and the Essequibo, assuming a residual westward current of 0.5 m/s. The mudbanks migrate westward at a rate of 1 - 3 km/yr reaching the Essequibo after about 500 - 1000 years. As discussed in Chapters 3 and 4, the mud is held near to the coast by the combined effect of tidal currents, wave action, gravitational circulation, and lag effects in the suspended sediment response to erosion and settling. Moreover, off the coast of Suriname the near-bed current over the shelf has a pronounced landward component, whereas the surface current moves in a more offshore direction (Eisma, 1967). Therefore, near-bed mud suspensions are likely carried onshore, as sketched in Figure 5.4 (A and B).

Figure 5.4 (b) sketches the sediment budget for the Amapa coast of Brazil, which can serve as proxy for the Guyana coastline.

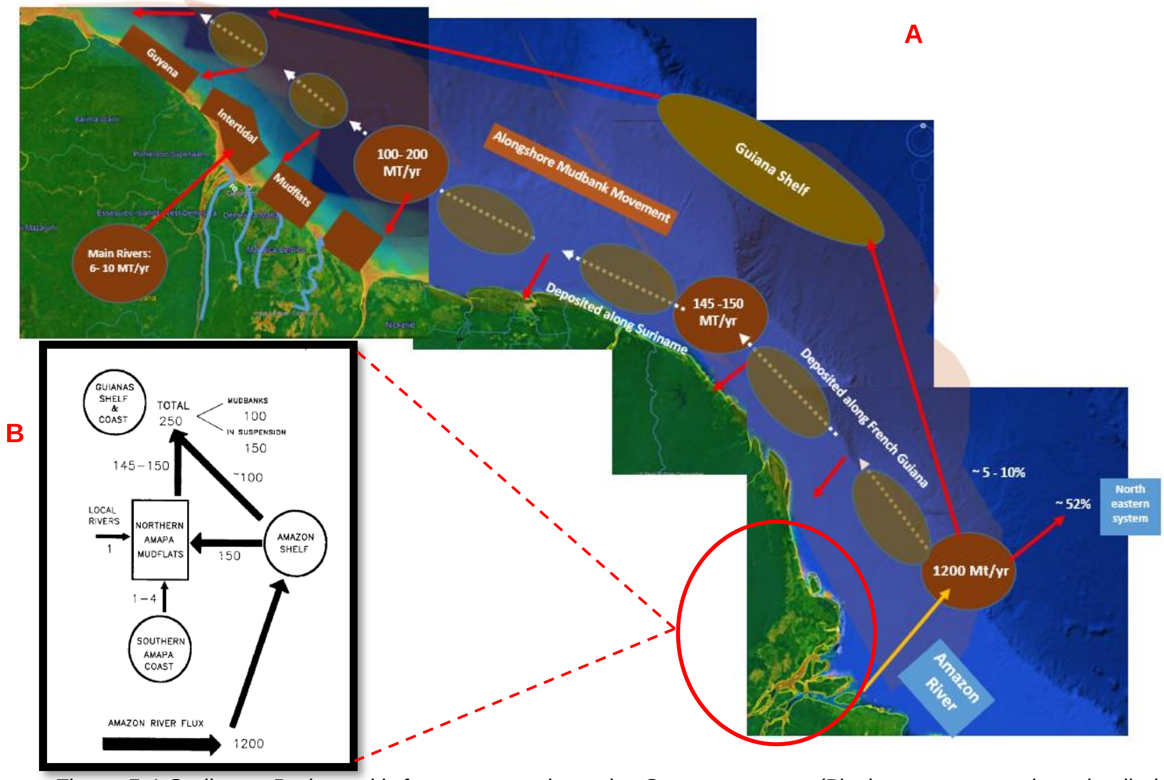


*Figure 5.4 Sediment Budget with focus approach on the Guyana system, (B) shows an example a detailed sediment budget for the Northern Amapa Mudflats along Brazil's coast with the transport of the Amazon supply. (Eisma et al 1971; Allision et al 1995)*

## 5.4 Mudflat Dynamics during Bank and Inter-Bank Periods

In this section, we examine the driving forces behind the sediment budget on the mudbank/ mudflat scale. The focus is on the variability in the natural system using a simple spreadsheet (Mangro-GUY spreadsheet). This spreadsheet provides estimates of the amount of sediment mobilized during mudbank migration and the amount of sediment required for mudflat formation, in other words estimates of the amount of sediment necessary for mangrove rehabilitation in relation to its availability.

*Cross–Shore Volumes Needed in Transitional Periods*

To estimate the volumes of sediment involves, we elaborate on measurements in the Chateau Margot mangrove fringe along the East Coast of Demerara. Figure 5.6 shows the migration and development of this mudflat over the six-year period from 2014 to 2020, wherein sections closer to the Demerara River expand while other sections further east are in transition to an inter-bank phase.

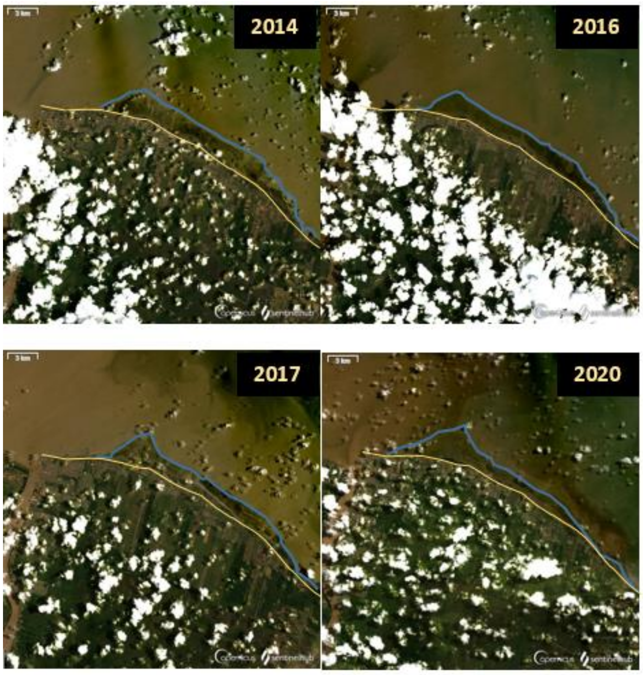


*Figure 5.5 Chateau Margot Mangrove Mudbank Dynamics where the yellow line shapes the profile of the existing concrete seawall and the blue line shows the outline of the mudflat at low tide.*

In 2010, *Avicennia germinans* seedlings were planted and allowed to naturally widen and prograde over the last 10 years. Prior to planting, the intertidal zone needs to be sufficiently high in to facilitate planting efforts. Before these works there was no vegetation in this stretch of coast for decades. Bathymetry measurements from both field and satellite sources shows the development of the mudflat from1970 to 2004 and further to 2020, see Figure 5.7. This figure suggests the presence of a mudflat in 1970, hence a mudbank further offshore as well. This mudflat eroded in the next few decades. The actual timing is not known though, as no detailed data are available over this period. Because of the absence of an upper intertidal zone in 2004 (Figure 5.7), vegetation establishment was impossible and seedling planting would have failed.

Between 2004 and 2008, the mudflat built up rapidly through the deposition of silt and clay particles. The analysis of the bathymetry measurements showed that volumes ranging from 8750 - 12,250 m³/m were deposited. Section 4.7 suggests that this mudflat could grow so extensively owing to the low migration speed of the mudbank, yielding abundant time for sediment deposition behind the bank.

Figure 5.8 shows the development of this mudflat over time, suggesting a sedimentation rate of about 750 m³/m/yr. We have no further spatial information, hence further to Google Earth images we assume that this mudflat is about 4 km long. The mean rate of total sedimentation would then amount to about 3 Mm³/yr, or with a dry density $\rho_{dry}$ = 400 kg/m³, about 1 Mton/yr of sedimentation.

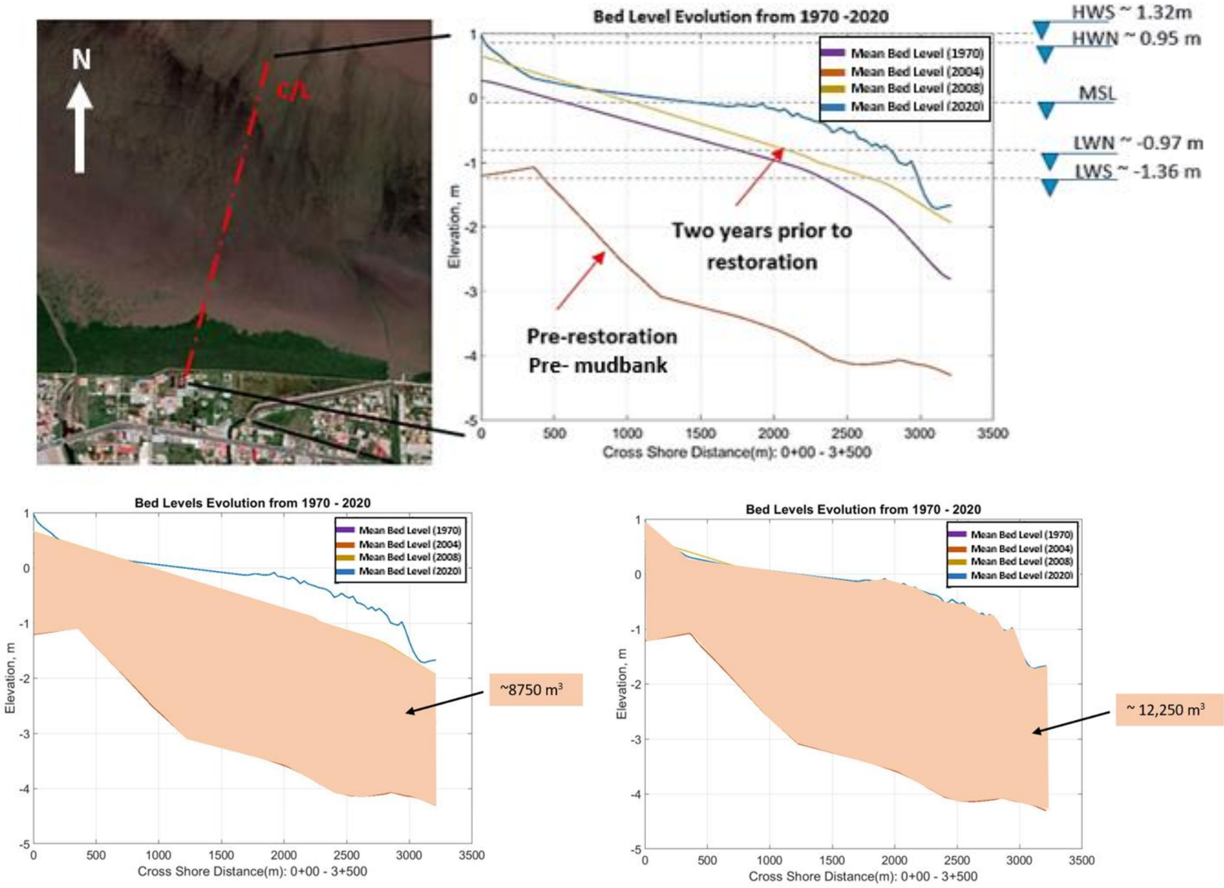


*Figure 5.6 The Bed Level Evolution of the Chateau Margot Mangrove Stretch from 1970 -2020 (top panel). The highlighted sections used in the computations for the volume needed for mudflat generation where 8750 m³ per m was required for the generation of the 2008 profile, while 12,250 m³ per m was needed to the 2020 profile with a baseline of 2004 (bottom panel).*

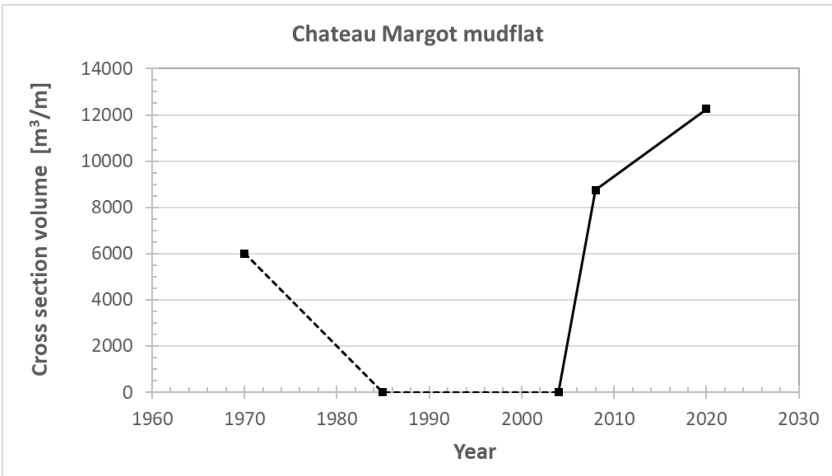


*Figure 5.7 Development of the Chateau Margot Mudflat.*

*Sediment Volumes Available during migration*

Figure 5.9 presents a schematic of the cross section of a mudbank migrating along the Guyana coastline. $S_2$ represents the volume that is displaced during its migration over a not yet defined period of time. From some algebra we find:

$$S_s = \frac{hL}{2}\left(1 - \left(\frac{L-\lambda}{L}\right)^2\right)$$

where λ represents the distance travelled in one year by the mudflat with height h and length L and width W. Further we assume a rectangular plan view of the mudbank with projected surface LxW. We assume dry densities of the mudbank of $\rho_{dry}$ = 500 or 600 kg/m³, which is a bit higher than the mudflat, owing to its larger degree of consolidation.

Table 5.2 presents a range of volumes and mass of sediment which would become available during mudbank migration as a function of its dimensions and migration rate, assuming that either 20% (“low onshore flux”) or 50% (“high onshore flux”) of the mobilized sediment is carried to the shore.

Hence from this simple analysis we may conclude that mudbank migration produces more than sufficient sediment to build out mudflats along the embanked Guyana coastline, for all parameter combinations considered. This is in agreement with the large flux of sediment along the Guyana coastline (220 – 260 Mton/yr).

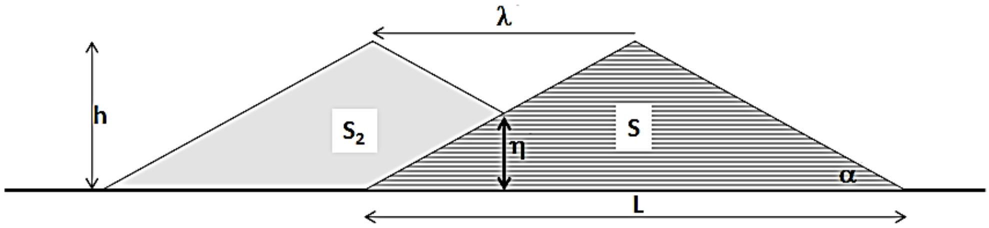


*Figure 5.8 Schematic of a migrating mudbank, where λ is the distance travelled in one year and S2 represents the volume mobilized during that migration.*

*Table 5.2 Example calculations for the volumes of sediment which are mobilized during transport along the Chateau Margot area.*

| L (m) | h (m) | Width of mudbank (m) | Dry Density, kg/m$^3$ | λ (m per year) | S (m$^3$ per m) | $S_2$ (m$^3$ per m) | Sediment load per m (kg/m) | Sediment Mass (kg) | Sediment Mass (Mton /yr.) | Low Onshore Flux (Mton/ yr.) | High Onshore Flux (Mton/ yr.) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 5000 | 5 | 10000 | 500 | 1000 | 1.25E+04 | 4.50E+03 | 2.25E+06 | 2.25E+10 | 24.80 | 4.96 | 12.40 |
| | | 20000 | 600 | 1000 | 1.25E+04 | 4.50E+03 | 2.70E+06 | 5.40E+10 | 59.52 | 11.90 | 29.76 |
| | 7 | 10000 | 500 | 2000 | 1.75E+04 | 1.12E+04 | 5.60E+06 | 5.60E+10 | 61.73 | 12.35 | 30.86 |
| | | 20000 | 600 | 2000 | 1.75E+04 | 1.12E+04 | 6.72E+06 | 1.34E+11 | 148.15 | 29.63 | 74.08 |
| | 10 | 10000 | 500 | 3000 | 2.50E+04 | 2.10E+04 | 1.05E+07 | 1.05E+11 | 115.74 | 23.15 | 57.87 |
| | | 20000 | 600 | 3000 | 2.50E+04 | 2.10E+04 | 1.26E+07 | 2.52E+11 | 277.78 | 55.56 | 138.89 |
| 10000 | 5 | 10000 | 500 | 1000 | 2.50E+04 | 4.75E+03 | 2.38E+06 | 2.38E+10 | 26.18 | 5.24 | 13.09 |
| | | 20000 | 600 | 1000 | 2.50E+04 | 4.75E+03 | 2.85E+06 | 5.70E+10 | 62.83 | 12.57 | 31.42 |
| | 7 | 10000 | 500 | 2000 | 3.50E+04 | 1.26E+04 | 6.30E+06 | 6.30E+10 | 69.45 | 13.89 | 34.72 |
| | | 20000 | 600 | 2000 | 3.50E+04 | 1.26E+04 | 7.56E+06 | 1.51E+11 | 166.67 | 33.33 | 83.33 |
| | 10 | 10000 | 500 | 3000 | 5.00E+04 | 2.55E+04 | 1.28E+07 | 1.28E+11 | 140.54 | 28.11 | 70.27 |
| | | 20000 | 600 | 3000 | 5.00E+04 | 2.55E+04 | 1.53E+07 | 3.06E+11 | 337.31 | 67.46 | 168.65 |
| 20000 | 5 | 10000 | 500 | 1000 | 5.00E+04 | 4.88E+03 | 2.44E+06 | 2.44E+10 | 26.87 | 5.37 | 13.43 |
| | | 20000 | 600 | 1000 | 5.00E+04 | 4.88E+03 | 2.93E+06 | 5.85E+10 | 64.49 | 12.90 | 32.24 |
| | 7 | 10000 | 500 | 2000 | 7.00E+04 | 1.33E+04 | 6.65E+06 | 6.65E+10 | 73.30 | 14.66 | 36.65 |
| | | 20000 | 600 | 2000 | 7.00E+04 | 1.33E+04 | 7.98E+06 | 1.60E+11 | 175.93 | 35.19 | 87.96 |
| | 10 | 10000 | 500 | 3000 | 1.00E+05 | 2.78E+04 | 1.39E+07 | 1.39E+11 | 152.95 | 30.59 | 76.47 |
| | | 20000 | 600 | 3000 | 1.00E+05 | 2.78E+04 | 1.67E+07 | 3.33E+11 | 367.07 | 73.41 | 183.53 |
| 30000 | 5 | 10000 | 500 | 1000 | 7.50E+04 | 4.92E+03 | 2.46E+06 | 2.46E+10 | 27.10 | 5.42 | 13.55 |
| | | 20000 | 600 | 1000 | 7.50E+04 | 4.92E+03 | 2.95E+06 | 5.90E+10 | 65.04 | 13.01 | 32.52 |
| | 7 | 10000 | 500 | 2000 | 1.05E+05 | 1.35E+04 | 6.77E+06 | 6.77E+10 | 74.59 | 14.92 | 37.29 |
| | | 20000 | 600 | 2000 | 1.05E+05 | 1.35E+04 | 8.12E+06 | 1.62E+11 | 179.02 | 35.80 | 89.51 |
| | 10 | 10000 | 500 | 3000 | 1.50E+05 | 2.85E+04 | 1.43E+07 | 1.43E+11 | 157.08 | 31.42 | 78.54 |
| | | 20000 | 600 | 3000 | 1.50E+05 | 2.85E+04 | 1.71E+07 | 3.42E+11 | 376.99 | 75.40 | 188.50 |
| 40000 | 5 | 10000 | 500 | 1000 | 1.00E+05 | 4.94E+03 | 2.47E+06 | 2.47E+10 | 27.21 | 5.44 | 13.61 |
| | | 20000 | 600 | 1000 | 1.00E+05 | 4.94E+03 | 2.96E+06 | 5.93E+10 | 65.31 | 13.06 | 32.66 |
| | 7 | 10000 | 500 | 2000 | 1.40E+05 | 1.37E+04 | 6.83E+06 | 6.83E+10 | 75.23 | 15.05 | 37.62 |
| | | 20000 | 600 | 2000 | 1.40E+05 | 1.37E+04 | 8.19E+06 | 1.64E+11 | 180.56 | 36.11 | 90.28 |
| | 10 | 10000 | 500 | 3000 | 2.00E+05 | 2.89E+04 | 1.44E+07 | 1.44E+11 | 159.15 | 31.83 | 79.57 |
| | | 20000 | 600 | 3000 | 2.00E+05 | 2.89E+04 | 1.73E+07 | 3.47E+11 | 381.95 | 76.39 | 190.98 |

## 5.5 Cheniers and Beaches

Cheniers may stabilize coastal defenses. However, they migrate, and such defenses are then temporarily. It is therefore attractive to try and arrest the cheniers, preventing them from further migration. In the following, we refer to beaches, i.e. immobilized cheniers. For example, along the Georgetown foreshore in 2014, geotube groynes were constructed to trap the silty-sand (with some shells) during an inter-bank phase which allowed for bed elevation increases of 0.5 m in some upstream sections of the groyne field.

Cross sections taken along the four 50 m groynes revealed significant changes in the volume of sediment retained by the groynes. Sediment volumes ranging from 40 $m^3$ to 498 $m^3$ were retained and comprised predominantly of silty sand (Best (2014). This increase was seen in both the cumulative values and the monthly values for the sediment retained. The accumulation of coarse sediment confirms the limited availability of fine sediments along the lower East Coast of Demerara at that time.

# 6 Wave Damping by Mangrove Vegetation

This chapter summarizes the physics of wave damping processes by vegetation and relevant literature and field measurements along the Guyana coastline. Wave damping by the mangrove fringe is a critical variable by which restoration works are designed and evaluated. This chapter recommends a minimum belt width of 500 m to be maintained during bank periods.

## 6.1 Physics of Wave Damping by Vegetation

Waves propagating through submerged and emergent vegetation lose energy due to turbulent flow separation induced by the stems, roots and branches. This also results in the creation of a drag force (Dalrymple et al.1984). As depicted in Figure 6.1, mangroves influence (wave-) hydrodynamics, and the extent of their impact depends upon their height, surface area, location, density, distribution and root structure. The (wave-) hydrodynamics in turn influences the conditions for mangrove growth and decay (Mendez- Losado (2004), Seymour et al., 1989; Mork, 1996).

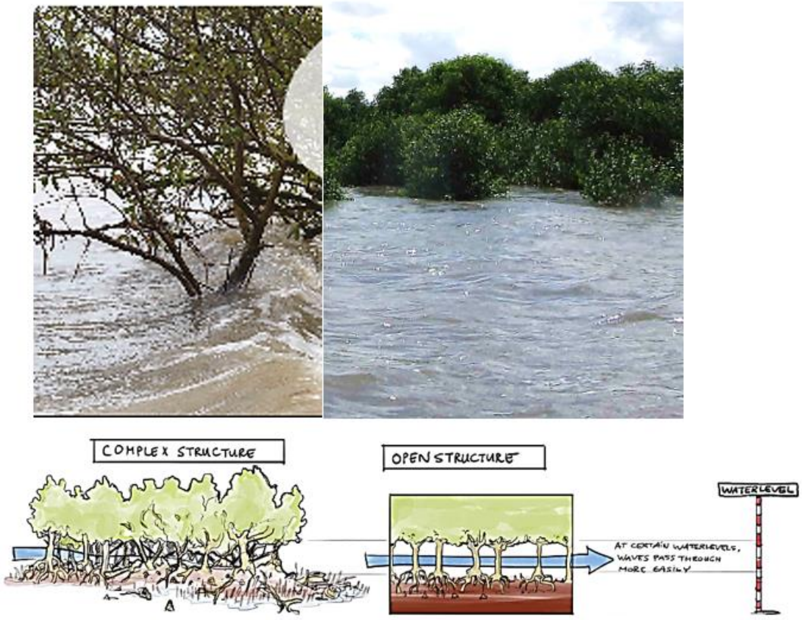


*Figure 6.1 Wave attenuation is attributed to the vertical variation in the mangrove dimensions and the complexity of the root network.*

Without vegetation, i.e. in the case of only a mudbank/ mudflat present, wind waves approaching the shore will shoal due to the change in depth. Waves increase in height and become steeper while maintaining their wave period. When the steepness exceeds 0.78-0.88, waves break dissipating their energy. With mangrove vegetation, most of the short-wave energy is dissipated at the seaward edge of the fringe, while wave attenuation continues inside the mangrove belt. Longer infragravity waves (if present) may propagate further into the mangrove forest (Kit, 2016, Ruessink, 1998). Figure 6.2, provides an analysis of field data for damping of the wave energy, both in the presence of vegetation and without. Here, it is observed that Mazda et al., (1997a) reported a damping of 50% from the seaward station (6) to a station within the mangrove fringe (2). From an extensive literature review, McIvor et al. (2012) concluded that wave heights can be reduced by between 13-66% over 100 m of mangrove forest. Other literature reports a reduction of 50-99% over 500 m of mangrove forest (Dekker, 2006, Kit, 2016, Spalding, et al., 2015, Spalding, et al., 2014).

The ability of coastal vegetation to dissipate wave energy is documented and quantified in numerous field studies in low-energy environments. Wave attenuation by vegetation is a function of the vegetation characteristics (such as the geometry, buoyancy, density, stiffness and spatial coverage) as well as the wave conditions (such as the incident wave height, period and direction). The mangrove-wave interactions are highly dynamic because the vegetation field which is exposed to the wave forcing, changes with time as the stems bend, flatten to bed or are washed away due to extensive erosion. The dynamics of this system is also a result of different plant species and their coverage. Therefore, the variability in the wave damping capacity of vegetation is quite large.

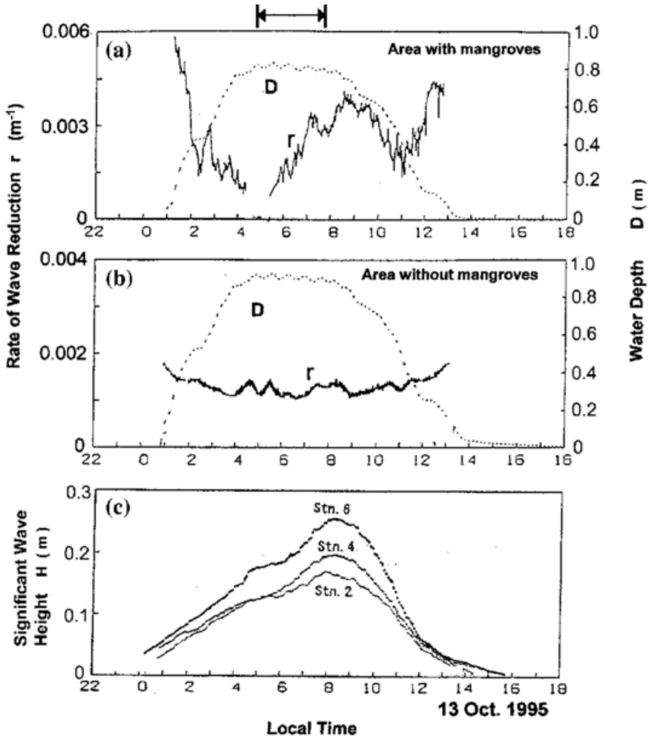


*Figure 6.2 Time series plots of the wave height, the rate of wave reduction and water depth across selected stations 2,4 and 6 presented by Mazda et al., (1997a). Station 6 is the furthest seaward while station 2 is located within the mangrove fringe (a) The rate of wave reduction in an area with mangroves and the water depth at Station 2. (b) The rate of wave reduction in an area without mangroves, and the water depth at Station 4. (c) The significant wave heights at Stations 2, 4 and 6.*

## 6.2 Wave Damping Capacity of the Mangrove-Mudflat Systems: Overview of Previous Studies

The dissipation of wave energy by vegetation has been studied analytically and empirically, as well as with field campaigns and numerical models since 1970's (Feagin et al., 2011). Dalrymple et al. (1984) explained that energy dissipation by vegetation causes an incident wave field to diffract and attenuate. He proposed that localized dissipation may be triggered by pockets of mud, large stands of vegetation or submerged trees or pile clusters. Using a cluster of cylinders (similar to a large stand of submerged trees), a parabolic model for the wave propagation (including refraction, diffraction and energy dissipation), was shown to be realistic. Since then, field and laboratory-flume measurements on wave attenuation over vegetated foreshores have shown that energy dissipation depends on incident wave energy, ambient water depth, the density, the (vertical) structure and the flexibility of vegetation.


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While earlier studies tend to quantify wave dissipation only within the vegetation, later studies compared vegetated and unvegetated areas to emphasize the importance of maintaining and creating wetlands for coastal protection (Quartel et al. 2007, Mazda et al. 2006, Cooper 2005, Möller and Spencer 2002, Möller et al. 1999). However, due to the inaccessibility of (natural) mangrove forests, a limited number of field studies has been executed in mangroves in Thailand, Vietnam, Australia and Japan (Table 6.1). These studies emphasize the positive contribution of mangroves to the dissipation of wind and swell waves of limited height and period. Nevertheless, observed wave reduction rates show significant variation with water depth and vegetation characteristics. Table 6.1 provides a summary w.r.t the vegetation types, the attenuation rates, the influencing factors as well as the approach taken with the respective references. This large variability of wave damping makes it very difficult to define a generalized behaviour of wave dissipation by vegetation. Therefore, closer examination of wave transformation along vegetation fields is highly desirable (e.g. by modelling). As a consequence, several authors have carried out theoretical and numerical work mainly concentrated on wave transformation induced by a vegetation field.

The theoretical models estimate wave-induced forces on the plants. It must be noted that the validity of each model depends on the geometrical and biomechanical characteristics of the plants (Seymour, 1996). Recent advances in numerical modelling explicitly resolve vegetation induced drag forces by integrating friction forces over a composition of one or several layers of rigid vertical cylinders (Suzuki et al., 2012, Vo-Luong and Massel, 2008). For a reliable representation of the vegetation, this approach compels detailed, site specific information on vegetation characteristics such as stem and root diameters, vertical vegetation distribution, vegetation densities and (bulk) drag coefficients. However, due to poor vegetation data the abovementioned models were calibrated by adjusting the vegetation parameters (Suzuki et al., 2012, Vo-Luong and Massel, 2008), which raises questions regarding their general validity (Horstman et al., 2014).

Field data comprising accurate measurements of both hydrodynamics (wave heights, water depths and, if possible, flow velocities) and vegetation parameters is indispensable for further development of the abovementioned numerical models (McIvor et al., 2012, Möller, 2012, Horstman et al., 2014). Both hydrodynamics and vegetation parameters are changing from site to site, depending on local geography, wave climate and vegetation composition. Although wave attenuation studies accurately quantified hydrodynamic conditions, usually only a very limited range of conditions is covered as data collection often spans a few tides only (Brinkman, 2006, Mazda et al., 1997a, Horstman et al., 2014).

## 6.3 Factors Affecting the Wave Attenuation in Mangrove Fringes

***Important Wave Attenuation Parameters***

The nature of the localized energy dissipation is shown by Equations 6.1 and 6.2. For cases of coastal flooding due to storms and through vegetation (trees and seaweed), Dalrymple et al. (1984) proposed that the wave height decay takes the form of Equation 6.2. However, in Vietnam waves measurements taken along a transect through mangrove forests were shown to experience an exponential reduction in height with distance (Boa (2011); McIvor et al. (2012)). Dalrymple et al. (1984) also proposed this exponential decay of wave heights but limited it to cases with long porous bottoms, viscous mud bottoms, laminar bottoms, and densely packed surfaces. Table 6.1 shows practical applications.

The rate of wave height reduction ($\alpha$) per unit distance in the direction of wave propagation is defined as the reduction in wave height ($\Delta H_{s,0}$) as a proportion of the initial wave height ($H_{s,0}$) over a distance ($\Delta x$) travelled by the wave (see Equation 6.1). The unit of '$\alpha$' is $m^{-1}$. For example, when wave height is reduced by 1% over a distance of 1 m, then r = 0.01 $m^{-1}$.

*Equation 6.1 The relation for the attenuation of wave energy*

$$\alpha = -\frac{\Delta Hs,0}{Hs,0}.\frac{1}{\Delta x}$$

Further, Dalrymple et al. (1984) provides the following relation, explicitly specifying the damping rate as a function of mangrove characteristics:

*Equation 6.2 Relation for the damping rates within mangrove fringes.*

$$\frac{H_s(x)}{H_{s,0}} = \frac{1}{1+\alpha x}; \quad \alpha = F\left(H_{s,0}, T, h, C_D, D, N\right)$$

where the damping coefficient α is a function of the incoming wave height and period ($H_{s,0}$ and $T$), the local water depth ($h$) and the thickness of the mangrove stems ($N$), their density ($D$) and a bulk drag coefficient ($C_D$). This explains why the damping rates decrease within the mangrove fringe.

***Depth Dependent Mangrove Vegetation Drag***

The most important factors affecting the rate of wave attenuation with distance in mangroves are the water depth (which is related to tidal phase) and the structure and characteristics of the mangrove vegetation. At shallow depths, the projected area of obstructions to the flow is caused by above-ground roots which create significant drag. As the water level increases, wave energy is transmitted further into the forest. At these water depths, the ratio of the projected area of obstructions to the total cross-sectional area of flow decreases because the water is now higher than the prop roots, so that the waves experience less drag and there is less wave attenuation (see Figure 6.2.

The *Avicennia spp*. has characteristic pneumatophores, aerial roots which grow out of the substrate. The aerial roots of *Avicennia* are thin and can reach 20 to 30 cm in height. Like the prop roots of *Rhizophora spp*., the pneumatophores act as turbulence generating elements to water movement at shallow depths, creating higher wave attenuation at these depths. Mazda et al. (2006) measured wave attenuation in a mangrove forest created by planting *Sonneratia* (similar to the *Avicennia*) in northern Vietnam. They found the highest attenuation at shallow depths, and lower wave attenuation as water levels rose, until the water levels reached the height of the branches and leaves. This trend was also observed in sections of coast without mangroves.

At larger water depths, when the waves reach the branches and leaves, wave attenuation is expected to increase. Quartel et al. (2007) found that the rate of wave reduction increases with water depth. This increase in wave attenuation at higher water depths is due to the densely packed branches and leaves dissipating the wave energy.

Additionally, the resistance to flow increased with the projected area of mangrove vegetation, and this resistance, the drag coefficient, can be approximated by the proposed function of Mazda et al. (1997a) where $C_D = 0.6\ e^{0.15A}$ (where ‘A’ is the projected cross-sectional area of the underwater obstacles up to a certain water depth).

***Slope Variation and Dissipation of Wave Energy***

The slope of the foreshore is a key factor affecting wave energy dissipation through its influence on the water depth and hence wave shoaling and breaking. Coastal fringes in Guyana are very gently sloping with a characteristic gradient of 1:1200 or 1:1500. This is maintained both along the mudflat and within the mangrove fringe.

There are no studies of mangrove growth along steep slopes, but Parvathy-Bhaskaran (2017), deduced from numerical models that reductions in wave energy (with mangroves) of 93 – 98%, 84% and 67% are garnered from mild slopes (1:80, 1:40), 1:20 slopes and steep slopes (1:10) respectively. The study reveals that the wave height decays exponentially for the mild slope, but as the bottom steepness increases, the wave height reduction becomes more gradual, and this can be attributed to the water depth variation, shoaling, breaking and reflection characteristics that are associated with different slopes occupied with the mangrove belt.

***Tree Age***

The age of the trees is important in determining their ability to attenuate waves, because the age relates to the size of individual plants as well as the number of plants. Table 6.2 shows the results of the study from Mazda et al. (1997a) at different stages of development. In this study, Mazda et al. (1997a) showed that wave attenuation through the youngest trees decreased with increasing depth. Wave attenuation was higher amongst the older trees, and it decreased little with increasing depth (as depicted in Table 6.2). As the trees get larger, the leaves and branches will play a larger role until wave attenuation increases with depth.

*Table 6.2 Expected wave reduction rates in mangrove forests based on the field measurements of Mazda et al. 2006.*

| **Age of Tree** | **Water Depth (m)** | | |
|---|---|---|---|
| | **0.6** | **0.8** | **1** |
| **6 months** | 0.08 | 0.05 | 0.04 |
| **3 - 4 years** | 0.125 | 0.12 | 0.1 |
| **5 - 6 years** | 0.18 | 0.17 | 0.16 |

*Table 6.1 Summary of Laboratory, Field and Modelling Studies carried out to quantify the wave attenuation rate in mangrove fields (Kit, 2016).*

| **Study sites** | **Methods/ approaches** | **Vegetation types** | **Hydrodynamic effect/ wave attenuation rate** | **Influencing factors** | **References** |
|---|---|---|---|---|---|
| ***Laboratory studies*** | | | | | |
| - | Electromagnetic flowmeter and 3D acoustic doppler velocimeter (ADV)/ scenarios of flow rates and water depths | *Rhizophora* (root and trunk) | ≈50% flow velocity reduction when roots were submerged; ≈ 75% flow velocity reduction when ¾ or a whole tree was submerged | Water level, vegetation density, mangrove structure | Zhang et al., 2015b |
| - | Pressure transducers and wave gauges/ scenarios of tsunami flow conditions (solitary wave and tsunami bore) and breaking/non-breaking waves | Parameterized *Rhizophora* (root and trunk) | Solitary wave transmission (Kt): 0.53 – 0.992 in non-breaking waves and 0.34 – 0.94 in breaking waves; Kt in tsunami bore: 0.24 – 0.5 for 1.5 m forest width and 0.1 – 0.25 for 3 m forest width | Foreshore, forest width, incident wave height, water depth | Husrin et al., 2012; Strusińska-Correia et al., 2013 |
| - | Velocity measuring device/ scenarios of mangrove forest with different vegetation density and stem diameter | *Rhizophora* (root) | Velocity in the creek 51 – 191% increases with 220 $m^{-2}$ density and 21 – 106% with 110 $m^{-2}$; decreases in water depth of 15 -25% in high flow condition and 2 – 10% in low flow | Vegetation density, stem diameter, flow velocity | Struve et al., 2003 |
| - | Elevation, current and pressure sensors/ scenarios of high and low wave heights across | Generic vegetation model with root, trunk and canopy | ≈ 25 – 60% of wave height reduction by vegetation (porosity 0.964 – 0.973); | Porosity/density | Harada et al., 2002 |

| | | | | | |
|---|---|---|---|---|---|
| ***Field studies*** | | | | | |
| Palian, Thailand | High and low frequency pressure sensors buried at locations along transects | *Avicennia* at fringe mangrove and *Rhizophora* at the back mangrove | 0.0032 – 0.012 $m^{-1}$ | Vegetation density, vegetation type, mangrove structure, incident wave height | Horstman et al., 2014 |
| Kantang, Thailand | High and low frequency pressure sensors buried at locations along transects | *Avicennia* at fringe mangrove and *Rhizophora* at the back mangrove | 0.0024 – 0.0061 $m^{-1}$; 0.0058 $m^{-1}$ during storm | Vegetation density, vegetation type, mangrove structure, incident wave height | Horstman et al., 2014 |
| Kien Giang coast, Vietnam | Manual/visual measurement using fixed poles along transects | Three dominant species: *Avicennia alba*, *Sonneratia alba* and *Rhizophora apiculata* | ≈ 90% of wave height reduction in transects with mangroves and breakwaters; ≈ 60% of wave height reduction in open areas | Vegetation density, incident wave height, mangrove structure, canopy closure | Nguyen, 2013 |
| Red River delta, Vietnam | Manual measurement of wave height by people standing along transects | Six dominant species: *Rhizophora mucronata, Sonneratia caseolaris, Sonneratia griffithii, Aegiceras corniculatum, Avicennia marina* and *Kandelia candel* | 0.0055 – 0.01 $m^{-1}$ | Vegetation density, incident wave height, mangrove structure, canopy closure | Bao, 2011 |
| Can Gio, Vietnam | Manual measurement of wave height by people standing along transects | Six dominant species: *R. mucronata, S. caseolaris, S. griffithii, A. corniculatum, A. marina* and *K. candel* | 0.017 $m^{-1}$ | Vegetation density, incident wave height, mangrove structure, canopy closure | Bao, 2011 |

| **Study sites** | **Methods/ approaches** | **Vegetation types** | **Hydrodynamic effect/ wave attenuation rate** | **Influencing factors** | **References** |
|---|---|---|---|---|---|
| Red river delta, Vietnam | Pressure sensors and electromagnetic flow devices attached to tripod and installed along transects | Dominated by *K. candel* with some *Bruguiera* spp. and *A. marina* | 0.004 – 0.012 $m^{-1}$ within mangrove; 0.0005 – 0.002 $m^{-1}$ outside of mangroves | Water depth, cross section vegetation cover, mangrove type | Quartel et al., 2007 |
| Can Gio, Vietnam | Pressure sensors installed above 1 cm sea bed along transects | *Avicennia* sp. and *Rhizophora* sp. in the first 100m; mainly *Rhizophora* sp. at back mangroves | Wave energy reduction of 50 – 70% within 20 m | Water depth and vegetation structure | Vo-Luong & Massel, 2006 |
| Vinh Quang, Vietnam | RMD-type wave Recorders | Predominantly *Sonneratia* sp. | 0.001 – 0.006 $m^{-1}$ within mangroves; 0.001 – 0.002 $m^{-1}$ at non-vegetated area | Water depth, incident wave height, vegetation structure and condition | Mazda et al., 2006 |
| Cocoa Creek, Australia | Wave gauges and pressure sensors along transects | Dominated by *R. stylosa*, *Aegiceras* sp. and *Ceriops* sp. | Energy transmission factor = 0.45 – 0.80 over 160 m | Water depth, distance of wave propagation in the mangrove | Brinkman et al., 1997; Brinkman, 2006 |
| Nadara river, Japan | Wave gauges and pressure sensors along transects | Dominated by *Bruguiera gymnorrhiza* | Energy transmission factor = 0.9 – 1.0 over 40 m | Water depth, distance of wave propagation in the mangrove | Brinkman et al., 1997; Brinkman, 2006 |
| Oonoonba, Australia | Wave gauges and pressure sensors along transects | Dominated by *Sonneratia* sp. and *Rhizophora* sp. | Energy transmission factor = 0.15 – 0.75 over 40 m | Water depth, distance of wave propagation in the mangrove | Brinkman, 2006 |

| | | | | | |
|---|---|---|---|---|---|
| Tong King delta, Vietnam | Water level gauges and electromagnetic current meters installed 2 cm above sea bed along transects | Replanted *K. candel* | 0.01 – 0.22 per 100 m | Vegetation density, mangrove structure, mangrove age | Mazda et al., 1997a |
| Shiira river, Japan | RMD-type wave Recorders | Dominated by *R. stylosa* | 0.45 – 0.85 per 25 m within mangroves; 0.05 – 0.06 per 25 m at non-vegetated area | Vegetation density, type, age and width; incident wave height and water depth | Magi et al., 1996 |
| ***Modelling studies*** | | | | | |
| Ben Tre province, Vietnam | SWAN-VEG (Stimulating Waves Nearshore + vegetation structural parameters) | Replanted forest dominated by *Rhizophora* sp. and naturally regenerated area dominated by *Avicennia* sp. | 60% wave height reduction in replanted forest; 40% in naturally regenerated forest; wave height reduction decreases from 60% to -4% when vegetation cover reduces from 70% to 0%; wave height reduction decreases from 46% to 21 – 29% when forest width decreases from 1.5 km to 0.5 km | Mangrove width, mangrove density, mangrove type | Cuc et al., 2015 |
| Merritt Island National Wildlife Refuge (MINWR), Florida, USA | Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST) model for Coastal Protection | *R. mangle*, *A. germinans* and *Laguncularia racemosa* | 48.5 ± 1.4 m and 114.4 ± 2.9 m of mangrove cross-shore extent required to reduce 75% and 90% incident wave height respectively | Mangrove width, incident wave height, mangrove structure | Doughty, 2015 |
| Kien Giang, Vietnam | Regression model developed based on field measurement by Bao (2011) | Three dominant species: *A. alba*, *S. alba* and *R. apiculata* | ≈ 75% less mangrove width required for coastal protection when density increases from 3500 stems $ha^{-1}$ to 7000 stems $ha^{-1}$ | Vegetation density, mangrove structure, mangrove width, incident wave height | Nguyen, 2013 |
| Cat Ba/ Can Gio/ Hoang Tan/ Thai Binh/ Tien Long, Vietnam | Regression model developed based on field studies at Red River delta and Can Gio, Vietnam | Dominant species at Cat Ba: *A. corniculatum*; Can Gio: *A. marina, R. mucronata, S. caseolaris*; Hoang Tan: *S. caseolaris; A. marina, A. corniculatum*; Thai Binh: *K. candel, A. corniculatum*; Tien Lang: *S. caseolaris* | Other than Can Gio, existing mangrove forests have less than required mangrove width (> 120 m); Can Gio forest offers moderate to strong protection | Vegetation density, mangrove structure, mangrove width, incident wave height | Bao, 2011 |
| Kanika Sands, Sri Lanka | SWAN-VEG | *R. mucronata* | ≈ 90% wave height reduction within 1000 m ; 90% less vegetation density decreases the reduction from > 90% to 70% in 300 m | Vegetation density, vegetation structure | Narayan, 2009 |
| Pakarang Cape, Thailand | Combination of linear shallow-water wave theory and nonlinear shallow water wave theory with parameterized bottom friction | *Rhizophora* sp. and *Bruguiera* sp. | ≈ 30% of tsunami height reduction; mangrove forest effective at 3 m inundation; 50% and 100% vegetation destroyed at 4.5 m and 6 m inundation respectively | Water level, tree size | Yanagisawa et al., 2009 |

## 6.4 Wave Attenuation Measurements in Guyana & Minimum Belt Width Recommendations.

Current field observations along the East Coast of Demerara represent relatively mild conditions with significant wave heights ranging from 0.5 m – 1.0 m. Figure 6.3 shows a comparison of the wave measurements on the mudflat and within the mangrove fringe along the Chateau Margot coast of Guyana. Figure 6.4 provides a clear depiction of the attenuating capacity of both the mudflat and the mangrove vegetation.

The wave height was significantly damped over the mudflat by some 85 – 90 % from 60 km offshore to the edge of the mangrove fringe. While, the mangroves, as seen in Figure 6.7, reduce the height further by 50% within the first one-third (120 m) of the fringe width. This corresponded well compared with other field measurements collected in some forests in Vietnam (Vo-Luong & Massel, 2006; Cuc et al., 2015). At the most landward point (~340-360 m from the mangrove edge), this section is predominantly dry except during spring tides. However, even during spring tides, the waves heights did not exceed 0.1 – 0.24 m within the landward sections of the fringe during the November 2019 to January 2020 field campaign in Guyana (Best et al., 2020). This corresponds to a further 30-40 % decline in the wave height.

The level of wave attenuation reported along mangrove coastlines in Table 6.1 varied between 0.0014 $m^{-1}$ and 0.012 $m^{-1}$. Using Equation 6.1, the attenuation rate within the Chateau Margot fringe corresponds to 0.003 $m^{-1}$ and as such Figure 6.5 provides the recommended belt widths for multiple wave heights from 0.1 m to 2.5 m. Therefore, with the observed wave heights of 0.2 m – 0.5 m at the fringe edge, belt widths ranging between 200 m – 300 m would be the minimum to achieve the required wave attenuation. However, to guarantee a certain level of safety during the interbank phases, when the greenbelt will likely reduce in size, **design belt widths should be at least 500 m**.

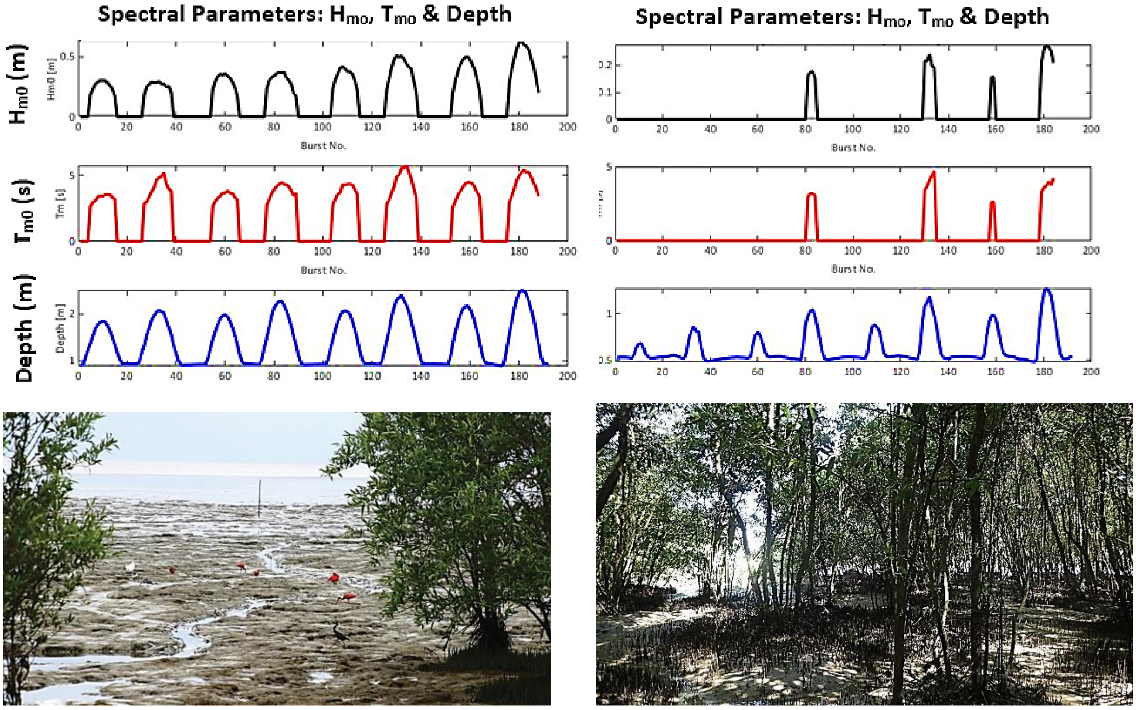


*Figure 6.3 Wave Heights, Wave Periods and water depths for (right) 1.6 km offshore and (left) at location approximately 25 - 30% of the fringe width (from the edge) along the Chateau Margot coast, Guyana.*

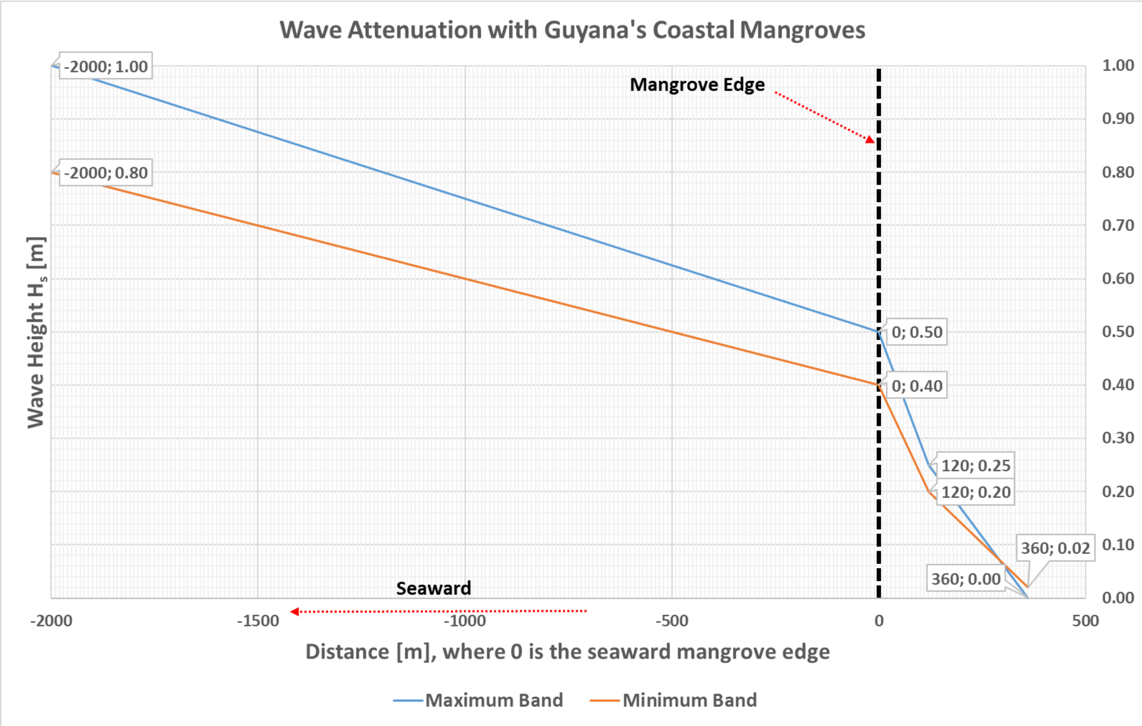


*Figure 6.4 Observed Field Results by Best et al. (2020) illustrating the attenuation of waves over the extensive mudflats and within the mangrove fringe along the Chateau Margot coastline of Guyana. The mangrove edge starts at 0 m, as indicated by the black line, and extends landward until 360 m.*

Further, studies show that a minimum dampening capacity of 50 % is needed to prevent wave reflection at the inner wall of the seawall which leads to increased scour volumes (see section 4.5).

Wave damping features of mangrove greenbelts can substantially reduce costs for retrofitting of levees under changing future wave climates. Thereby, in wave prone areas, inclusion of ecosystems into flood defence schemes constitutes an adaptive and safe alternative to only hard engineered flood risk measures (van Wesenbeeck et al., 2021).

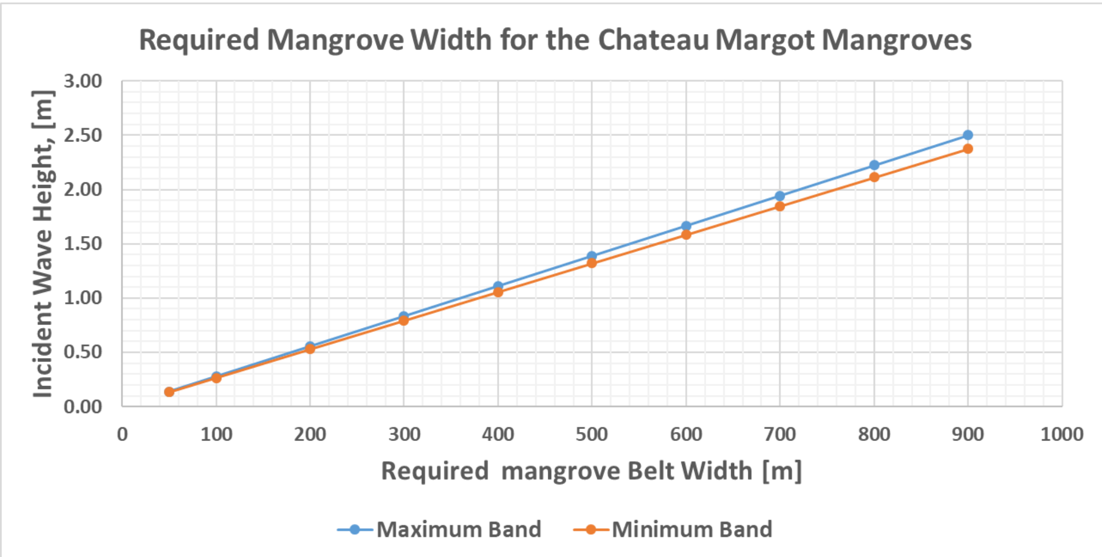


*Figure 6.5 Required Mangrove Belt Widths for the Chateau Margot area with consideration to wave heights ranging from 0.1 m – 2.5 m. The belt widths are determined using the observed attenuation rates.*

# 7 Permeable Dams and Groynes

One technique to promote the “green” part of Green-Grey Coastal Infrastructure is to promote the formation of mangrove habitat, i.e. intertidal mudflats, by trapping sediment. Another technique is to reduce erosion rates during interbank periods. The following classes of techniques are discussed in subsequent sections:

1. Sediment Trapping Units are configurations to trap sediment and accelerate the formation of mudflats (mangrove habitat). These sedimentation basins are formed by dams/fences of low-reflective permeable structures, preferably constructed with bio-degradable materials (bamboo),
2. Permeable fences are temporal configurations to dampen wave loads. They consist of one or more rows of closely spaced bio-degradable poles forming a low-reflective permeable wall to protect mudflats and mangrove fringes in interbank periods,
3. Permeable groynes are permanent configurations to dampen wave loads. They consist of rows of durable poles, placed parallel and in front of existing seawalls; they are constructed for instance from concrete,
4. Coast-perpendicular groynes to trap/block longshore sediment fluxes. These are permanent structures and consist of rubble mound, geotubes/textiles, or other durable materials and are not permeable, and
5. Detached breakwaters, i.e. coast-parallel structures to trap/block longshore sediment fluxes. These are permanent structures and consist of rubble mound, geotubes/textiles, or other durable materials and are not permeable. We believe these are not applicable in Guyana.

The rate of wave dissipation for the first three structures can be assessed from recent work by Gijón et al. (2021).

## 7.1 Sediment Trapping Units

Permeable structures are used to erect more or less rectangular sedimentation basins (STU – Sediment Trapping Units), as in the examples of Figure 7.1, with dimensions of about (50-100)×(50-100) m$^2$. Such structures have been built with brushwood dams in NW Europe for centuries and are locally known as salt marsh works (see Winterwerp et al., 2020). These basins gradually fill up with sediment until salt marshes develop (accelerated by creating drainage channels, see Figure 7.1, upper panel) and over time this results in a seaward expansion of the coastline. Various configurations have been deployed in the past (Figure 7.1, upper panel) but also more recently (Figure 7.1, lower panel).

The permeable structures (dams) are meant to damp waves through the dissipation of turbulence within the structures, while reflecting only a minor part of the incoming wave energy. This implies that the incoming waves are partly transmitted through the dam, and partly reflected (about 10 – 20%). Winterwerp et al. (2021) reason that these structures should damp about 50 – 60% of the incoming wave height to be effective. Because of the low reflection rates, scour in front of the permeable dams is small, and extension of the sedimentation basins further offshore remains possible. However, the dams are fairly impermeable to sediment-laden tidal and residual currents. The sedimentation basins are therefore provided with openings to facilitate throughflow of sediment-laden currents – these openings are about 5 m wide. Flow through these opening also create tidal channels/gullies which function as drainage channels when the mudflat becomes vegetated. Note that these sedimentation basins can only be used to trap sediments that are suspended in the water column and are not suitable to trap sediments (fluid mud) transported by streaming (see Chapter 4).

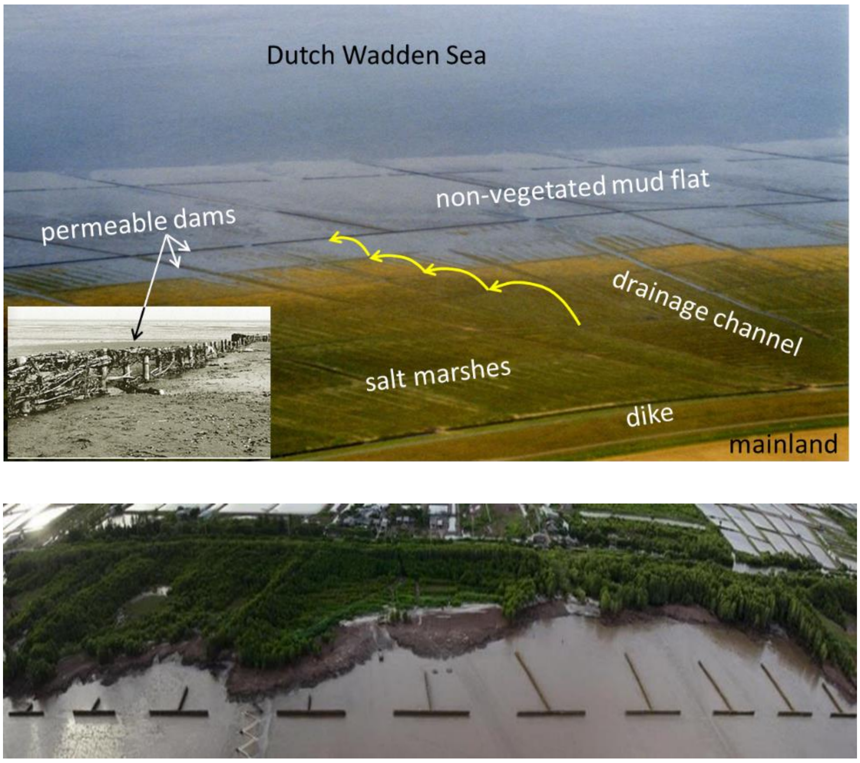


*Figure 7.1 Sedimentation basins constructed by permeable structures in the Wadden Sea, The Netherlands (above) and in Vietnam (below).*

Traditionally, the permeable dams have been made of bundles of brushwood placed in between and tight to vertical poles hammered into the soil (Figure 7.1 insert and Figure 7.2, left panel). These structures require much maintenance and are not very durable in tropic environments – the brushwood is easily lost, and scour is likely to occur underneath the brushwood bundles (see Figure 7.2 and Winterwerp et al., 2020). Therefore, an alternative structure has been proposed recently (Winterwerp et al., 2021) consisting of rows of vertically placed (bamboo) poles, as in Figure 7.2, right panel. It can be shown that the required wave damping of 50 – 60% can be attained with a single row of bamboo.


*Figure 7.2 Left panel: "classical" permeable structure with brushwood; right panel: bamboo fence (both deployments in Indonesia)*

Placed in multiple rows, spaced one quarter of the incoming wavelength apart, arrays of fences can be very effective because of resonance of the waves in between the rows. Figure 7.3 presents a schematic of this concept, where subscript 0 refers to the incoming wave, subscript 1 and 2 to fence 1 and 2, respectively, and subscript t and r to transmitted and reflected, while the distance L between the two fences should measure about $\lambda/4$, with $\lambda$ = length of incoming wave. However, in Guyana we propose to build dual fences closer together to gain space (see Chapter 15).

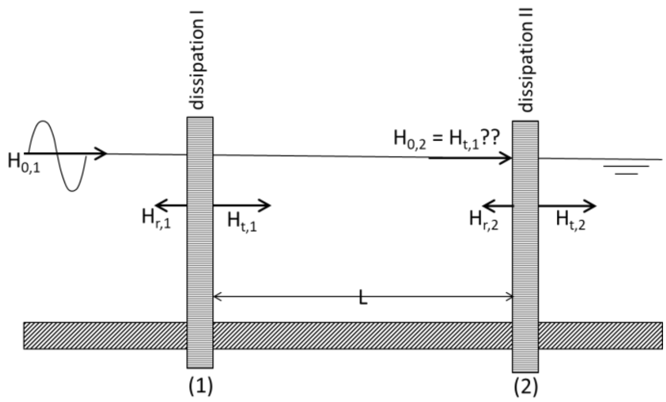


*Figure 7.3 Schematic of multi-row bamboo fence with L = quarter length incoming wave.*

Winterwerp et al. (2020) conclude that these sediment trapping structures should preferably be placed in the intertidal zone to trap sediment sufficiently fast, i.e. around mean low water or higher. Being emerged part of the time slows biodegradation of the wooden poles, thus also lengthens the life of the structures. In Indonesia, many structures were inundated permanently, thus prone to shipworm-induced degradation. The bamboo poles therefore lived only 1 – 2 years. Bamboo poles placed on the intertidal in Guyana have proven lifetimes of 5 – 7 years. The top of the structures is generally at the high-water level, as some overtopping at high-high water spring will not negatively affect their functioning.

## 7.2 Permeable Fences and Coastal Protection

As permeable structures damp waves at low reflection rates, they may also be used as coastal protection units. We foresee an application to protect mangrove fringes during interbank periods. After the passage of a mudbank complex, mudflats with its mangrove fringes are subject to erosion during the interbank period; our ultimate objective is that part of these fringes survive the interbank periods. Erosion rates may be slowed down by protecting mudbank and mangroves against wave attack by permeable fences. As erosion will not be stopped by this technique, new fences may have to be placed further back after some time. Therefore bio-degradable material is recommended for these fences, such as bamboo. The authors of these guidelines are not aware of any such application, and some small-scale experiments are therefore advised before large-scale application.

## 7.3 Permeable Groynes and Coastal Protection

Permeable structures can be used also to reduce wave reflection against seawalls. In the interbank period, waves penetrate onto the Guyana seawalls, and partly reflect, scouring the foreshore, resulting in deep, highly turbulent waters unfavourable for mudflat formation in the future. Permeable groynes placed parallel and in front of the embankments will reduce wave loads on the seawalls, and reduce reflection rates, thereby reducing scouring of the foreshore. Note that these structures are placed at deeper water and are permanent submerged. They will have to last many years and will experience large wave forces. Likely they have to be constructed from concrete – therefore we refer to permeable groynes, emphasizing their required long lifetime.

Note that these permeable groynes will not unfavourably affect the mechanisms that form mudflats upon the arrival of a next mudbank.

These structures are erected at deeper water and may be combined with e.g. mussel cultures, or other productive activities, to provide income for local communities and raise funds for their construction and maintenance (see Chapter 10).

## 7.4 Coast-Perpendicular Groynes for Muddy Environments

Groynes are solid structures meant to interrupt littoral transport, i.e. sediment transport along a coast driven by currents and/or waves. Often such groynes are constructed from rubble mound, though other materials, such as geotextiles filled with sediment (often referred to as geotubes) may be used. Though initially (a bit) permeable, the pores in the structure fill in rapidly with sediments, and groynes should therefore be treated as impermeable structures.

Figure 7.4 shows a Google Earth image of a part of the Guyana coast near Anna Regina, along the left bank of the Essequibo River mouth. Four groynes with a length of a few 100 m were erected around 2015. In 2020, the area in between and down-drift of the groynes is vegetated with mangroves.

No fluid mud can be formed in the mouth of the Essequibo River, as fine sediment cannot settle at the large velocities occurring there. However, suspended fine sediment concentrations are apparently large enough to build up intertidal mudflats rapidly in between the groynes. The construction of groynes along Guyana's coast is therefore an option to promote the formation of intertidal mudflats in front of the seawalls. Such groynes should be long enough to be effective, with a proper foundation to prevent sinking into the soft soil, and, most importantly, oriented such that the mudbank dynamics are not frustrated by these groynes.

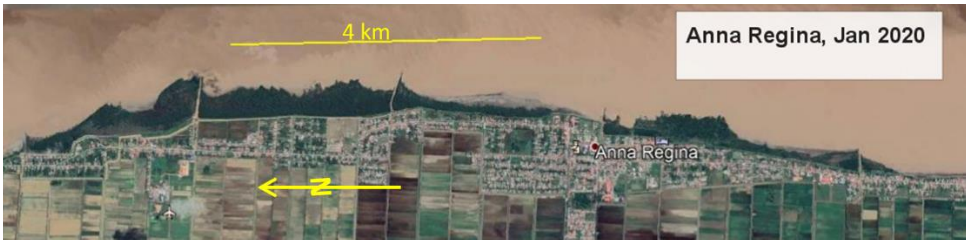


*Figure 7.4 Mangrove development in between groynes near Anna Regina, left bank of the mouth of the Essequibo River.*

Note that interruption of the littoral transport of sand in the breaker zone generally would induce erosion problems further down-drift. This is not the case in Figure 7.4, as alongshore transport is governed by advection by the tidal flow, in conjunction with an abundance of fine sediment, and not by wave-induced littoral transport.

## 7.5 Coast-Perpendicular Groynes for Sandy Environments

At present a 40 – 100 m wide beach of about 1 km length is found in front of the Georgetown seawall, Kingston district, stabilized by a series of groynes, as depicted in Figure 7.5. We believe that this beach is critical in protecting the local seawall in front of Georgetown.

Though not a green approach, beaches can be considered as a nature-based configuration to reduce wave heights and runup on dikes and seawalls facing such beaches (e.g. Chapter 2), as they can dissipate wave energy efficiently and are low-reflective. The development of these beaches is therefore analysed in more detail hereafter.


*Figure 7.5 Sandy beaches in front Georgetown seawall (Kingston district, Google Earth image Jan 2020).*


*Figure 7.6 Sandy beaches in front Georgetown seawall (Kingston district, Google Earth image Sept 2016).*

*Table 7.1 Overview of groynes along greater-Georgetown coast*

| groyne # | name | construction material | length [m] | operational |
|---|---|---|---|---|
| **1** | Fort Groyne | concrete hollow mound | 210 | pre-1980 – present |
| **2** | cg 2 | rubble mound | 60 | pre-2002 – present |
| **3** | cg 3 | concrete | 60 | pre-2002 – present |
| **4** | cg 4 | concrete | 60 | pre-2002 – present |
| **5** | gt 5 | geotube | 100 | 2014 – 2018 |
| **6** | gt 6 | geotube | 100 | 2014 – 2017/2018 |
| **7** | gt 7 | geotube | 100 | 2015 – present |
| **8** | gt 8 | geotube | 100 | 2015 – 2017/2018 |
| **9** | Kitty groyne | concrete | 330 | pre-1980 – present |

Figure 7.6 presents the location of the various coast-perpendicular groynes which have been erected along the Demerara east coast. Table 7.1 summarizes dates of erection/collapse and their length.


*Figure 7.7 Beach development near Georgetown (Google Earth images) at two different spatial scales to visualize coastal response to natural development and cutting of Kitty Groyne mangroves.*

In 2002, a beach of about 20 m wide existed along the Georgetown coastline, apparently kept in place by three groynes (Fort groyne, cg3 and cg4). In the next decade, this beach did not change much. Further to the East, a triangularly shaped deposit started to develop since 2006 behind Kitty groyne, with a width of about 200 m and an alongshore length of about 500 m. This deposit became colonized by mangroves. These were illegally cut in the course of 2015, destabilizing the deposit. A little to the West of Kitty groyne, a narrow fringe of sand also emerges between 2011 and 2014. Also, in the period of 2002 (no earlier images available) – 2011, a mudbank passed, and substantial mudflats were found along the coast. These mudbank apparently did not become high enough and did not become colonized by mangroves (see also Chapter 4).

In the years after 2015, the sediments behind Kitty groyne and the narrow fringe of sand moved the West, being trapped by the concrete groynes in front of Kingston district. The geotextile groynes (geotubes 5 – 8, see table 7.1) were not maintained, and their effect on the littoral sand transport was only limited and temporal.

The Fort groyne plays a crucial role, as sand passing this groyne is lost for stabilizing the Demerara east coast. The volumes of sand passing this part of Guyana coast does not seem to be very large (Chapter 5). It is therefore recommended to stabilize these sandy beaches, and where possible increase their width, by increasing the length of the existing groynes. Note that such planning should be based on proper bathymetric data, including offshore of the groyne's regions of influence, and possibly some numerical modelling of the local coastal processes.

## 7.6 Detached Breakwaters

Figure 7.8 shows a Google Earth image of a series of detached breakwaters, relative short permanent structures parallel to the coast, erected along the sandy Adriatic coast of Italy. Behind these breakwaters, so-called tombolos develop in response to the interrupted littoral drift. Such interruptions often induce problems down-drift, and indeed large parts of the Adriatic coast had to be protected with these structures.

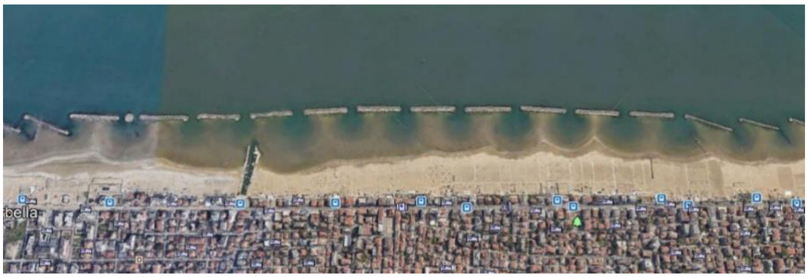

*Figure 7.8 Tombolo formation behind intermitted detached breakwaters along the Adriatic Sea, Italy.*

Coast-parallel detached breakwaters in front of the Guyana embankments are likely to reduce wave impacts on these embankments, in particular in the interbank areas. Moreover, there is a fair chance that mudflats will develop in the calm water areas behind such groynes.

However, the disadvantages of these structures are large, as:

- waves are reflected against these breakwaters, deepening the foreshore, and destabilizing the structures themselves – the seabed in front of these structures will become unsuitable for mangrove restoration,
- as the breakwaters will need to withstand strong wave action, they will have to be solid, and bed protection is required – there is a danger the breakwaters elements may sink into the soft soil, and
- a series of coast-parallel breakwaters will disrupt the formation of intertidal mudflat through streaming of fluid mud and sediment-laden water leading to onshore transport during the migration of mudbanks.

In other words, deployment of coast-parallel detached breakwaters is not a favorable option for the Guianas coastal system.

## 7.7 Debris Management

The first two structures proposed are preferably made of natural, bio-degradable materials, such as bamboo. If mangrove colonization is too slow and/or erosion rates in interbank periods too fast, these materials may degrade over time by shipworm etc. and/or break during storms. The debris from such structures should be managed properly, as it can damage mangrove stands and block drainage channels, as shown in Figure 7.9.

*Figure 7.9 Debris from permeable structures in mangrove forest, Thailand (left panel, courtesy Cherdvong Saengsupavanich) and in a drainage channel near Weg aan Zee, Paramaribo, Suriname (right panel, courtesy Els van Lavieren)*

# 8 Mangrove Accommodation Space

## 8.1 The Concept of Managed Realignment

As discussed in Chapter 4, reflective structures, such as dikes, seawalls, etc. may disturb natural sedimentary processes with subsequent narrowing and loss of intertidal area (the mangrove habitat). This is also known as “coastal squeeze” (Doody, 2004): there is not enough accommodation space to allow for natural processes. This can be mitigated by so-called managed re-alignment or retreat. Examples are set-backs in the Humber estuary (UK, moving dikes inland, e.g. Jeuken et al., 2008) and depoldering in The Netherlands (opening polders to the sea). These interventions aim at restoring the natural sediment dynamics and giving accommodation space for intertidal ecosystems, such as intertidal flats and salt marshes (here mangrove habitat), which is especially relevant in times of sea level rise. Wolters et al. (2005) provide an overview of the success in revitalizing salt marshes by realignments in European coastal waters. Managed realignment can, however, be cumbersome from a socio-economic perspective, as often cultivated and/or inhabited land is given back to the sea. Hence, proper involvement of local stakeholders is essential to manage relocation or setting up alternative sources of livelihood for local residents. Note that in the end, land loss by the implementation of a managed realignment strategy may prove to be smaller than without such interventions in case large pieces of land are lost by breaches and erosion.

Though the managed realignment approach has been applied frequently applied in NW Europe (Wolters et al., 2005; Townend et al., 2021), no experience exists in tropical environments, as far as known to the authors. In the following we discuss how managed realignment may help to restore mangrove habitat along Guyana’s coastline. We distinguish between active and opportunistic realignment. The first approach would imply a policy in which (part of) the seawall is set back to induce the formation of a wide intertidal area. We will not elaborate on this approach because of its large socio-economic consequences. The opportunistic approach is treated in the next section.

## 8.2 Opportunistic Realignment

Near De Kinderen, the seadike breached in 2018 in response to sand depletion of the local cheniers induced by an arriving mudbank (Section 4.7), and a large area was flooded (Figure 8.1). Repairing this breach appeared cumbersome and was not yet realized in 2021. This breaching would provide an opportunity to carry out a pilot experiment with realignment, possibly temporarily, thus creating accommodation space for intertidal mudflats and mangrove habitat. As the breach was unintentional, we refer to opportunistic realignment.

One strategy would be to open the breach further, allowing more and a more evenly distributed entrance of sediment-laden seawater onto the inundated area, thus accelerating the heightening of the polder bed (Figure 8.1). It is unlikely that such sedimentation would occur evenly distributed over the inundated area, risking the formation of water logging in the back of the polder. Sedimentation patterns and the estimated filling time have therefore to be assessed, likely with the use of a numerical model. Mangrove management in the form of e.g. creating drainage channels may be necessary to create favourable conditions for the mangroves, and for future re-cultivation of the land when dry again.

A second strategy would be to erect a new embankment/seawall some 100 – 200 m inland from the existing/breached seawall – also in this case the breach has to be enlarged, possibly the entire remaining seawall is to be removed (Figure 8.1). This provides intertidal area, which is likely to be colonized rapidly by mangroves, enhancing sediment trapping further, similar to the example of Clonbrook below. This mangrove fringe will protect the dike behind, and can induce further mangrove expansion along the coast, in particular upon the arrival of a mudbank. The land behind the new embankment can be drained and re-cultivated.

Moreover, this mangrove fringe is well protected by the existing seadike at either side from erosion, even in interbank periods. This robust mangrove fringe could become a catalyst for mangrove expansion when conditions become favourable, which is further explained in Section 8.3.

Note that the De Kinderen inundated polder is located a few kilometre downdrift of extensive mangrove fringes along either side of the Mahaicony River. If mangrove re-establishment around the De Kinderen polder could be integrated with further westward extension of these fringes, a fairly robust mangrove forest may be formed along this part of the coast, i.e. a robust Green-Grey Coastal Infrastructure. Further studies are required, but likely application of sediment trapping units and/or coast-perpendicular groynes (Chapter 7) will be instrumental.

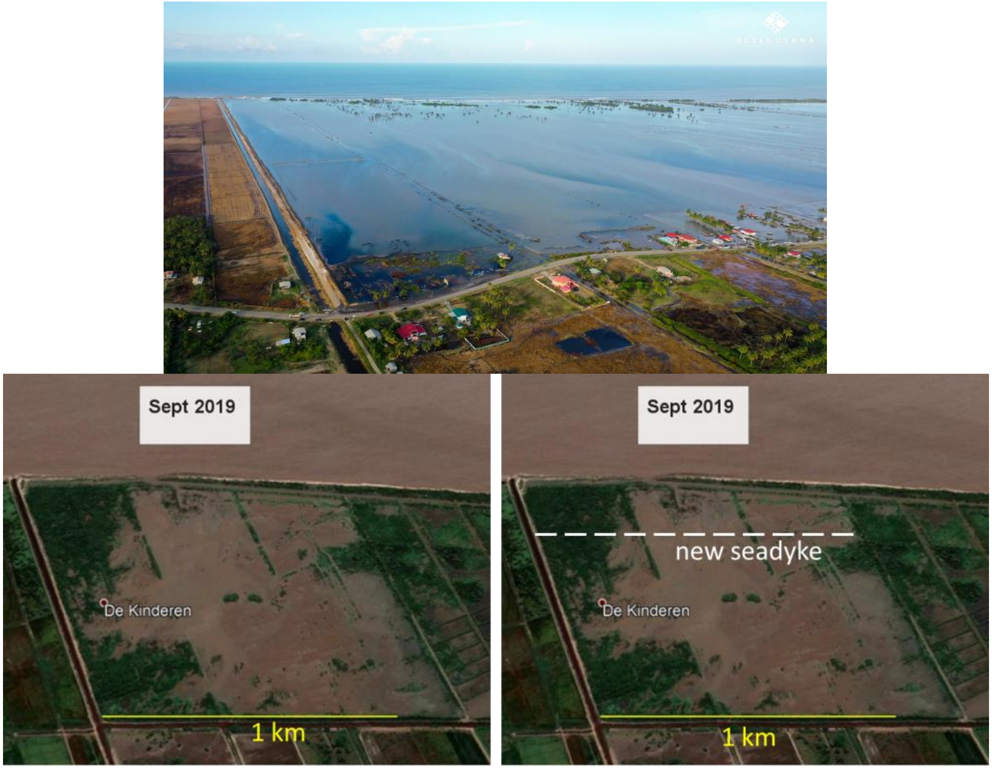


*Figure 8.1 Upper panel: breaching and inundation near De Kinderen; lower left panel: keep entire inundated polder open for sediment-laden water to enter; lower right panel: erect new embankment/seawall 100 – 200 m inland from the original one.*

An analysis of a sequence of Google Earth images suggests that the De Kinderen breach occurred in front of the arrival of a mudbank, as explained in Section 4.7. This would make the proposed opportunistic realignment timely.

## 8.3 Mangrove Fringes as Catalyst

Mangroves can be regarded as “eco-engineers” in the sense that they modify hydrodynamic conditions, sedimentation patterns and soil stability to their own benefit. When the conditions are favourable, mangrove fringes can grow rapidly. These characteristics can be used to promote mangrove developments, as the Clonbrook example below shows.

In front of the Clonbrook shoreline, close to the mouth of the Mahaica River, a small mangrove fringe of about 400 m length and 50 – 70 m width has proved a catalyst for developing Green-Grey Coastal Infrastructure, at small scale though. This is illustrated by the five Google Earth images of Figure 8.2. Upon the arrival of a mudbank between 2008 and 2011, mangroves develop in front of an existing mangrove fringe (the “catalyst”, 2011-image). From there, this new mangrove fringe develops towards the East (against the residual flow) along the solid seawall of Clonbrook, see 2013-image. This development continues, forming a 400 – 500 m wide mangrove fringe in 2017 (maximal extension), after which the fringe is eroded in the following years after passage of the mudbank. Apparently, this small fringe of mangroves within the continuous coastline can induce mudflat formation and mangrove colonization in up- and downdrift direction, thus forming a “natural” Green-Grey Coastal Infrastructure.


*Figure 8.2 Development of natural grey-green infrastructure in front of Clonbrook, close to the left bank of the Mahaica River (Google Earth images).*

## 8.4 Temporary Managed Realignment

Managed realignment/retreat is an ensemble name for interventions with the aim to restore the mangrove habitat. The ultimate argumentation is that in the end a "business-as-usual" strategy may result in larger losses than the sacrifices made for managed retreat. An intermediate policy would be introducing a concept known in The Netherlands as "wisselpolders", implying a temporary opening of a polder so that sediment-laden (sea)water can enter, heightening the polder's bed through sedimentation (e.g. Zhu et al., 2020). When the bed is high enough, the polder is closed again, prepared for re-cultivation, and a neighbouring polder is opened. The inundated polder does not have to be unproductive – temporary aqua-culture practices for instance may be considered. We refer to TOP polders, i.e. Temporary OPen polders to top up the bed. Fig. 8.3 provides a schematic of this approach.

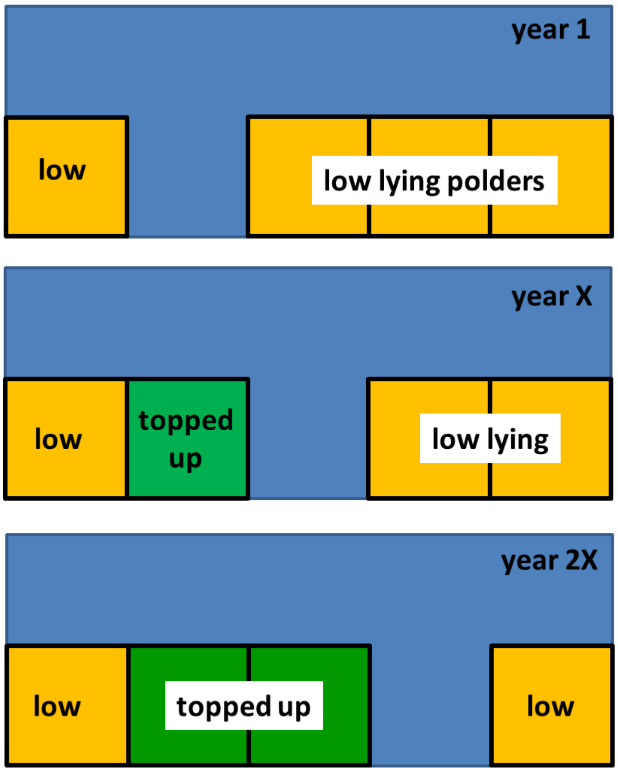


*Figure 8.3 Schematic of the Temporary Open Polder concept (TOP polder).*

In The Netherlands, some low-lying polders in the SW province Zeeland suffer from salty seepage, seriously affecting fertility and productivity of agricultural lands. Application of the

TOP polder concept would resolve these problems in the long run – studies suggest that after 10 – 20 years sufficient sediment would have deposited to restart sustainable agriculture practices. This time span, of course, is a function of the local suspended sediment concentrations, decreasing with higher concentrations. Though already on the agenda for a few decades, this concept could not yet be realized because of opposition from local stakeholders.

In Guyana, the TOP polder concept may be applicable to rise (parts of) the hinterland. The opportunistic realignment of Section 8.2 can be regarded as an example of such an approach.

# 9 Mangrove Management

This chapter briefly introduces mangrove characteristics and species, and subsequent sections describe degradation of mangrove forests, techniques for ecological mangrove restoration, suitable abiotic conditions for healthy mangrove growth and conditions when mangrove planting may be useful. The chapter then elaborates on the conditions for mangrove growth in Guyana, making specific recommendations for mangrove restoration.

## 9.1 Key Messages

- Zonation of mangrove species should be taken into account for mangrove restoration efforts, as mangrove species have different characteristics that enables them to grow in certain parts of the coastal zone.
- Pioneer mangrove species should naturally colonize intertidal mudflats if the (abiotic) conditions are suitable for mangrove growth.
- Instead of planting mangrove seedlings, first analyze the local reasons that inhibit mangrove colonization at your restoration site. Then restore the (abiotic) conditions to enable natural colonization.
- Possible intervention methods to ameliorate abiotic conditions, can consist of creek digging, sediment nourishment and erecting wave dissipating structures.
- If, and only if the availability of mangrove seeds is the limiting factor, consider enrichment multispecies planting or sowing. Common mistakes in mangrove planting are outlined in section 9.6.
- Specific recommendations for mangrove management in Guyana:
    - The minimum width of the mangrove forest during the interbank phase should still provide the necessary wave attenuation capacity to reduce the incoming wave height at the toe of the seawall. Therefore, the aim should be to develop a wide enough mangrove greenbelt during the mudbank phase, to be able to protect the coast during the next interbank phase.
    - Once mangroves start to colonize the mudflats at one location, natural colonization will extend the mangrove forest rapidly in western direction, as this is the direction of propagule dispersal. In order to extend the initial mangrove forest in eastern direction, sowing of propagules at the right window of opportunity may speed up mangrove colonization largely.

## 9.2 Mangrove Characteristics and Species

Mangroves are found along tropical shorelines around the world between 30º N and 30º S. They are located at intertidal areas, frequently inundated by tides. They have special physiological adaptations to deal with salt in their tissues and within their root systems to support themselves in soft mud sediments and transport oxygen from the atmosphere to their roots, which are largely in anaerobic sediments (Lewis, 1982). Most have floating seeds (propagules) that are produced annually in large numbers and float to new sites for colonization.

Pioneer mangrove species, such as *Avicennia*, can colonize the upper intertidal area of a bare mudflat. Mangrove habitat is found between mean sea level (MSL) and highest astronomical tide (HAT), or even between mean high water (MHW) and HAT in case of large waves (Clough, 1993). These topographies are flooded less frequently. Mangroves require areas inundated approximately 30%, or less of the time by tidal water (Lewis, 2005). Being inundated causes lack of oxygen, because their aerial roots are not able to breathe (Adams & Human, 2016).

High salinity levels by e.g. water logging can be lethal to the trees (Hossain & Nuruddin, 2016). Inundation free moments are also necessary for seedling recruitment. After propagules have stranded and established roots, juvenile mangroves can grow that can withstand considerable hydrodynamic forcing and stabilize the bed sediment, see section 9.5. Once these pioneer species have established and grown, successive species can colonize the area as well and become the dominant species at some stage.

*Mangrove species and zonation in Guyana*
Mangroves are the constituent plants of tropical intertidal forests. Communities of these halophytic (salt tolerant) plants are dominated by some trees and shrubs within the families *Avicenniaceae*, Combretaceae, *Rhizophoraceae*, *Sonneratiaceae*. In South-East Asia the family Palmae has a single genus (Nypa) that is classed as a mangrove. In addition to the main mangrove species, there are a number of other halophytic plants that are 'mangrove associates', which help to make up the overall intertidal community.

In the Guianas of South America there are a limited number of mangrove species. Traditionally three species were noted, dominated by the Black mangrove (*Avicennia germinans* (=nitida)). This plant was known local in Guyana as "courida" and this term has historically been used both for the species and for the overall mangrove fringe along the coasts. The traditional three species are: *Avicennia germinans* (Black mangrove), *Rhizophora mangle* (Red mangrove), and *Laguncularia racemosa* (White mangrove. *Rhizophora mangle* is the most common species of this genus in the region, although both *R. racemosa* and *R. harrisonii* have been recorded from British Guiana. The zonation patterns of mangrove species in the Guianas are summarized in Table 9.1.

In Guyana, large areas of the coast have become effective monoculture stands of *Avicennia* (and hence the courida fringe). There is no evidence that pioneering *Rhizophora* have been present along certain parts of the coast. This is the main pattern of mangrove development along the Atlantic coast from the Corentyne to the Essequibo River.

*Lazuncularia rac mosa* is also able to colonize these parts of the Guyana coast. On the large developing sand banks and mudflats that dominate the coast in the west Corentyne Region, *Laguncularia* and *Avicennia* are both found as pioneering species within the mudflats. At Good Hope, *Laguncularia* has colonized parts of the small developing mudflats.

The pattern of coastal *Avicennia* dominance changes along the riverbanks and the coasts adjacent to the mouths of river and creeks with *Rhizophora* dominating in the estuary and mainly along the western coast. The *Rhizophora* spread along the coast is possibly dependent on the flow rate of the river. Along the Corentyne and Essequibo Rivers, the development of seawalls has diminished the mangrove fringes, but *Rhizophora* is still present in both river mouths, and along the western coast adjacent to the mouth of the Demerara River. This pattern of riverine distribution is also reported from the San Juan River estuary and its adjacent coast in Venezuela (Pannier and Ramcharan. 1983).

This distribution in Guyana is similar to the entire coast of the Guianas, and a number of theories have been advanced to explain why *Avicennia* rather than *Rhizophora* is the pioneering species of the coast. Augustinus (1978) discusses these theories and proposes that “the sling-mud along the coast of the Guianas is so little consolidated that it can be fluidized by wave action to a certain depth”, thus preventing the settlement of *Rhizophora*. *Avicennia* embryos on the other hand can establish in this regime, and so *Avicennia* become the single pioneering species.

*Table 9.1 Zonation patterns of mangrove in the Guianas (Augustinus, 1978).*

| Zonation Pattern | Description | Species |
|---|---|---|
| **Seaward Zone** | Portion of swamps daily affected by tidal inundation including neap tides. Species found are called front liners and are of true mangroves; soil type range from sandy to sandy loam and mud flat. | A. germinans, A. marina |
| **Landward Zone** | The back portion of mangrove swamps which remains unaffected by tidal inundation, except during spring tide. Soil is generally clayey to silty clay.<br>Vegetation is diverse (vines and epiphytes). | L. racemosa, C. erectus |
| **Riverine Zone** | Portions of swamps along or indenting the river system, and mouths of rivers and canals. | R. mangle, R. harrisonii, R racemosa, R. apiculata |

To summarize, the mangrove species found in Guyana and their zonation are:

- *Rhizophora mangal* (red mangroves) is the most common species occupying soft, muddy soils especially near riverbanks, although *Rhizophora racemose* and *Rhizophora harrisonii* have also been recorded
- *Avicennia germinans* (black mangroves) is the most common pioneer species along the coastal areas not affected by erosion
- *Laguncularia racemose* (white mangroves) border mangrove swamps along the coast

*Mangrove seed availability*

In the tropics, propagules of *Avicennia* and *Rhizophora* are released throughout the year, independent of the rain season, as depicted in Figure 9.1 copied from Van der Stocken et al. (2017). Once released, the majority of the propagules remain within a few kilometres from their producing trees (Figure 9.2, right panel), half of which may survive five months floating in the water before anchoring and rooting (Clarke, 1993).

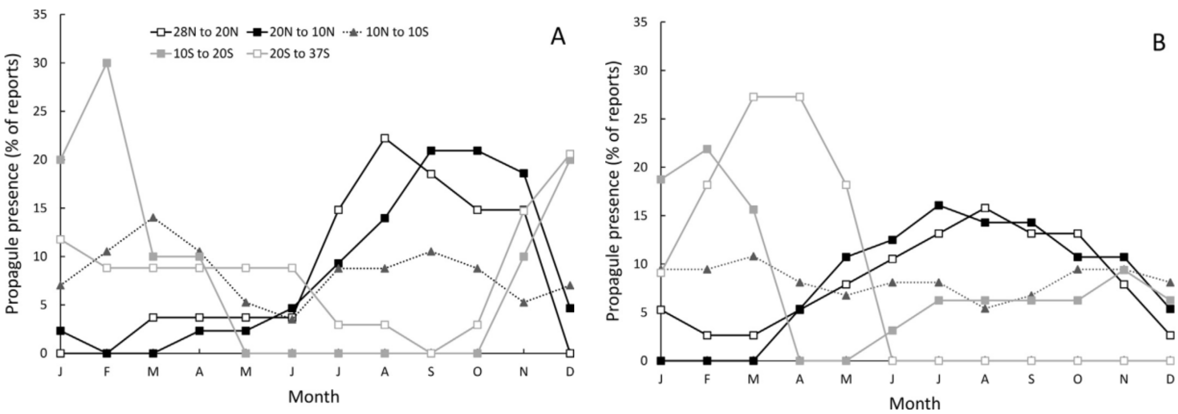


*Figure 9.1 Propagule release and availability of propagules from Avecennia (A) and Rhizophora (B) (after Van der Stocken et al., 2017).*

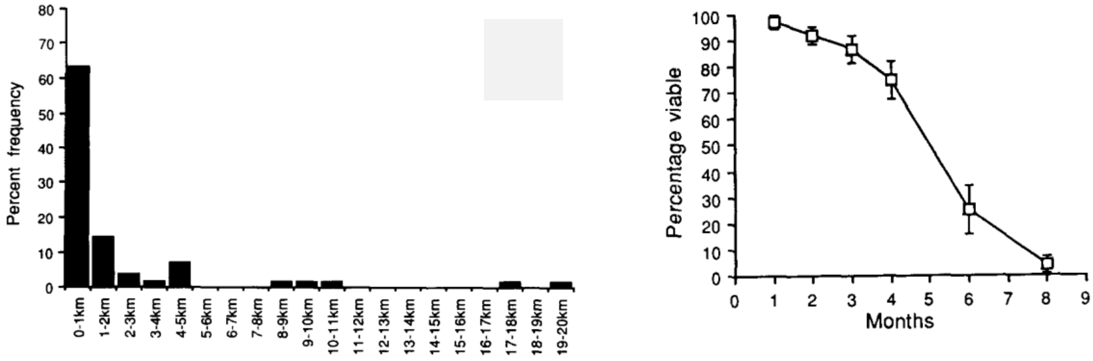


*Figure 9.2 Dispersion of Avecennia propagules from propagule producing trees (left panel) and survival time of propagules with pericarp (skin) floating in water (from Clarke, 1993).*

## 9.3 Degradation of Mangrove Forests

Worldwide, mangrove systems are under severe pressure, with a reported global decline from 18.8 million hectares in 1980 to 15.2 million hectares in 2005 (FAO, 2007). Based on these enormous rates of mangrove mortality, mangrove forests have not been managed very well. The most important cause for mangrove degradation is deforestation and land use changes aiming for short-erm economic gains. Often, mangrove forests are removed and converted to aquaculture ponds (Stevenson et al., 1999; Van Wesenbeeck et al., 2015) or agriculture plantations, as is the case in Guyana, among other types of land use (urbanization, industrialization, construction of infrastructure and even selling the mangrove timber).

Other causes of mangrove degradation are dredging and filling for coastal development (Lewis, 1977) and disruption of the hydrology of mangrove forests. The tidal and freshwater flows within the forests determine the hydrology and govern critical periods of inundation and dryness, which are important for the health of the forest (Lewis, 2005). Biogeochemical studies by Nickerson and Thibodeau (1985), McKee (1993, 1995), and McKee and Faulkner (2000) have shown that survival of healthy mangrove forests mainly depends on the depth, duration and frequency of flooding and soil saturation. Therefore, engineering works constructed in the vicinity of mangrove forests, should be designed to allow for sufficient free exchange of seawater with the adjacent ocean or estuary, and not interrupt essential upland or riverine drainage into the mangrove forest (Lewis, 2005). Not properly accounting for these essential water inputs and exchanges will lead to stress and possible mortality of the mangrove forest.

## 9.4 Mangrove Restoration Principles

Restoration of damaged or destroyed mangrove forests has been widely described in literature (e.g. Lewis, 1982, 1994, 2000; Cintron-Molero, 1992; Field, 1996, 1998; Turner and Lewis, 1997; Ellison, 2000; Lewis and Streever, 2000 and Saenger, 2002). A common method for restoring mangrove forests is simply planting of mangrove seedlings. However, this approach is not often successful, particularly when the causes for mangrove degradation were not eleviated prior to planting new seedlings or propagules (Lewis & Gilmore, 2007). When the stressors are removed and suitable environmental conditions for mangrove growth, such as hydrodynamic stressors or erosion of the sediment bed, are provided, natural regeneration processes can recover mangroves. A successful mangrove restoration project therefore not necessarily includes a planting phase (Kamali & Hashim, 2011). The above indicates the need for expert knowledge and natural system analysis (Primavera & Esteban, 2008).

Based on these principles, standard Ecological Mangrove Restoration methods for mangrove restoration and conservation were outlined by Lewis (2005):

1. The hydrology of the mangrove forests should not be disrupted. First analyze and understand the local hydrological conditions.
2. Do not just plant mangrove seedlings at an area currently devoid of mangroves. There is a reason why mangroves are not already there, were not there in the recent past or have disappeared recently. Investigate the limiting factors for natural mangrove colonization.
3. Once the limiting factors have been identified, try to restore the conditions that currently prevent natural colonization. If those conditions cannot be restored, the site is not suitable for mangrove restoration and a different site should be selected.
4. Examine the right environmental conditions corresponding to a reference system in your particular area (McDonald et al., 2016). Monitor the tidal hydrology using tide gauges to establish the same hydrology at your restoration site.
5. Mangrove forests do not have flat floors, but instead have subtle topographic variations that control tidal flooding depth, duration and frequency. Understand the elevation and small-scale topography of the reference mangrove forest floor and establish the same range of elevations at your restoration site.
6. Construction of tidal creeks within restored mangroves forests facilitates flooding and drainage. Creeks and rivers debouching in a mangrove system feed the mangroves with sediment and drain the soil (McLachlan et al., 2020). Obstructions of the flow that hamper sedimentation in the forest may affect the formation of sediment bed levels or cause water logging.
7. Evaluate costs of restoration early in project design to make your project as cost-effective as possible.

Possible intervention methods to ameliorate abiotic conditions, can consist of creek digging, sediment nourishment and erecting wave dissipating structures. Dredged sediments from the major rivers could be used for nourishments – if not contaminated - aiming to increase bed levels and reduce submergence time for mangrove recruitment (Van Wesenbeeck et al., 2021b). The implementation of permeable dams as wave dissipating structures is extensively described in section 0. Once hydrodynamic energy is dissipated and sediment is trapped to sufficiently increase the bed level, mangrove seedlings can naturally colonize the sheltered areas landward of the dams.

## 9.5 Abiotic Conditions for Mangrove Establishment and Growth

Balke et al (2011) quantified physical processes limiting the colonization of bare tidal flats by pioneer mangroves based on flume tests and field observations for *Avecennia Alba*. Their Windows of Opportunity approach consists of three phases that have to be passed until a seedling is successfully established (Figure 9.3): (1) stranded propagules need an inundation-free period to rapidly develop roots that are long enough to withstand displacement by flooding, (2) roots need to become long enough to withstand seedling dislodgement by hydrodynamic forces from waves and currents, with the required root length being proportional to the force that needs to be resisted, (3) even longer roots are needed to survive high energy events that cause sheet erosion and can thereby induce seedling dislodgement.

The first phase is governed by the effects of tides and surges on the water level and has a duration of approximately 2-3 days. During the second phase mangrove seedlings can withstand small stresses in the range of 0.2 – 0.5 $N/m^2$, depending on the root length (see Figure 9.4). Generally, a root length of 4 cm is reached after approximately 8 days. Note that increased bed shear stresses due to wave reflection especially threaten the establishment and growth of juvenile mangroves. For the third phase the critical amount of erosion is linearly correlated with the maximum root length. In practice this implies that propagules settling on an emerging mudflat just after spring tide have the largest chance to develop into *Avecennia* trees.

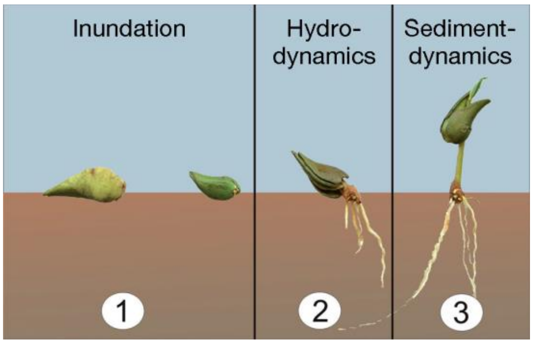


*Figure 9.3 Windows of opportunity for colonization of pioneer mangroves (Balke et al, 2011). (1) propagules need an inundation-free period for initial root development, (2) a period of limited hydrodynamic energy from currents and waves to allow root growth for withstanding seedling dislodgement, (3) a period of limited sediment bed erosion to obtain longer roots needed to survive high energy erosion events.*

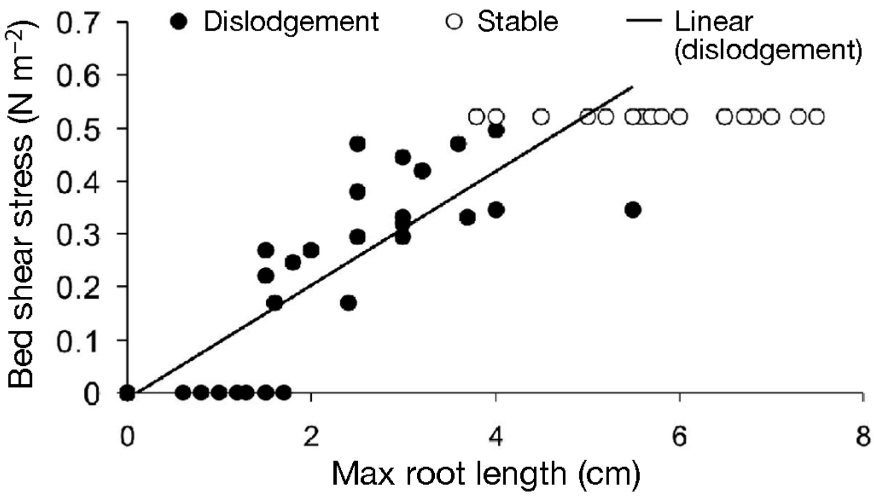


*Figure 9.4 Results of experiments by Balke et al (2011) for Avicennia alba. The hydrodynamic force expressed as bed shear stress that can be resisted before seedlings with maximum root length were dislodged from Balke et al (2011). N.B. Seedlings with ≤2 cm roots would float up when flooded, even in the absence of any waves or current. The bed shear stress experienced by seedlings on the flume bottom at the moment of dislodgment increase linearly with maximum root length. Once the maximum root length exceed 4 cm, all seedlings were stable and can resist the highest level of bed shear stress applied in the flume.*

## 9.6 Mangrove Planting

As described in the previous sections, planting of mangroves will likely not be successful as long as the abiotic conditions are unfavorable for mangrove establishment, growth and survival. Where natural recruitment does not provide the required quantity of successfully established seedlings (e.g. because seed availability is the limiting factor), mangrove planting could be considered (Lewis and Marshall, 1997). Only at locations where this is the case, the principles outlined in section 9.3 may be supplemented with possible enrichment multispecies planting. Such multispecies planting efforts should be based on a thorough understanding of the auto-ecology (individual species ecology) of the mangrove species at the site, in particular the patterns of reproduction, propagule distribution and successful seedling establishment.

Common mistakes in mangrove planting are:

- not correcting the non-suitable abiotic conditions prior to planting, which will cause killing of the planted seedlings;
- planting of the wrong mangrove species, e.g. *Avicennia spp* are more resilient against highly energetic conditions than *Rhizophora spp* (Thampanya et al., 2002), and are more resistant to fluctuations in salinity (Hossain & Nuruddin, 2016);
- planting at the unfavorable elevations, e. not between MSL and HAT but lower in the intertidal zone, consequently the planted seedlings will be killed by stresses due to inundation and seedling dislodgement;
- Planting at the wrong time with respect to freshwater availability and/or the phase of the tide.

## 9.7 Favorable Conditions for Mangrove Growth in Guyana

For proper mangrove management in Guyana, it is important to thoroughly understand the natural system dynamics, as described in Chapter 3. For Guyana specifically, the mudbanks, described in Chapter 4, are of major importance for the coastal sediment balance. Section 4.5 described the cyclic coastal response to the migrating mudbanks. When a mudbank is present in front of a pristine coast, intertidal mudflats accrete and prograde seaward. During these 'mudbank' phases, a wide mangrove forest can develop. However, during the interbank phases, the intertidal mudflats erode and mangrove habitat is lost. Following the Green-Grey philosophy outlined in Chapter 2, a wide enough mangrove greenbelt should develop during the mudbank phase, to protect the coast during the next interbank phase. Ideally, the minimum width of the mangrove forest during the interbank phase still provides the necessary wave attenuation capacity to reduce the incoming wave height at the toe of the seawall. If this approach is successful, the natural cycle of mangrove response to mudbank migration is restored, with a net accretion over longer time scales. Therefore, in general we recommend to actively promote mangrove colonization through mangrove management for all MudBank Dynamics (MBD) locations described in Chapter 13.

With respect to seed dispersal, the currents in the Guianas coastal zone follow a zig-zag pattern towards the West (as discussed in section 3.3) – they never reverse in direction towards the East. Consequently all propagules to colonize the mudflats must arrive from eastern sources, which may be far away in case of Guyana's east coast (and may therefore limit the colonization speed). Combining this information with the Windows-of-Opportunity described in Section 9.5 leads to the following recommendations.

If propagules arrive at the mudflat currently just east of Georgetown (as depicted in Figure 4.) around spring tide, they get the opportunity to anchor and root in the period towards neap tide, thus surviving the next spring tide. After a couple of years, the trees are old enough to produce propagules themselves, the majority of which will stay within a few kilometres from the trees (Clarke, 1993). Then the mangrove canopy extends rapidly in western direction, as this is the direction of propagule dispersal. This implies that if one wants to extend the initial mangrove canopy in eastern direction, sowing of propagules at the right window of opportunity may speed up mangrove colonization largely. Instead of sowing, propagules may be locally anchored in a cage, and/or juveniles may be planted, all with the aim to produce propagules at the desired locations.

Propagules need freshwater to grow. In the natural system the most favorable conditions for freshwater therefore occur during the wet season. On the other hand, wind speeds are lower during the wet season, which causes lower wave heights and therefore less mudflat formation (which is necessary to provide favorable bed level elevations). This trade-off between favorable hydrological and morphological conditions may limit the available period in which natural mangrove colonization can occur and should be investigated in more detail to identify the most suitable period of the year for mangrove establishment.

## 9.8 Recommendations for Mangrove Restoration in Guyana

Ecological Mangrove Restoration methods for mangrove restoration and conservation by Lewis (2005) are further elaborated for the coastal zone of Guyana:

1. Currently this does not seem to be a major issue in Guyana (see Chapter 14), but hydrological aspects should be taken into account when designing new Coastal Infrastructure. More specific recommendations on freshwater management are provided in Chapter 14.
2. Instead of planting, the limiting factors for natural mangrove recruitment should be investigated. A natural factor that may limit natural mangrove recruitment is formed by the migrating mudbanks. During interbank phases, the coastline is more exposed for wave impact, resulting in mangrove mortality and erosion of the mudflat. Moreover, choosing the right location is very important, as mangroves require areas inundated approximately 30%, or less of the time by tidal water (Lewis, 2005). Mangrove habitat is therefore located at elevations between mean sea level (MSL) and highest astronomical tide (HAT), or even between mean high water (MHW) and HAT in case of large waves (Clough, 1993). Manmade causes that limit natural mangrove recruitment include construction of infrastructure (e.g. dredging and filling for coastal development), in the vicinity of mangrove forests, without considering the free exchange of seawater with the ocean or essential upland or riverine drainage into the mangrove forest (Lewis, 2005).
3. Correcting the conditions that prevent natural colonization depends on the specific local causes (as analyzed in step 2). Important measures include sustainable land use (i.e. assigning designated areas for mangrove restoration), providing favorable hydrological conditions and restoring the sediment balance. It may be necessary to select a different site with the right hydrological conditions or bed level elevations.
4. A reference system where natural mangrove recruitment occurs should be selected in the same coastal area. Do not copy solutions from locations across the world, but instead learn from natural success stories in the same coastal system. Investigate the hydrology, topography of the bed, local wave conditions and the sediment balance at the reference site. Monitor and understand the conditions that are favorable for mangrove colonization in your coastal system.
5. Establish the same range of favorable conditions at your restoration site for the hydrology, topography of the bed, wave conditions and sediment balance.
6. Possible interventions methods to ameliorate abiotic conditions, can consist of creek digging, sediment nourishment and erecting wave dissipating structures:
    a. Construction of tidal creeks within restored mangroves forests facilitates flooding and drainage. Creeks and rivers mouthing in a mangrove system feed the mangroves with sediment and drain the soil (McLachlan et al., 2020). Obstructions of the flow that hamper sedimentation in the forest may affect the formation of sediment bed levels or cause water logging.
    b. Nourishment with sediment aims to increase bed levels and reduce submergence time for mangrove recruitment (Van Wesenbeeck et al., 2021b).
    c. The implementation of permeable dams as wave dissipating structures is extensively described in section **Error! Reference source not found.**. Once h ydrodynamic energy is dissipated and sediment is trapped to sufficiently increase the bed level, mangrove seedlings can naturally colonize the sheltered areas landward of the dams.

7. Learn from previous mangrove restoration projects, which are described in section II.7.3. Evaluate costs of restoration early in project design to make the project as cost-effective as possible.

On top of these principles to enable natural mangrove colonization, some additional measures are suggested specifically for the local conditions in Guyana:

- Protecting mangrove trees from breaking and uprooting by use of cages made from biodegradable materials.
- Protecting mangrove propagules from dislodgement by binding them to small wooden sticks, applying reefballs (although this is quite costly) or using biodegradable fascine mattresses or coconut fibre mattresses.
- Steering the freshwater outflow from the hinterland that is now discharged by sluices towards the mangrove habitat.

More detailed recommendations on mangrove restoration in Guyana with respect to spatial planning are provided in Chapter 13.

## 9.9 Previous Mangrove Restoration Projects in Guyana

The management and rehabilitation of mangroves in the coastal system falls under NAREI, the National Agriculture Research and Extension Institute. As a follow-up on the Mangrove Restoration Project, the Guyana Mangrove Restoration and Management Department was integrated within NAREI. Various rehabilitation projects were initiated (Figure 9.5), amongst which: 1) Planting of mangrove and Spartina grass, 2) Construction of sediment traps, permeable dams and breakwaters, 3) Construction of restrictive gates and fences to reduce the impact of anthropogenic activities, 4) Community based mangrove management and livelihood initiatives such as tourism and beekeeping and 5) Extensive public awareness and education (Bovell, 2019).

Based on data from the most successful sites and comparison with the natural forest, NAREI has established a guideline for planting *Avicennia germinans* at 2.3 - 2.7 m above chart datum. During 2010-2018 over 500,000 seedlings were produced in community nurseries and planted along the coastline. Permeable dams were constructed with local, resilient bamboo, which has a lifetime of about 3 – 7 years, to form Sediment Trapping Units (STUs) as elaborated further in Chapter 13. Figure 9.6 shows an aerial photo of some of the dams erected near Georgetown. The dams near Georgetown did not have durable results. The reasons for this lack of success have not been reported in detail, although Bovell (2019) mentions that "the sites that were lost were the ones that were planted with *avicennia* seedling alone and probably suffered as a result of inadequate sedimentation due to the dynamic nature of the shoreline and the rapid changes which occurred". However, along the left bank of the Essequibo River (Anna Regina and Devonshire Castle, west of Georgetown) 1.5 – 2 m siltation was monitored behind a 100 m long dam between 2013 and 2016. The higher siltation rate yielded bed levels a bit higher than the optima for mangrove rehabilitation. Part of the mangrove planting took place on these deposits. Moreover, Bovell (2019) reports that the experience of mangrove restoration activities between 2010 and 2018 has shown effective methods for establishing coastal structures nearshore to reduce wave impact and allow sediment accumulation along the coastline. The structures have created suitable conditions for natural mangrove colonization and planted seedlings have thrived at these locations.

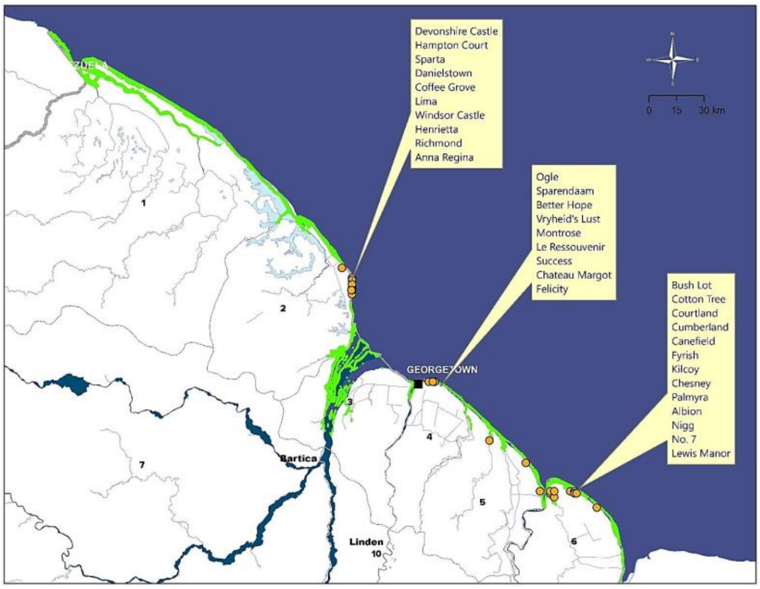


Figure 9.5 Various rehabilitation projects initiated by NAREI

*Figure 9.6 Aerial photo of some of the dams erected near Georgetown*

# 10 Setting up a Master Plan

Implementation of Green-Grey Coastal Infrastructure along Guyana's shoreline requires long-term commitment from and planning by the national government and other authorities/institutions. This can be achieved by making Green-Grey Coastal Infrastructure part of an Integrated Coastal Zone Management (ICZM) Master Plan. Such a Master Plan should embody a holistic and integrative approach to address complex social and ecological issues in the coastal area. It seeks to engage participation and cooperation of all stakeholders to realize the overall goal of having a sustainable and resilient Guyana coast by harmonizing sectorial objectives (environment, economic, social, cultural and recreational). Over the last decades, efforts by the Guyana government and consultants have resulted in valuable material for an ICZM Master Plan. Recent developments include the update of the Sea Defense Act, and the national Low Carbon Development Strategy. In this chapter we will discuss how the technical guideline for Green-Grey Coastal Infrastructure could be adopted in an ICZM Master Plan. More information on ICZM Master Plan development can be found in guidelines such as World Bank (2017) or example Master Plans such as the Manila Bay Sustainable Development Master Plan (NEDA, 2020).

## 10.1 Developing an ICZM Master Plan

An ICZM Master Plan is based on proper system understanding, including the natural, social-economic and institutional system (EcoShape 2020). It should be borne in mind that the elements are intricately linked and mutually dependent. Hence, failure of one element may jeopardize the entire Green-Grey strategy. With this knowledge, the Master Plan can be organized in line with the hierarchy in nature's coastal processes, such as the dominant role of the migrating mudbank complexes (Section 4), covering all components of the natural system involved, e. physics, biology and ecology. A Master Plan should also distinguish between the regional scale of the entire Guyana coastal system, and a variety of local scales, which can be managed as spatial entities, as elaborated in Chapter 13.

**The green part of the Green-Grey Coastal Infrastructure will not protect the low-lying coastland from flooding, hence seawalls and embankments remain necessary.** A proper inventory of the status of these structures is therefore necessary as well, including an inspection program, which should be part of the Master Plan. Possibly, requirements for these grey elements must be adapted, amongst others in response to climate change effects. This evaluation is preferably based on a risk assessment, which consists of an analysis of the hazards to be expected, including the effects of climate change, the exposure, which includes an analysis of the socio-economic conditions of the hinterland, and an analysis of its vulnerability, such as possible mitigating measures against flooding (e.g. United Nations, 2015; and various IPCC reports).

Any Master Plan should start with explicitly formulating the objectives and sub-objectives to be met – these sub-objectives may differentiate for different coastal regions/districts. Chapter II.4 proposes that along most of the coastline east of the Demerara River, up to the Corentyne River, Green-Grey Coastal Infrastructure should be based on restarting the mudbank motor generating intertidal mudflats along the existing embankments, to form mangrove habitat on intertidal mudflats. Part II describes how this can be realized, while the Master Plan should set the objectives in terms of areal to be recovered, width of the mangrove greenbelt to be realized, budgets allocated, etc. Locally along this coastline, in the vicinity of the smaller and larger rivers, and west of the Demerara River, other interventions are proposed (Section II.4), for which objectives must be set as well. Within an ICZM Master Plan, these objectives ideally cover multiple functions of the coast such as flood risk reduction, livelihood and ecosystem health.

One of the large challenges of implementing grey-green coastal defense infrastructure at the large scale proposed here is the long time frame and large budgets to be allocated permanently to this approach. These time frames exceed political horizons largely, and commitment should not become dependent on the political wind that may blow one day. The Netherlands was facing a similar dilemma. This was solved by drafting the “Delta Law”, which legally formulates how managing authorities in The Netherlands should respond to the effects of climate change. This law formulates the distribution of responsibilities between the various ministries and (governmental) institutions as well.

## 10.2 Institutional Embedding

Institutionalization and enforcement are important for effective implementation of ICZM (NEDA, 2020). To support ICZM in Guyana, the Sea and River Defence (SRD) legislative bill is currently being updated. One of the adjustments was to better recognize the role of mangroves as natural flood defenses. This update is an important step towards the planning and implementation of Green-Grey Coastal Infrastructure.

In the different phases of drafting an ICZM plan, implementing local measures and monitoring and maintaining the coastal defenses, both ‘vertical’ and ‘horizontal’ cooperation between different governmental authorities can increase effectiveness. Vertical cooperation refers to aligning the strategy planning on national level of ministries with the local level of the democratic councils in the coastal villages. International cooperation between the Guyanese government and neighboring countries is also an example that through exchange of knowledge on the system behavior and effectiveness of coastal protection measures can help in optimizing the ICZM plan and implementation. Horizontal cooperation of the relevant agencies across different sectors should lead to coordination and integration of activities and avoid policy conflicts (Bhola-Johnson, 2019). Only for mangrove management, many different agencies have jurisdiction. These include the Ministry of Public Infrastructure (MoPI), Guyana Forestry Commission (GFC), Ministry of Agriculture (MoA), National Agricultural Research and Extension Institute (NAREI), the Municipalities of Georgetown and New Amsterdam, Guyana Lands and Surveys Commission (GLSC), Environmental Protection Agency (EPA) and the Local Democratic Organs of the Ministry of Communities. Adding the agencies responsible for Sea Defense, one can imagine that coordination and alignment of all these agencies is a difficult task. A shared and adopted ICZM Master Plan can play an important role in the coordination between these agencies.

## 10.3 Stakeholder Involvement

Stakeholders need to be engaged throughout the process of the ICZM planning and design of projects. Relevant stakeholders can be identified for green-gay infrastructure projects, using for example a power-interest matrix (Green-Grey Community of Practice, 2020). In 2018, stakeholder consultation took place to revise Sea Defense Acts and Disaster Risk Management (MOPW, 2018) There, weighting of the different interests, costs and benefits should be executed with extra care/caution. If Guyana authorities would contemplate on a pro-active or passive “managed realignment” strategy (Chapter 8), in combination with the TOP polder concept or not, extensive dialogues with local communities/stakeholders is a must for local acceptance and support. Successful small-scale pilot projects could serve as a show case to convince local stakeholders.

The grey-green coastal defense infrastructure will be implemented mainly along the existing embankments and seawalls of Guyana coastal system. As the majority of the Guyanese people lives along the coast, one of the relevant stakeholder groups are local communities. As part of the North Brazil Shelf Mangrove Project, an assessment of local community beneficiaries of mangrove forests was performed in Guyana (Bollini et al., 2019). In Guyana, local community beneficiaries of mangrove ecosystem services were identified to include fisher folk, those employed in the tourism, sugar, or rice industries or agriculture more generally, beekeepers, coastal ecotourism operators, indigenous communities, women, and communities that live along the coast. In addition to the benefits of Sea Defense of Green-Grey Coastal Infrastructure, these community beneficiaries will profit additionally to the restoration of mangrove habitat. Small-scale economic use of the mangrove fringes, such as (crab)fishing, honey production, etc. may be encouraged to stimulate local stakeholder involvement. Also eco-tourism may add to rising awareness and some additional economic activities for the local communities. The Bio-rights concept (van Eijk & Kumar, 2009) was developed and applied in Indonesia to involve local stakeholders in coastal management and eco-system services in return for short term (financial) incentives.

Communication about the effectiveness of Green-Grey Coastal Infrastructure is important. Without support of the governmental authorities and (local) stakeholders, the implementation of Green-Grey Coastal Infrastructure will most likely not be successful. To this date, ‘hard’ solutions are still perceived as most effective for flood risk reduction both by many inhabitants and governmental officers. This technical engineering guideline can play a role in transferring knowledge on the effectiveness of Green-Grey solutions for the coast of Guyana.

## 10.4 Technical Engineering Plan

Based on the system understanding, risk assessment and the Master Plan objectives, a strategy for ICZM can be developed. The interventions can be selected for the different coastal sections, based on their effectiveness, cost-benefit analysis and the local needs and capacity. The planning of the actual interventions can then be captured in the Technical Engineering Plan (TEP), which describes locations of interventions, inventory of materials required, construction methods, maintenance and monitoring plans, etc.

Thus the MP shall cover a period of about one century and contain the following ingredients:

1. An outline of the **understanding of the natural system** as presented in Part I of the Guidelines, updated with data, and the results of possible further studies,
2. **Evaluation of the status of grey coastal infrastructure**, and assessment of future design conditions and requirements,
3. An overall **monitoring/survey plan** to establish location and size of the mudbank complexes and their migration speed; assessment of the intertidal mudflat extensions and development,
4. Assessment of **priorities** and site selection; establishment of type of interventions,
5. Explicit formulation of **objectives and targets** for each selected site,
6. A **scheme to evaluate lessens-learned and update the TMP accordingly** – it is recommended that interventions, successes, and failures are punctually recorded in a logbook available for future generations of coastal managers,
7. **Detailing** TEP’s for each selected site, consisting of:
    a. local design conditions (waves, currents, fresh water, availability of propagules),
    b. a local and recurrent surveying plan, and its execution,
    c. detailed spatial and temporal planning to initiate interventions,
    d. construction plan and inventory of construction materials required,
    e. a mangrove management plan – kind of species, sowing, planting, etc.,
    f. a hydrology management plan, addressing sluiced fresh water, drainage of the mangrove fringes, etc.
    g. a debris management plan,
    h. a monitoring plan,

i. a maintenance plan,
j. budgets required, and
k. a scheme to analyze monitoring results and update the TEP's accordingly.

## 10.5 Adaptive Approach

The time scales of the natural system are governed by the migration of the mudbank complexes, which covers several decades. At a higher level, a time scale of about one century has been identified at which large-scale variations in Trade Wind speed and direction have been observed (Augustinus, 2004), affecting size and migration speed of the mudbank complexes. The Master Plan should therefore cover a time frame of about one century, which requires frequent updating of the Master Plan, accounting for new data and findings – the Master Plan requires an adaptive approach and should be a “living document”. Governing authorities should ultimately responsible that such updates are carried out and implemented. Not only the natural processes themselves are uncertain, but also the response of the natural system to the interventions proposed. These interventions should therefore be adaptive, hence the ICZM Master Plan and Technical Engineering Plan should be adapted to the lessons-learned. This is at the heart of the Building with Nature approach advocated in these Guidelines.

## 10.6 Monitoring and Maintenance

Part I of the current Guidelines presents a concise overview of our understanding of the natural system, but it is not complete, as detailed data are scarce. Yet, from the available data, it is concluded that the natural system is characterized by large variability, such as the size and migration speed of the mudbank complexes. These uncertainties are likely to increase over time, owing to uncertainties in hydrodynamic boundary conditions in response to climate change, such as sea level rise, modifications in the Trade Wind system, and frequency and severity of storm conditions. Surveying and monitoring therefore forms an important part of the Master Plan (Section II.9).

When Green-Grey Coastal Infrastructure is adopted as a flood risk management strategy, a few years of negligence can dangerously increase risks of flooding and may yield high costs to mitigate/recover damages later. Therefore, monitoring and maintenance of the (Green-Grey) Coastal Infrastructure is an important issue of which responsibilities, financial and technical support should be arranged beforehand. The ICZM Master Plan can be used to formulate how long-term commitment to the ICZM strategy can be guaranteed.

Local communities can be involved in monitoring and maintenance of Green-Grey Coastal Infrastructure. This requires communication with and education of local communities, preventing illegal mangrove cutting such as in 2015 behind Kitty groyne (Section 7.3). Several public awareness and education programmes have been undertaken by GMCS and NAREI to solicit the involvement of stakeholders in the mangrove management process (Bhola-Johnson, 2019). In addition law enforcement and legal provision is needed to prevent illegal cutting of mangroves (Bhola-Johnson, 2019). Involvement of local communities in monitoring and maintenance is already seen in de appointment of local rangers by NAREI to monitor the sea defenses with a form that is similar for all regions, allowing for national analysis of data. In a similar way, monitoring and maintenance of mangrove forests and permeable dams could be allocated to or in cooperation with local communities. Bhola-Johnson (2019) addresses that the cooperation with and involvement of local communities in monitoring and maintenance can be facilitated by improving the legislation that allows for the transfer of governance authority to local communities and NGOs, in addition to providing technical and financial support. Also, participation of private landowners could be strengthened.

# 11 Coastal Structures

This chapter builds onto the more generic concepts for seawall design in combination with fronting mangroves provided in Chapter 2 and describes:

- the existing coastal management districts in Guyana;
- the existing coastal flood risk management structures;
- methods to inspect the current state of these structures; and
- considerations for combining mangroves and structures in the Guyana coastal system.

## 11.1 Coastal Management Districts

The management of the Guyana coastal system is organized through regions and districts (Planet, 2016), as indicated in Figure 11.11.1. The borders between the various districts are defined by rivers, from West to East: District 1 is located to the West of the Essequibo River; Districts 2 and 3 are located in the Essequibo River mouth; District 4 is located between the Essequibo River and the Demerara River; District 5 is located between the Demerara River and the Mahaica River; Districts 6 and 7 are located between the Mahaica River and the Berbice River; District 8 is located east of the Berbice River till the Corentyne River, border with Suriname. Estimates of the vertical elevation of the districts are provided in Table 11.1.

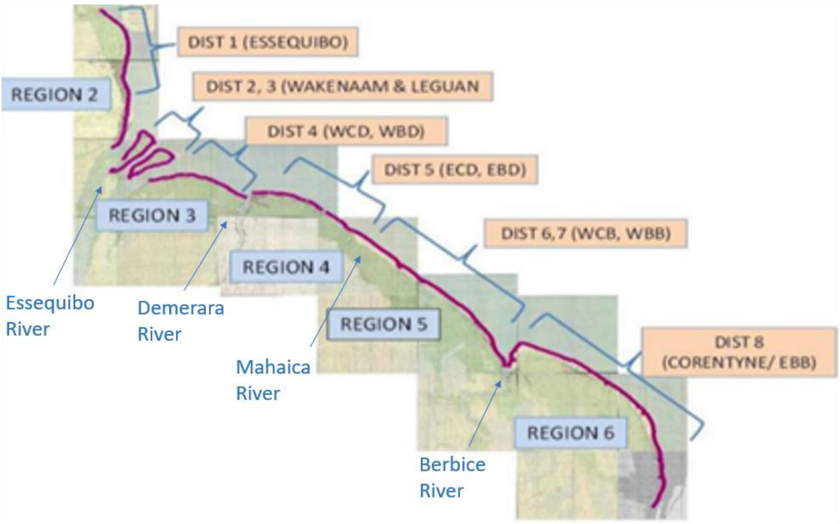


*Figure 11.11.1 Regions and districts according to Sea Defense Act. These districts cover the coastal stretches abbreviated as: WCD: West Coast Demerara; WBD: West Bank Demerara; ECD: East Coast Demerara; EBD: East Bank Demerara; WCB: West Coast Berbice; WBB: West Bank Berbice; and EBB: East Bank Berbice.*

*Table 11.1 Rough estimates of Ground-levels relative to Guyana Datum (15.56 m below MSL) and relative to the current Mean Sea Level (MSL) along the coast, from NEDECO (1972)*

| District | Location | Level relative to G.D. (m) | Level relative to MSL (m) |
|---|---|---|---|
| **1** | Essequibo West Coast<br>1. Maria's Delight – Hampton Court<br>2. Hampton Court – Suddie<br>3. Behind Tiger Island<br>4. Essequibo river banks | <br>15.7<br>15.5<br>15.7<br>16.0 | <br>+0.14<br>- 0.02<br>+0.14<br>+0.44 |
| **2 and 3** | Essequibo Islands, Wakenaam and Leguan | 16.0 | +0.44 |
| **4** | Demerara West Coast<br>1. Paprika – Uitvlugt<br>2. Uitvlugt – Vreed en Hoop | <br>16.0<br>15.7 | <br>+0.44<br>+0.14 |
| **5 and 6** | Demerara East Coast and Mahaica<br>1. Georgetown – Planters Hall | <br>15.2 | <br>-0.32 |
| **7** | Berbice West Coast<br>1. Planters Hall – Rosignol | <br>16.2 | <br>+0.59 |
| **8** | Berbice East Coast and Courentyne Coast<br>1. New Amsterdam – No. 63<br>2. No. 63 – Crabwood Creek | <br>16.5<br>16.8 | <br>+0.90<br>+1.20 |

## 11.2 Description of Existing Coastal Structures

Lees (2009) extensively described the sea defense structures and their status at the time. The condition of the structures must be inspected frequently as part of the Green-Grey Coastal Infrastructure approach. Here, a brief, largely qualitative overview is provided of the different types of sea defenses and their historic application. This overview is not complete because of lack of accessible data.

The existing coastal defense structures up to the early 1970s are described by NEDECO (1972). According to the most recent estimates (Lees et al., 2009), sea defence structures along the Guyana coast include:

- 100 km of concrete seawalls
- 170 km of earthen embankments (of which 50 km are in critical condition with no mangrove left in front and in urgent need of rehabilitation);
- 130 km of natural mangroves is said to be eroding rapidly.

Table 11.2 provides an overview of the types of sea defenses in the coastal districts. Though in reality these individual types of sea defenses are often mixed, either by design (e.g. earthen slopes behind mangroves) or as a result of poor management.

Other areas of the coastline are not additionally protected from coastal flooding. In the early 1970s natural sand reefs (the cheniers) were present in front of 47 km of coastline, which dissipated wave energy and provided reasonable protection from flooding in some areas but were found inadequate as permanent sea defenses as they cannot withstand erosion (NEDECO, 1972), see also Section 4.6. Nowadays these natural sand reefs are largely supplemented with structures, but along some small stretches of the Berbice West and East Coast, these sand reefs remain the only remaining coastal protection.

*Table 11.2 Overview of sea defenses along the coast of Guyana in the 1970s (NEDECO, 1972) and 2000s (Lees et al., 2009)*

| **1970s** | **District** | **Length of sea defense** | | | | |
|---|---|---|---|---|---|---|
| | | **Earth dams** | **Seawall** | **Mangroves** | **Reefs** | **Total** |
| **1** | Essequibo West Coast | 16.0 | 7.0 | N/A | 2.8 | **25.8** |
| **2** | Island Wakenaam | 16.7 | 3.3 | N/A | - | **20.0** |
| **3** | Island Leguan | 12.4 | 3.7 | N/A | 6.8 | **22.9** |
| **4** | Demerara West Coast | 9.5 | 10.0 | N/A | - | **19.5** |
| **5** | Demerara East Coast | 5.3 | 12.6 | N/A | - | **17.9** |
| **6** | Berbice West Coast I | 28.9 | - | N/A | 12.3 | **41.2** |
| **7** | Berbice West Coast II | | | | | |
| **8** | Berbice East Coast (incl. Courentyne Coast) | 17.0 | 6.6 | N/A | 25.4 | **49.0** |
| | **Total length of sea defense (km)** | 106 | 43 | N/A | 47 | **196** |
| | **Typical defense (% of total length)** | 54% | 22% | N/A | 31% | **100%** |
| **2000s** | **District** | **Length of sea defense** | | | | |
| | | **Earth dams** | **Seawall** | **Mangroves** | **Misc.** | **Total** |
| | **Total length of sea defense (km)** | 170 | 100 | 130 | 25 | **425** |
| | **Typical defense (% of total length)** | 40% | 24% | 31% | 6% | **100%** |

This guideline on Green-Grey Coastal Infrastructure may be considered in line with those recommendations and a first step for the technical point of view.

Earth dams are present along long stretches of coastline. In some areas slope or toe protection is applied to these dams with or without copings, whereas the majority of the dams is not additionally protected (Van Duivendijk and Pieters, 1983).

A variety of seawalls is applied along the coastline, with boulder face slopes, boulder grouted slopes, concreted faces boulder slopes and reinforced concrete slopes. Many types of copings (finishing) have been applied on the seawalls (NEDECO, 1972). The crest height of the seawall is rather low at some locations, although it should be noted that the coastal defense structures are not designed to prevent all wave overtopping. Currently the structures have been designed to limit wave overtopping to 20 L/s/m seawall (Lees, 2009), thus much higher than the maximum discharge of 2 L/s/m seawall recommended to avoid damage to the crest and back slopes (MacDonald, 2060). Section 2.3 describes the relevant background concepts on wave overtopping and provides additional guidance for design of the seawall.

In recent years, the need to encourage accretion and stabilization of coastal mud banks is increasingly recognized and resulted in the construction of rubble-mound groynes and groynes consisting of geotextile tubes, as well as brushwood sediment trapping units (Boven, 2019). These types of structures are not considered as coastal defense structures, but as sediment management measures, and their application is elaborated in Chapters 13 and 15.

## 11.3 Inspection of the Current State of Existing Coastal Structures

The current state of the existing coastal flood risk management structures, i.e. the existing embankments, seawalls and dikes, must be thoroughly inspected before implementing any new measures. Inspection should include structural integrity of the structure itself as well as the surrounding soil to identify maintenance and reparations requirements. An extensive guidance for inspection and monitoring of structures is included in The Rock Manual (CIRIA, CUR, CETMEF, 2007) {Chapter 10}.

The Shore Zone Management System (SZMS) is a GIS-based database system and was established in 2011 as a monitoring and strategic planning tool for the Sea and River Defense Division (SRDD). It contains condition survey data for approximately 244 km of coastal flood risk management structures for regions 2, 3, 4, 5 and 6 (Planet, 2016). Recommendations on monitoring and maintenance are elaborated in Chapter 17.

## 11.4 Considerations for Combining Mangroves and Structures in the Guyana Coastal System

In Chapter 2 generic considerations for combining mangroves and structures are provided. This section elaborates on these considerations specifically for the Guyana coastal system.

*Wave reflection*
As explained in Section 2.5, wave reflection may cause mangrove mortality and erosion of the sediment bed in front of structures. Therefore, it is recommended to minimize wave reflection in the design of new structures or redesign existing structures. This can be achieved by maximizing the wave dissipation, or in front of the structures (Section 7.3 and Chapter 13). If no structure is present along the coast yet, the position of any newly constructed structure should be carefully selected, such that it does not induce wave reflection. A main rule of thumb is to not construct new seawalls in the intertidal area, but above the high astronomical tidal level, thereby reducing the incoming wave energy as much as possible.

If an existing structure provides the necessary flood risk reduction, wave reflection can be minimized in four stages:

1. Where possible, a wide and stable convex-up mudflat should be aimed at to significantly reduce the incoming wave energy;
2. Where conditions are favorable, a wide mangrove greenbelt can further dissipate wave energy;
3. Where necessary, dissipative elements (such as a rough slope or rock armor) in front and on the slope of the structure can dissipate wave energy;
4. Application of the permeable groynes discussed in Section 7.3.

*Wave run-up*
Wave run-up does not play a big role in the Guyana Coastal system, since governing wave heights are relatively small and vertical seawalls – which have limited wave run-up – have been constructed along large parts of the coast. However, even minimal wave run-up may destabilize structures, in particular sea dikes, and also plays a role in wave overtopping. Measures to reduce wave reflection may cause additional wave run-up, if wave energy is not dissipated. Therefore, the recommendations to minimize wave reflection all aim to dissipate wave energy.

*Wave overtopping*
When combining conventional coastal defense structures with a mangrove greenbelt, the incoming waves are attenuated, reducing the wave height at the toe of a structure. Consequently, the wave overtopping discharge and the wave impact on the structure decrease, which reduces the required seawall crest height as explained in Section 2.3 and can reduce

the damage to the structure and associated maintenance needs. Thereby, the construction and maintenance costs are both reduced.

# 12 Design Boundary Conditions & Return Periods

## 12.1 Introduction

For the design of flood risk and sediment management measures, typically a safety standard is used in terms of a *return period* of certain water level and wave conditions. The return period is a statistical recurrence interval and is expressed as a number of years (e.g. conditions that occur once in 10 years). It states how often a certain condition (e.g. wave height of 2.0 m) is exceeded on average. This is based on the probability of exceedance of that condition and is therefore a statistical parameter. Crucially, the return period does not indicate when that condition occurs, nor its short time frequency (e.g. a ten-year occurrence may occur two subsequent years).

The return period for the design of coastal protection measures should be selected by the responsible authorities based on the desired safety level and an acceptable risk level, taking into account socio-economic aspects as well. For example, a measure can be designed for conditions that are exceeded typically once in 10 years (i.e. a return period of 10 years) or once in 100 years. The hydrodynamic conditions for 100 years will be more severe than that of 10 years, and the associated costs to achieve that safety level will be higher accordingly. This use of return periods is a well-known method for conventional 'grey' measures. For combined 'Green-Grey' measures, however, this is a rather new concept. Since green measures (e.g. permeable dams) have a more dynamic character (e.g. mudflat, mangrove) than grey measures (e.g. seawalls), the associated lifetime can be much shorter (e.g. 5 years in a dynamic coastline). The lifetime of a stable mangrove forest is considerably longer (i.e. 50-100 years).

This chapter outlines how the return period of design boundary conditions can be determined. As an example, the relevant return periods are determined for the design wave height. Note that this example computation is only meant for illustrative purposes and should not be used for design projects. Moreover, a similar analysis should be executed to determine other relevant design parameters, such as the design water level. In the remainder of this chapter the available wave data is described in Section 12.2 and a wave data analysis is carried out in Section 12.3 to obtain return periods for extreme wave heights and wave periods at Guyana coastline. Finally, Section 12.4 recommends on the use of return periods for implementation of Green-Grey Coastal Infrastructure in Guyana.

## 12.2 Wave Data Set

To analyze long-term wave statistics, it is important to use a data set that covers at least a few dozen years or more (Holthuijsen, 2007). For example, ERA5 wave data[1] is a good resource and was used for this example analysis of long-term wave statistics. This dataset contains a hindcast of hourly estimates for many atmospheric, land and oceanic climate variables for the period 1979-2017. Data was extracted at three locations on a transect close to Nieuw-Amsterdam (5° 52' 21.51" N , 58° 02' 38.82" W; Figure 12.1):

- P1 (6.375 N; -57.375 W): 10 km offshore (may be affected by proximity to coast)
- P2 (6.500 N; -57.250 W): 30 km offshore
- P3 (6.625 N; -57.125 W): 50 km offshore

[1] Source: https://www.ecmwf.int/en/forecasts/datasets/reanalysis-datasets/era5

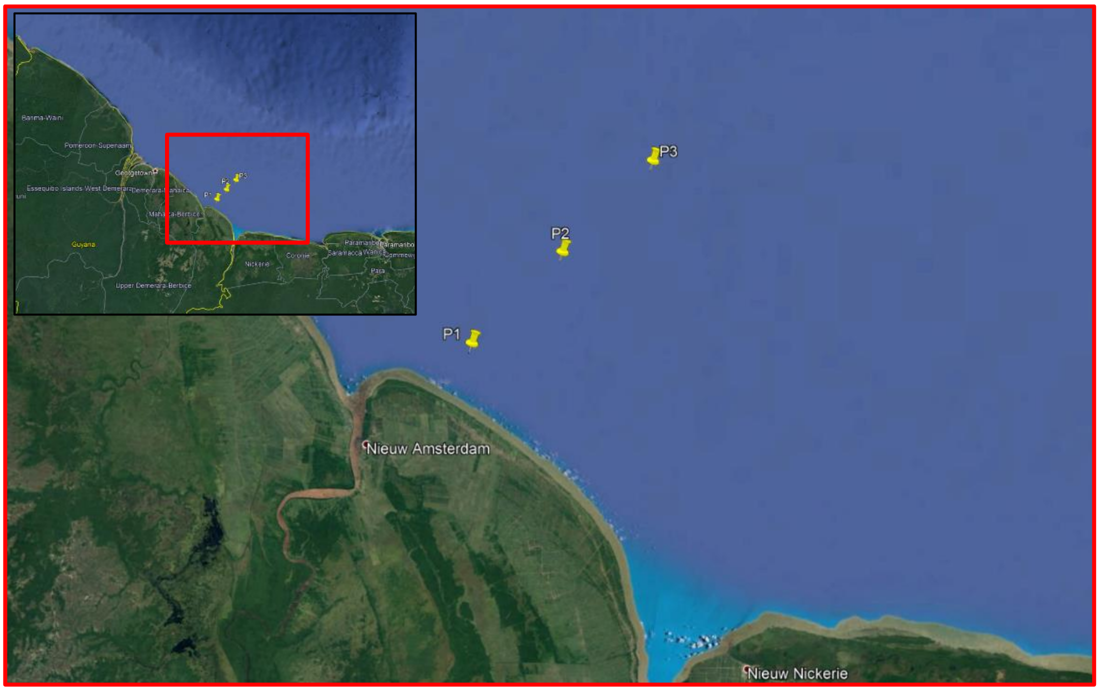


*Figure 12.1 Location of the transect at which the ERA5 wave data was extracted, in front of the coast of Nieuw-Amsterdam at locations 10 km offshore (P1), 30 km offshore (P2) and 50 km offshore (P3). The smaller panel (top left) provides a large-scale perspective of the Guyana coastline, and the larger panel (red box) provides a zoom near Nieuw-Amsterdam.*

## 12.3 Wave Data Analysis

*Wave characteristics*

The wave data contains relevant wave characteristics on the significant wave height, the mean wave period, the mean wave direction and the wind speed. Time series of wave height are included in Figure 12.2 . The average wave height and wave period at locations P1, P2 and P3 are provided in Table 12.1 The distributions of the these wave characteristics are expressed as a probability of non-exceedance (which is the probability that a certain condition will *not* be exceeded), also known as the Cummulative Density Function (CDF), depicted in Figure 12.3.

*Table 12.1 Wave characteristics at locations P1, P2 and P3.*

| Location | Average sign. wave height (m) | Average wave period (s) |
|---|---|---|
| **P1: 10 km offshore (6.375 N; -57.375 W)** | 0.87 | 3.9 |
| **P2: 30 km offshore (6.500 N; -57.250 W)** | 1.27 | 4.4 |
| **P3: 50 km offshore (6.625 N; -57.125 W)** | 1.40 | 4.6 |

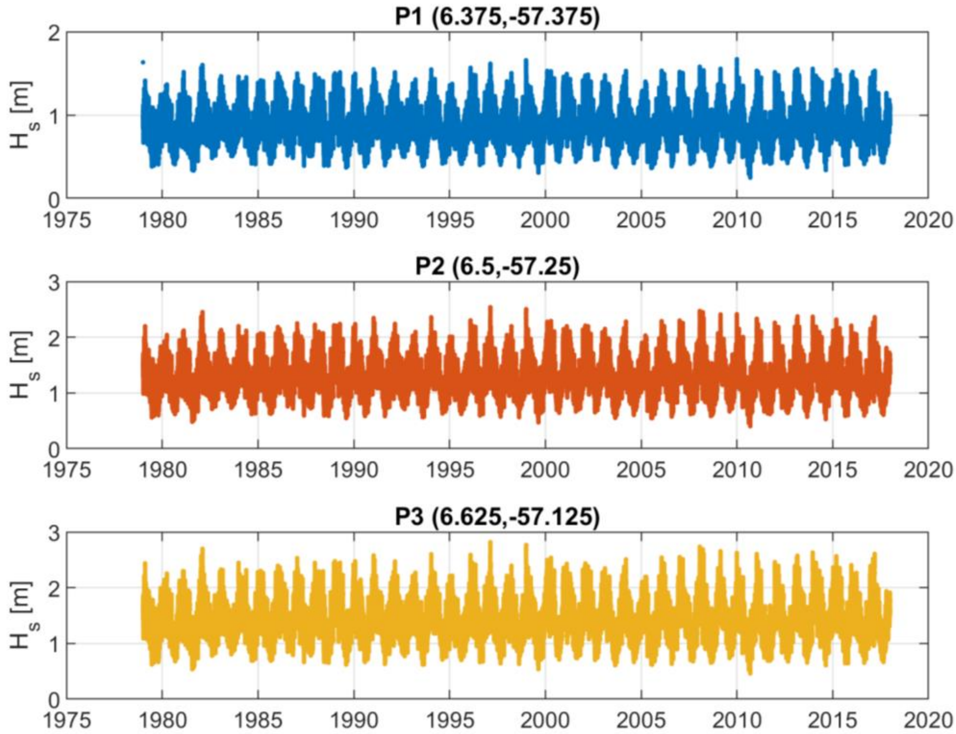


*Figure 12.2 Time series of significant wave height (m) at locations P1, P2 and P3.*

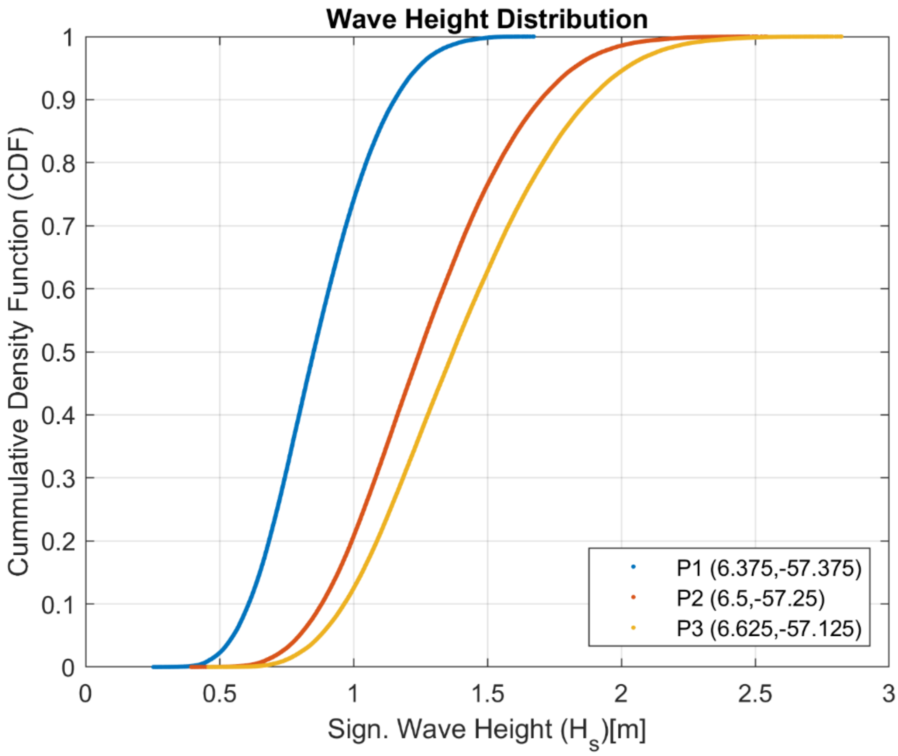


*Figure 12.3 Cumulative Density Function (or: probability of non-exceedance) of wave height*

*Peak-over-Threshold approach*
The long-term wave statistics are estimated from the maximum value during storms using a peak-over-threshold approach (Ferreira and Soares, 1998). A storm is defined here as an uninterrupted sequence (for instance 2 days) of $H_s$-values all exceeding a certain, fairly high threshold value ($H_{s,thresold}$), preceded and followed by a lower value (Figure 12.4; Holthuijsen, 2007). The selected threshold value depends on local conditions, such that a sufficient number of storms (preferably several dozen or more) can be identified in the long-term time record. For each storm the maximum significant wave height is then identified as the highest (i.e. peak) value in that storm: $H_{s,peak}$.

In the case of the wave data that are available at location P3 50 km offshore from the Guyana coast, a threshold value of 1.9 m was used, roughly corresponding to the 10% largest waves (CDF=0.9 in **Error! Reference source not found.**).

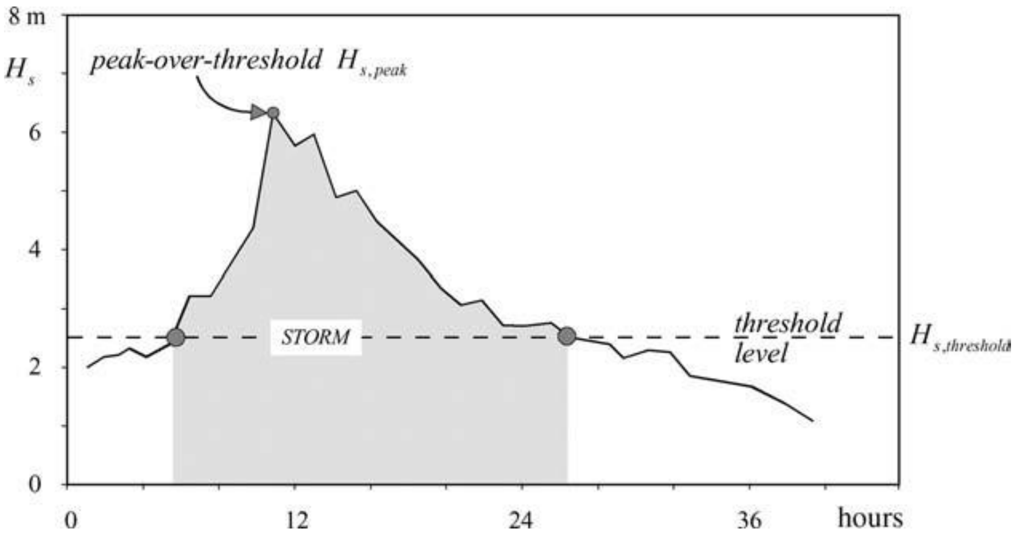


*Figure 12.4 Example of a storm between two successive crossings of the threshold significant wave height (2.5 m in this example from Holthuijsen (2007))*

*Extreme-value Distributions*
Long term wave statistics can be interpreted based on extreme-value theory if the following fundamental conditions are fulfilled: the values in the time series must be statistically independent from each other and they must have the same distribution (i.e. each value should be an independent random sample from one and the same population; Goda, 1992). For statistical independency, the values should be sufficiently far separated in time, which is why the maximum value during storms (resulting from the peak-over-threshold method) is used. For identical distribution only waves from one source can be considered, separating sea wind waves from swell waves (Repko et al., 2000), which is the case for the available dataset.

The extreme-value theory (e.g., Castillo, 1988; Coles, 2001) tells us that the distribution of the maximum in such a sequence of values above a threshold is the Generalized Pareto Distribution (Arnold). In other words, the maximum significant wave height in a storm should be Pareto distributed (under certain conditions, e.g., the values must be independent and identically distributed, and the threshold value must be relatively high). Other well-known extreme-value distributions, such as Generalized Extreme Value distributions, Gumbel (1958) and Weibull (more suitable for individual wave heights, can also be fitted to the data (van Gelder and Vrijling, 1999). Once the parameters of the distribution of $H_{s,peak}$ have been determined by fitting the distribution to the data, an estimate of the return period can be made, often by extrapolation of the available data.

For the wave data available at location P3 (50 km offshore from the Guyana coast), these extreme value distributions were each fitted to the maximum values during storms obtained from the peak-over-threshold analysis. A Generalized Pareto Distribution (GPD) was indeed the best fit for this data (Figure 12.5). The return periods of certain wave heights can then be obtained from the fitted distribution (Caires and Sterl, 2003, 2005). Vice versa the governing wave height for design conditions can be obtained for a desired return period (safety standard), as provided in Table 12.2. Note that this example computation is only meant for illustrative purposes and should not be used for design projects.

*Table 12.2 Return periods (years) and corresponding significant wave height (m) at location P3.*

| **Return period (years)** | **1** | **3** | **5** | **10** | **30** | **50** | **100** |
|---|---|---|---|---|---|---|---|
| **Sign. Wave height (m)** | 2.44 | 2.59 | 2.65 | 2.72 | 2.82 | 2.86 | 2.90 |

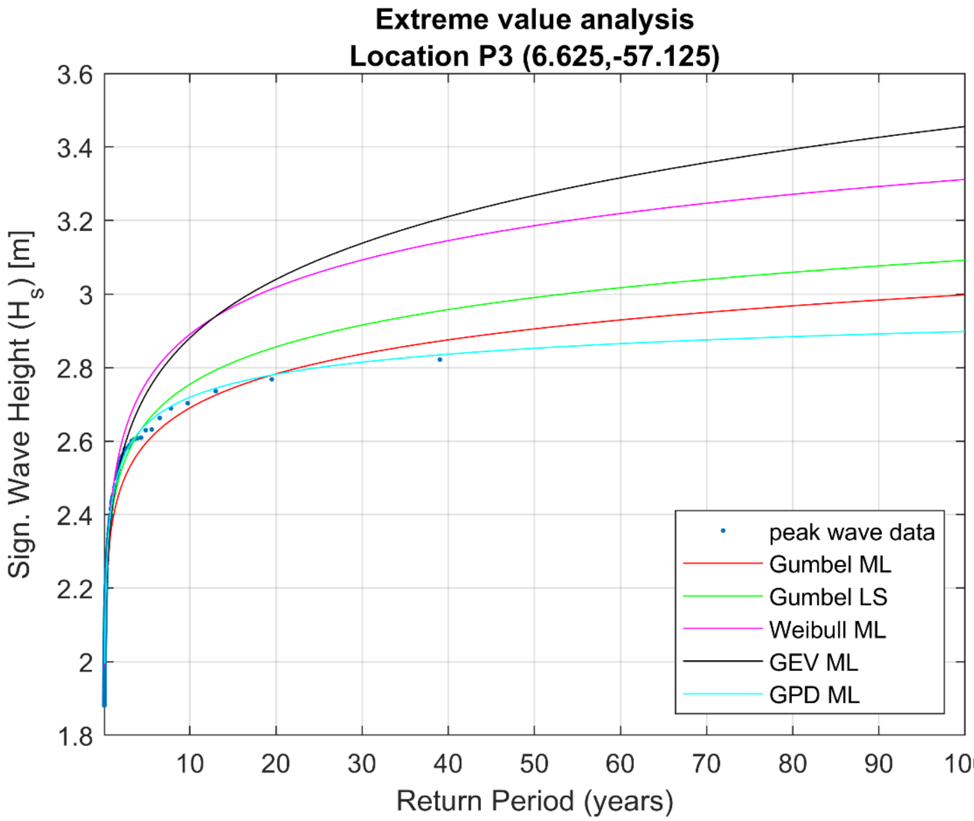


*Figure 12.5 Extreme-value distributions fitted to the data at location P3. Best fit for the Generalized Pareto Distribution (GPD ML, cyan line).*

## 12.4 Recommendations on Boundary Conditions & Return Periods

For the design of conventional coastal protection structures along the Guyana coastline a return period of 30 years is used (pers. Comm. Roberto Narine). The return period can be interpreted as the time duration how often such a condition would occur *on average*. This is a statistical parameter, representative for the long-term statistics of the period 1979-2017, which does not imply that two extreme conditions may not occur in one year. For example, the maximum significant wave height that occurred within the considered period was 2.82 m on 17 February 1997 and the second largest significant wave height of 2.77 m occurred on 1 January 1999. So, these events occurred only two years apart, but in the remainder of the 38-year period such conditions did not occur anymore.

The governing design wave height is typically used as input for design computations of conventional coastal protection structures, e.g. wave overtopping and structural stability. This analysis method outlined in the previous sections should be completed as part of the design process to determine the local design conditions at other sites. Based on the example from the previous section, a significant wave height of 2.8 m was obtained as first indicative value for the governing design wave height at Nieuw-Amsterdam. Note that this value is specific to that location and should not directly be used as input for design computations, at this location or elsewhere. Moreover, the offshore design wave height is not equal to the wave height at the toe of the seawall, since the waves transform as they propagate towards the shore, a process which requires extensive measurements and/or modelling efforts to determine properly.

# 13 Spatial and Temporal Planning

## 13.1 Green-Grey Coastal Infrastructure Elements

Further to Chapter 7, the elements that can be used to stimulate the formation of mangrove habitat, i.e. intertidal mudflats, are:

**STU**: Sediment Trapping Units, yielding sedimentation basins to trap suspended sediment, formed by permeable structures/dams. These are to be deployed on intertidal (mud)flats, where sediment-laden water, driven by the tide and Guyana Current can enter the basins (Chapter 7). Timing of deployment is not critical, and their deployment can be considered as a no-regret intervention.

**CPG**: Coast-Perpendicular Groynes, consisting of long (500 – 1000 m) structures from rubble mound and/or filled geotextiles ("sand sausages"). These are to be deployed at locations with a pronounced littoral current, such as along a river mouth (generally the left bank, except for the large Essequibo River), trapping part of the longshore suspended fine sediment transport (Chapter 7). Timing of deployment is not critical. CPG's can also be used to stabilize sandy beaches (Section 7.2).

**MBM**: Use of the natural mudbank dynamics to restart the MudBank Motor, forming intertidal mudflats. This approach consists of three elements. These may be deployed separately, but their combination and integral use give the best chance of restoring coastal resilience along large parts of Guyana's coastline in a durable way. STU's are placed at the seaward and eastern edges of natural mangrove recruitments on the intertidal mudflats behind the mudbanks (Chapter 4 and 7). At the windward side of the mudflats and mangrove fringes (thus the east side of the migrating mudbanks) permeable fences (**PF**) are erected to slow down erosion. In the interbank areas, permeable groynes (**PG**) are erected in front of the embankments. Timing of deployment is critical.

Figure 13.1 presents a schematic of the MudBank Motor concept. Currently, the natural cycle of accretion and retreat of the mangrove-covered coastline in response to the arrival and departure of a mudbank is disturbed by the erection of seawalls. The strategy behind the MBM-concept is to induce a mangrove greenbelt during a mudbank phase that is so wide that it will not be entirely eroded during an interbank phase. The surviving mangrove greenbelt should be wide enough to dampen waves almost entirely, see Chapter 6. In other words, during an interbank phase the seawall will remain protected by a mangrove greenbelt.

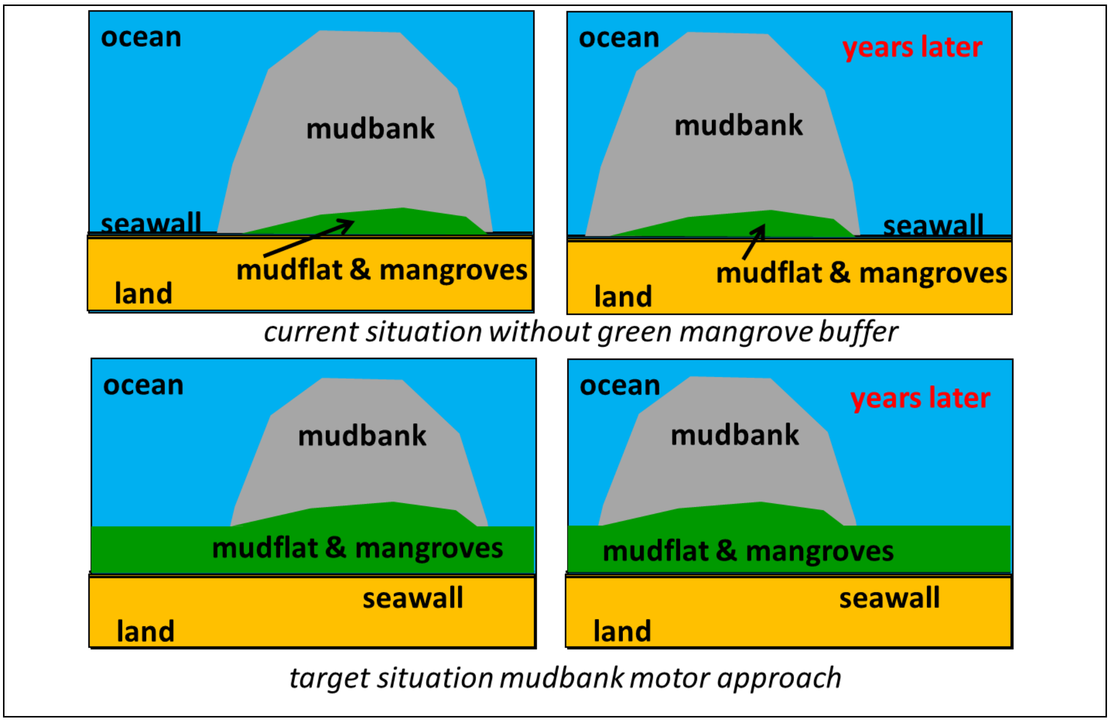


*Figure 13.1 Schematic of MudBank Motor approach.*

Application of STU's and permeable fences on intertidal mudflats implies that the extend and development of the mudflats must be surveyed frequently, preferably twice per year for monitoring and planning purposes, as elaborated further in Chapter 17. This can be done at low water with drone- and/or airborne surveys.

## 13.2 Spatial Planning

Figure 13.2 summarizes the consultant's recommendations on application of Green-Grey Coastal Infrastructure per district, with further elaboration below.

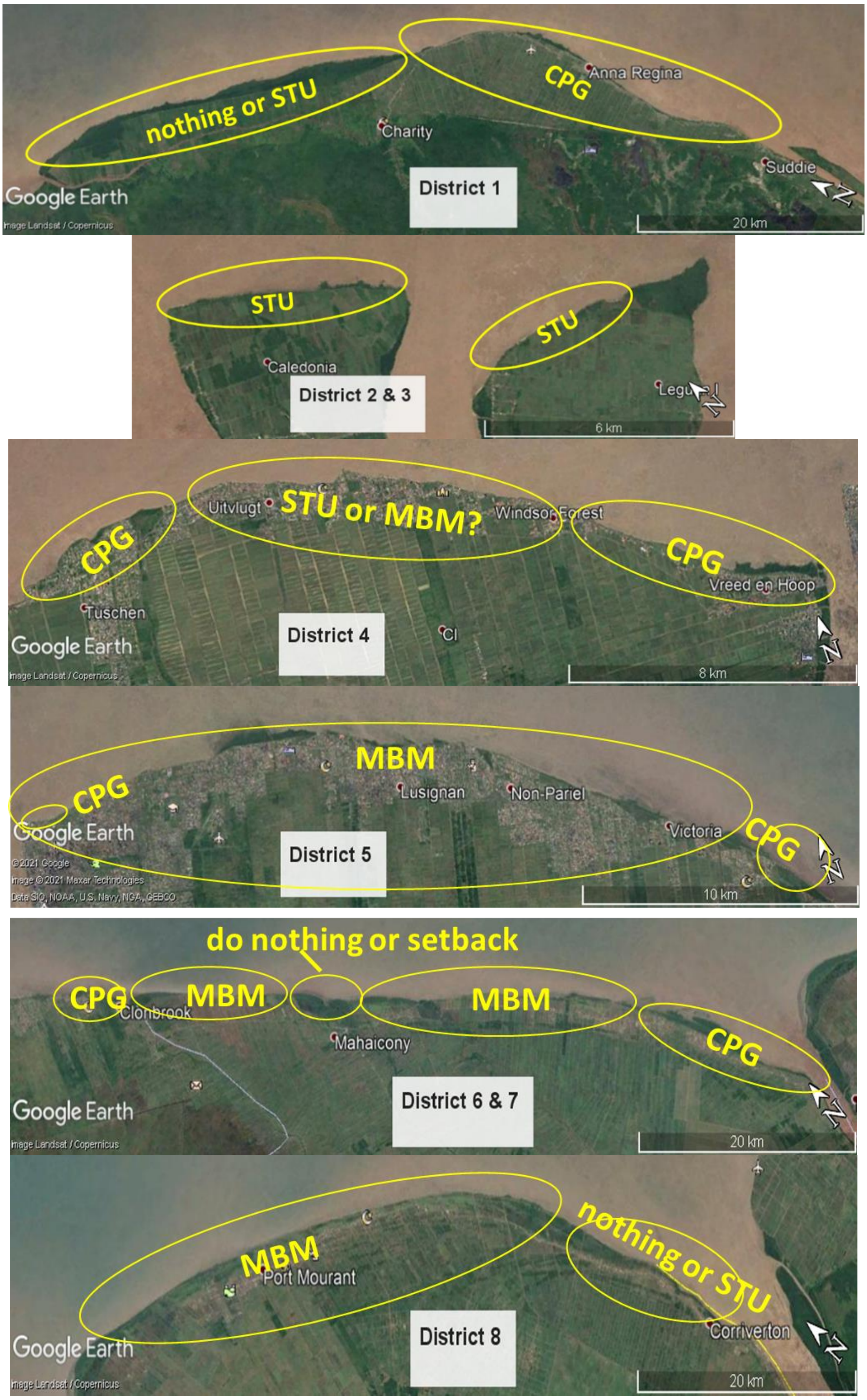


*Figure 13.2 Spatial overview of application of Green-Grey Coastal Infrastructure per district.*

**District 1 (Essequibo West Coast)**: In the western part of District 1, a narrow mangrove fringe has developed over the last 30 years, today up to more than 2 km wide. It is recommended not to intervene, though to monitor the development and status of these fringes and of the mudflat in front. When retreating, the mangrove-mud coast can be stabilized with STU's.

The eastern part of District 1 is largely affected by the outflow of the Essequibo River, and CPG's can be deployed, as has been demonstrated in the vicinity of Anna Regina (Section 7.2.). We recommend erecting more groynes along this part of the coastline, monitor their efficiency and maintain them properly over time. Optimization of the design of these groynes must be supported by numerical modelling of the local coastal processes. We recommend letting natural colonization take place and monitor whether mangrove habitat establishes after mudflats are formed.

**District 2 & 3 (Essequibo Islands, Wakenaam and Leguan)**: The available Google Earth images reveal narrow mangrove fringes along the northern coasts of these islands, with a considerable canopy along the eastern tip of District 2 (up to 2 km wide). Mudbank dynamics are likely too far offshore to affect these coastlines. However, suspended fine sediment concentrations in the river mouth are large, and STU's are therefore recommended along almost the entire coastline, building out into the ocean over time. This will help to restore the sediment balance and create elevations suitable for natural mangrove colonization. We recommend tests with sowing mangrove propagules of the naturally occurring species composition (Chapter 9), as propagule abundancy may be low. Sowing should be done in the week directly after spring tide, each day on the emerging part of the intertidal mudflat.

**District 4 (Demerara West Coast)**: The western part (up to Tuschen) is still under the influence of the Essequibo outflow, and CPG's are likely to be effective, as around Anna Regina, District 1. Similarly, the eastern part (up to Winsdor Forest) is affected by outflow of the Demerara River, and also here CPG's are likely effective – note that at the beginning of the 21$^{st}$ century, a few 100 m wide mangrove fringe was found along this part of the coast, but now eroded. These river outflows ensure the availability of freshwater and potentially also seed supply. Further studies are required to make a solid recommendation for interventions along the remainder of the coastline of District 4. For instance, it is not known whether passing mudbanks can induce mudflats along this part of the coast, as these may be too far offshore. If not, STU's may be effective. It is recommended to start a pilot. Again, we recommend monitoring the effectiveness of the CPG's and STU's and if so, to let natural colonization take place. If this colonization does not start after one year, we recommend sowing mangrove propagules of the naturally occurring species composition (Chapter 9). Sowing should be done in the week directly after spring tide, each day on the emerging part of the intertidal mudflat.

**District 5 (Demerara East Coast )**: The very eastern part of District 5 coastline is affected by the small Mahaica River (not only its outflow, but also its tidal volume), and deployment of CPG's is likely effective (see also Chapter 8). This is also a location where the efficiency of permeable fences (PF's) may be tested. To the west, in front of Kingston district (Georgetown), the seawall is protected by a 40 – 100 m wide, 1 km long beach, stabilized by four concrete CPG's. We recommend lengthening these groynes, trapping as much of the littoral sand transport as possible. If successful, the mangrove canopy will extend rapidly in western direction, as this is the direction of propagule dispersal. It is likely that sand passing Fort Groyne is not deposited along district 4 coastline, thus lost for coastal protection.

The remainder of the coastline is affected by the interplay of the embanked coastline and the migration of mudbanks (Section 1.4.6). Hence the MBM-strategy is required – this strategy is further elaborated in Section 13.3. As the existing CPG's are small in comparison to the mudbank complex dimensions, CPG's and MBM can be deployed jointly (see also Figure 7.7

showing a mudflat covering the smaller groynes cg2 – cg4). To speed up mangrove colonization we recommend tests with sowing mangrove propagules of the naturally occurring species composition (Chapter 9), with anchoring these propagules using cages and with planting juveniles of the naturally occurring species. Sowing should be done in the week directly after spring tide, each day on the emerging part of the intertidal mudflat.

**District 6 (Mahaica)**: The mangrove-mud coastline around the mouth of the Mahaicony River (near Mahaicony village) seems stable since the first satellite images became available, hence no interventions are recommended. A bit further to the west, near De Kinderen, the seawall was breached, and a polder area of more than 1 $km^2$ is still inundated. As mentioned in Chapter 8, this could be a pilot location to test the temporary realignment concept with a mangrove catalyst function to initiate further mangrove developments. Along the mouth (left banks) of the Mahaica and Berbice Rivers, CPG's are likely efficient and are recommended. These CPG's do not have to intervene with an MBM-strategy along the remainder of the coastline (see below). If seed supply appears to be the limiting factor for mangrove recruitment, sowing mangrove propagules of the naturally occurring species composition (Chapter 9). Sowing should be done in the week directly after spring tide, each day on the emerging part of the intertidal mudflat.

**District 7 & 8 (Berbice West & East Coast)**: The east part of District 8 is affected by the Corantyne River, with fringes of mangroves a few 100 m wide. For the time being no interventions are recommended, but monitoring of the coastline and mangrove habitat is mandatory. In case of coastal losses, deployment of CPG's is recommended. Elsewhere along District 7 & 8 coastline, MBM-strategy is recommended (see below).

## 13.3 Restarting the Mudbank Motor (MBM-Strategy)

As announced, the timing and maintenance of the MBD-strategy is highly critical, as needs to be synchronized with the natural dynamics of the mudbanks. The philosophy behind this strategy is to erect STU's and PF's along (emerging) mangrove fringes with two objectives (see also Fig. 13.1):

1. to accelerate natural mangrove habitat formation, which would be possible along naturally developing mudflats, and
2. to protect earlier formed mangrove habitat at locations where natural mudflat formation stopped and erosion becomes likely.

The STU's are to be erected on the intertidal mudflats, about 50 – 100 m from the (emerging) mangrove trees. This implies that the locations of the intertidal areas must be surveyed prior to the planning and construction of STU's. Care must be taken that juvenile mangrove are not damaged during the works.

In the next figures, an indication is presented on where STU's are to be constructed along the fringes of the newly emerging mangroves just east of Georgetown (Chateau Margot), and along the more mature trees to the East. Figure 13.3 presents a false-colour Landsat image (March 2021) of the mangrove fringes and mudflats along the shoreline.

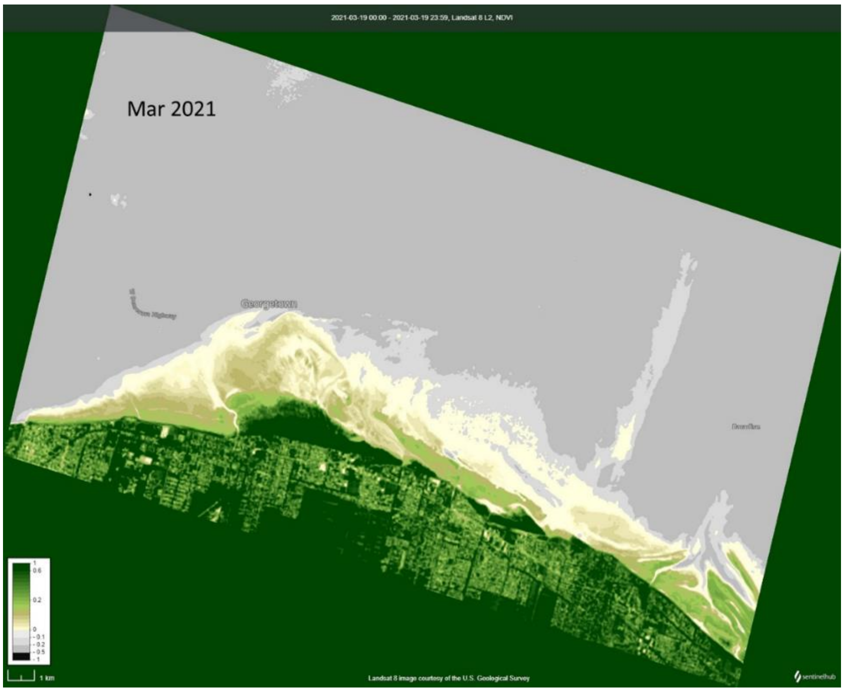


*Figure 13.3 False-colour Landsat satellite image of Guyana coastal zone around Georgetown.*

Further to our arguments above, it is recommended to erect STU's along the emerging mangroves fringes, and the more mature fringes which developed a few years ago. This would imply about 5 km of STU's, as illustrated in Figure 13.4. No STU's are to be constructed along the western side of the mudbank complex to prevent disturbing the natural formation of mudflat by streaming (Section 4). Local inspection determines the location of the placing of permeable fences.

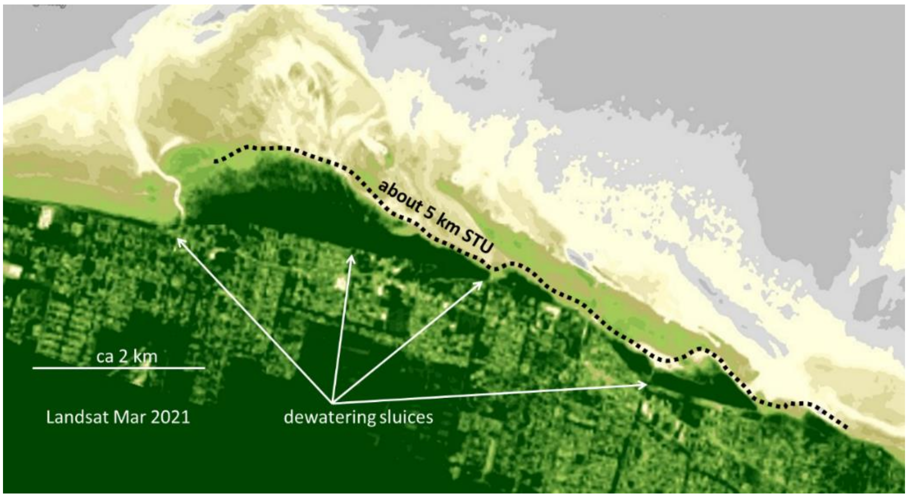


*Figure 13.4 False-colour Landsat satellite image of Guyana coastal zone around Georgetown and indicative location for STU-construction.*

At locations where natural mudflat formation continues, a second series of STU's can be constructed after 1 or 2 years, when the sediment deposits in the sedimentation basins within the STU's are high enough for mangrove recruitment. Depending on the conditions (in particular height) of the mudflats, this next series of STU's should be placed some 50 – 100 m further offshore, as suggested in Figure 13.5, and of course further to the West, assuming migration of the mudbank complex. To the East, at the trailing edge of the mudbank complex, erosion may start. This would be a place to protect by permeable fences (PF), to be placed upon inspection and analysis of the developments in the coming years.

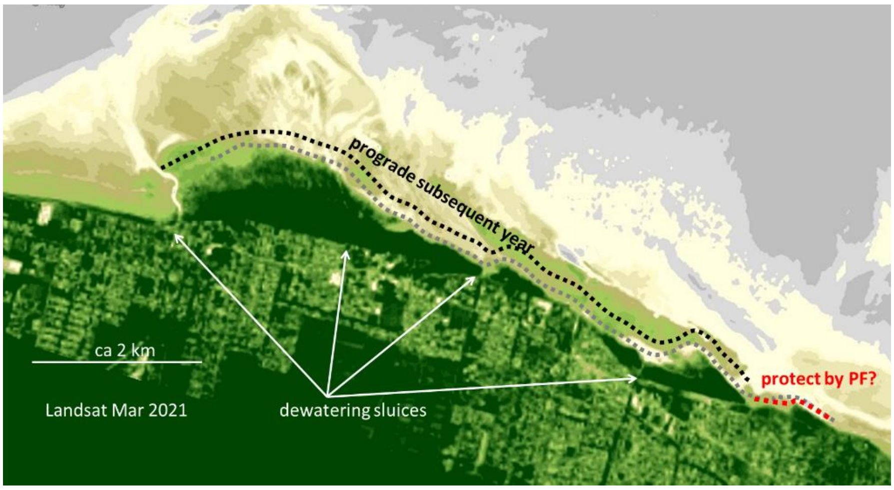


*Figure 13.5 False-colour Landsat satellite image of Guyana coastal zone around Georgetown and indicative location of subsequent STU-constructions in coming years.*

Figure 13.6 presents a coastal stretch a bit further east, more or less midway District 5. Along the coastline of Prado Ville, a jetty was built in the end of the 20th century, behind which a stable 100 m wide mangrove fringe developed. West of this fringes, no mangroves are found, even when mudflats seem to develop. This is likely due to flow separation at the edge of the jetty, inducing eddies with velocities too high for mangrove colonization. We recommend the construction of STU's to create calm water conditions where mangroves can settle.

Google Earth images suggest that also this part of the coast is sheltered by a large "Georgetown" mudbank, with substantial tidal flats. Possibly depths are too (still) large for mangrove colonization. As this area is towards the edge of the mudbank, it is unlikely that the mudflats here will become much higher in the coming years. Therefore, we recommend the erection of STU's to trap sediment forming mangrove habitat as fast as possible to create a buffer for the coming interbank period.

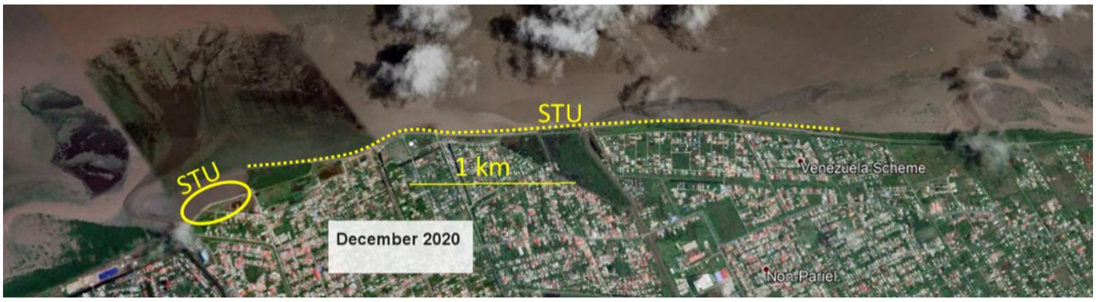


*Figure 13.6 Detail of suggested coastal interventions halfway District 5, Prado Ville.*

Figure 13.7 shows the coastline a bit further east, west and around De Kinderen, where the coastline was breached some years ago. This part of the coastline is affected by a shortage of sand to compensate for the migration of the cheniers, induced by the approaching mudbank (Section 4.7). We would recommend building permeable groynes in front of the seawalls to lower the stresses on the seawall, and to prevent excessive scouring of the foreshore.

As suggested in Chapter 8, the breach at De Kinderen may be used as an opportunity to test the temporary managed realignment concept, and a catalyst role of emerging mangroves.


*Figure 13.7 Coastline of eastern part of District 5, west of De Kinderen.*

## 13.4 Temporal Planning

Temporal planning of the initial placement of STU's and CPG's is not critical, as not depending on the mudbank migration dynamics. However, whence erected, they must be inspected and maintained regularly, and seaward extension to stimulate mudflat formation and the subsequent development of mangrove habitat should follow nature's time scales. Twice per year monitoring, i.e. before and after the months with higher waves (Chapter 2), is critical to inform planning of maintenance and seaward extension.

Temporal planning of the MBM-strategy is critical and should be opportunistic, i.e. synchronized with the natural mudbank complex dynamics. This implies that the migration of the mudbank(s) and development and extend of the intertidal mudflats must be monitored, again twice per year before and after the months with higher waves. It is noted that the predictability of mudbank migration in the coming years is low, owing to the anomalous low migration rates in recent years (Section 4.8).

## 13.5 Mangrove Management

When habitat conditions are favourable, mangrove colonization often occurs naturally. However, as discussed in Chapter 9, propagules cannot be transported in eastern direction, as reversal of the alongshore flow does not occur. This may delay mangrove colonization considerably. Hence to build out mangrove fringes to the East rapidly, nature must be helped by active mangrove management. In general, we recommend to actively promote mangrove colonization through mangrove management for all MBD applications.

## 13.6 Debris Management

Large quantities of wood, bamboo and possibly other (natural) materials are involved in the plans indicated in these Guidelines. In case the mangrove trees overtake the structures, the materials can be left in place, degrading slowly within the forest. However, if such overtaking would exceed the materials live time, debris is produced, which can be harmful to other structures, the mangrove forest and/or drainage channels and the like (Section 7.5). It is essential that debris is cleared from the sites, which activities should be planned in advance.

# 14 Managing Fresh Water from the Hinterland

This chapter provides an overview of the freshwater sources in Guyana which discharge along the intertidal area. These sources provide the fresh water supply needed for recruitment and growth of the mangrove vegetation. As such, this chapter expounds on forms of adaptive management required to maintain the freshwater supply to the intertidal vegetation.

## 14.1 Conditions for Mangrove Health and Survival in Saline Environments

Mangrove vegetation is halophytic, i.e. it has a high tolerance for saline environments such as along the Guyana coast. Hogarth (2015) indicated that mangroves grow in environments where the salinity is between that of fresh water and sea water (sea water: 35 g salt/L ~ 35 ppt). The reduction (or the cutting off) of the fresh water supply to these vegetated areas may result in their death (Waisel et al., 1986; Werner and Stelzer, 1990; Melcher et al., 2001). Within the Chateau Margot mangrove fringe, salinity values were observed to comply with Hogart's observation, and ranged between 20 – 35 ppt.

## 14.2 Fresh water Supply from the Rivers

In Guyana, the three main rivers, the Essequibo, Demerara and Berbice Rivers, contribute significantly to the fresh water supply to the foreshore (See Chapter 3 for more details). Figure 14.1 presents a map of all the primary and secondary rivers in Guyana and aerial photographs of the three main rivers. The annual average freshwater discharge from the Essequibo River is about 4100 m³/s, with the monthly-averaged discharge ranging from 1850 m³/s to 8700 m³/s (Hydromet Office in Guyana (1965 - 1998)). For the Demerara River the freshwater discharges are lower, with an annual average of about 75 m³/s, and a monthly-averaged discharge ranging from 35 m³/s to 160 m³/s. The Berbice River has an annual average of about 45 m³/s (see Table 3.3).

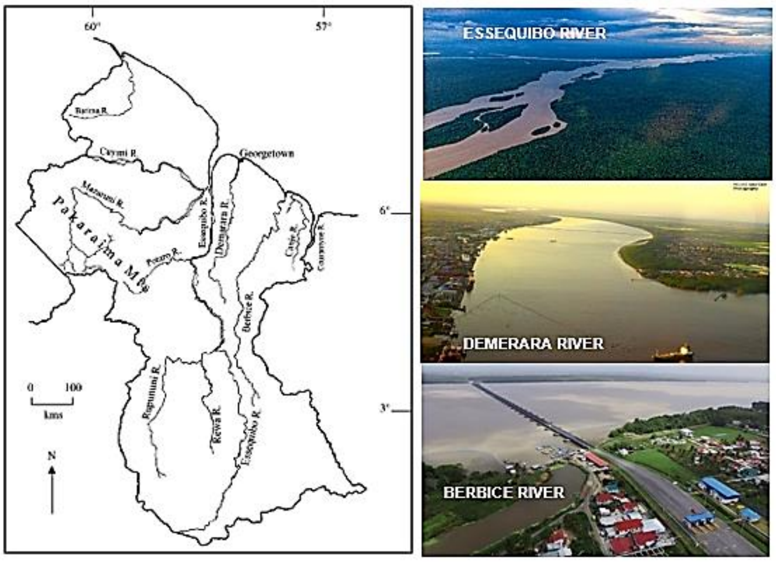


*Figure 14.1 (Left) The location of the main and secondary rivers which contribute to the fresh water supply to the foreshore (Lehman, 2004). The main rivers, shown on the right, are the Essequibo, Demerara and Berbice River.*

Figure 14.2 shows a schematic of the coastal areas which are affected by freshwater discharge from the rivers. Due to the volume of water discharged and the drainage channels along the foreshore, Google Earth imagery suggests that the discharge from the Essequibo may extend from Suddie to Charity and from Parika to Windsor Forest on the West Coast Demerara. The Parika to Windsor Forest area receives freshwater from the Demerara River. The Berbice River discharge may extend to the areas between the No. 27 Village and the Waterloo area. However, the exact extent of freshwater volumes is limited by the saline front and internal mixing. Therefore, hydrological studies should be included in restoration monitoring and maintenance works to ensure the recruitment, establishment and expansion of mangrove fringes. See section 14.4 for additional details on adaptive management.


*Figure 14.2 Schematic of the likely spatial extent and reach of the freshwater discharge from the main rivers in Guyana, (top) the Berbice River, (middle) the Demerara River and (bottom) The Essequibo River .*

## 14.3 Fresh water Supply through Sluices and Pumping Stations (Local Drainage)

With Guyana's foreshore residing below mean sea level during high-tide, the coastal hinterland is drained by drainage sluices (outfalls, locally known as "kokers") during low-tide periods and/or periods of prolonged rainfall, while at some locations, active pumping occurs. For the intermediate areas between the main rivers, freshwater is provided by the drainage sluices. These structures were first constructed during colonial time. Coastal plantations were established in a rectangular pattern to collect water from the inland areas for irrigation. These plantations faced a river or the Atlantic Ocean while in the back the plantations are bounded by wet savannahs and creeks. Parallel canals along the plantations run from the back lands to the Atlantic Ocean or river and debouche through the sluices. Smaller canals (or trenches) cut across the breadth of the plantation to connect to the main parallel canals, and smaller sluices controlled the flow of water *through them*.

*Table 14.1 Compilation of the reported values for the sluices constructed in Regions 4 (E.C.D), 5 and 6. Source: National Drainage and Irrigation Authority (NDIA)*

| No. | Name | Latitude | Longitude | No. of Doors | Width of Door (m) | Region |
|---|---|---|---|---|---|---|
| **1** | Ogle | 6.8230 | -58.0989 | 2 | 2.9 | 4, ECD |
| **2** | Montrose | 6.8203 | -58.0792 | 1 | 5.38 | |
| **3** | La Bonne Intention | 6.8169 | -58.0647 | 2 | 4.22 | |
| **4** | Triumph | 6.8124 | -58.0539 | 2 | 5.31 | |
| **5** | Buxton | 6.7990 | -58.0230 | 1 | 4.87 | |
| **6** | Strathspey | 6.7921 | -58.0132 | 3 | 3.05 | |
| **7** | Enmore-Hope | 6.7701 | -57.9872 | 1 | | |
| **8** | Enmore-Foulis | 6.7703 | -57.9875 | 2 | 2.89 | |
| **9** | Victoria's | 6.7540 | -57.9679 | 2 | 4.22 | |
| **10** | Belfield / Victoria | 6.7520 | -57.9649 | 1 | 3.65 | |
| **11** | Belfield I | 6.7502 | -57.9618 | 1 | 4.26 | |
| **12** | Hope | 6.7455 | -57.9553 | 2 | 3.20, 4.42 | |
| **13** | Hope 8 Door | 6.7408 | -57.9527 | 8 | | |
| **14** | Greenfield | 6.7292 | -57.9379 | 2 | 4.36 | |
| **15** | Mosquito Hall | 6.7063 | -57.9216 | 1 | 4.92 | |
| **16** | Mosquito Hall small | 6.7064 | -57.9215 | 1 | 1.37 | |
| **17** | Spring Hall | 6.6983 | -57.9195 | 1 | 1.91 | 5 |
| **18** | Voorzigtigheid Flap gate | 6.6856 | -57.9162 | 1 | 1.83 | |
| **19** | Hand En Veldt | 6.6830 | -57.9165 | 1 | 1.98 | |
| **20** | Cottage Sluice | 6.6366 | -57.8350 | 2 | 4.97 | |
| **21** | Farm Sluice | 6.5916 | -57.8042 | 2 | 4.44 | |
| **22** | Retrieve Sluice | 6.5679 | -57.7976 | 3 | 3.78 | |
| **23** | Little Abary Sluice | 6.5440 | -57.7433 | 1 | | |
| **24** | Profit Sluice | 6.5375 | -57.7312 | 2 | 5.05 | |
| **25** | Trafalgar Sluice | 6.4355 | -57.6204 | 2 | 5 | |
| **26** | D'Edwards Sluice | 6.2815 | -57.5353 | 3 | 5.3 | |
| **27** | Seawell Sluice | 6.2914 | -57.5090 | 2 | | 6 |
| **28** | Borlam | 6.3065 | -57.4071 | 1 | 5 | |

Table 14.1 provides an overview of the sizes and discharge potential of the sluices in Regions 4, 5 and 6. This table does not reflect all sluice (koker, outfall) locations, but only those disclosed by the National Drainage and Irrigation Authority (NDIA). At the time of this study, we were not able to determine which locations were drained by drainage pumps. From zero-order calculations using the sluice dimensions and assuming a discharge velocity of 1 m/s, it is estimated that the minimum freshwater discharge from the drainage outfalls is approximately 200 $m^3/s$. Further investigation should be carried out to accurately determine the expected discharge from these structures. This should be done in conjunction with the National Drainage and Irrigation Authority (NDIA) and should be coupled with monitoring works to determine possible relations between the vegetation health and the freshwater supply and or salinity level. This will inform decisions taken to protect existing mangrove fringes (e.g. hydrological restoration) and to identify key sites for restoration.

Some discharge channels in the foreshore are maintained by local fishermen who use these outfalls as a hub for fishing operations and the transport of goods. The Maritime Administration (MARAD) maintains the depth of the shipping channels, but it is not clear under whose authority falls maintenance of the sluice channels. These channels are the primary collectors and distributors of the discharged freshwater to the intertidal vegetated areas. As such, they should be maintained regularly.

## 14.4 Adaptive Management of Fresh Water Supplies to Mangrove Areas

Further to the arguments presented above, the following is recommended to ensure that the freshwater needs of the intertidal vegetation are met, and the depths of the drainage channels are maintained in applying green - grey infrastructure measures.

- Channels depth at the sluices and within the mangrove greenbelt are vital for the fresh water supply to and the health of natural mangroves (see Figure 14.3).
- A hydrological database should be developed in conjunction with National Drainage and Irrigation Authority (NDIA) and Maritime Administration Department (MARAD) to ascertain the following:
  - Drainage capacity (design and operation) and location of all outfalls, pumping stations and rivers.
  - Proximity of restoration sites/natural mangrove sites to freshwater sources.
  - Temporal and spatial variation in the saline front.
  - Seasonal fluctuations in salinity at project sites.
- Regular maintenance dredging of the outfall channels should be incorporated within restoration efforts by the governing bodies.
  - Study whether dredged material can be placed directly on the foreshore, enhancing mangrove habitat.
  - Ripening of dredged material is a natural dewatering or ’drying' process and can be used as covers for earthen dikes, landfill areas or can be used locally to heighten the land.
- Secondary to the main drainage outfall channel, there is a network of internal channels which serve to irrigate and drain the mangroves. These need to be maintained through the monitoring and maintenance efforts of the Guyana Restoration and Management Department, NAREI; see Figure 14.3 for the practical application of the terminology. While manipulating the intertidal system with permeable dams or any other Green-

Grey measure, the maintenance of the natural drainage capacity should be a primary concern.

- Mangrove recruitment can be stimulated with active freshwater management, steering the direction of outflow by proper channel design (Thampanya, 2006). Thampanya, (2006) concluded that both the germination rate and the survival rate were affected by the salinity levels in mangroves belts in Thailand. Therefore, the steering of fresh water through the network of channels sustaining the vegetation can help mangrove recruitment. The Mangrove Restoration and Management Department has carried out such hydrological adaptations in the Wellington Park area. This project consisted of the excavation of two 200 m channels to re-introduce tidal flow into the local salt pan to restore the natural hydrology of the area. These projects can be used to guide similar works.

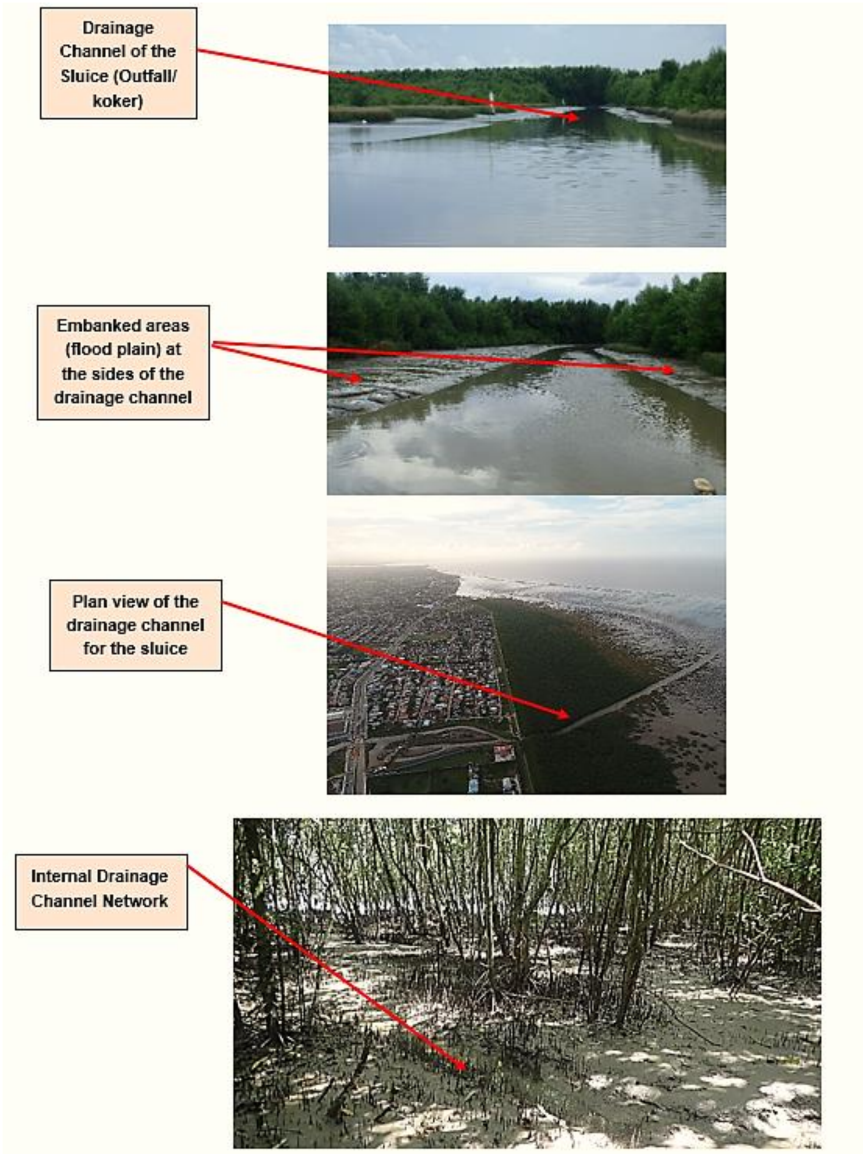


*Figure 14.3 Components of management of the Freshwater supply to mangroves along the coast. Here, the terminology referred to in the chapter is presented w.r.t the outfall channels and the internal drainage network within the fringe.*

# 15 Conceptual Design Permeable Fences and Sediment Trapping Units

All interventions are addressed in the Master Plan, which is frequently updated and adapted on the basis of accurate and up-to-date information on bathymetry and the lessons learned. The Master Plan also sets priorities in the execution of the work.

## 15.1 Sediment Trapping Units

Here we discuss only Sediment Trapping Units (STU) constructed of fences of vertical (bamboo) poles. We anticipate that the common brushwood permeable structures will not be deployed as less practical, requiring more expertise and skill to construct and more maintenance. Winterwerp et al. (2020) argue that mangrove habitat can develop behind the dams if not more than about 50 – 60% of the incoming wave height is transmitted through the dams. This is reflected by the transmission coefficient $k_t$:

$$k_t = H_{s,0} / H_{s,t} \qquad (15.1)$$

where $H_{s,0}$ and $H_{s,t}$ are the significant wave height of the incoming and transmitted wave, respectively. Based on the work by Gijón et al. (2021a, 2021b), the transmission coefficient as a function of the fence porosity *n* can be established for one row of fences and for two rows, assuming an effective drag coefficient $c_D$ = 5 and pole diameter *D* = 0.1 m, see Figure 15.1.

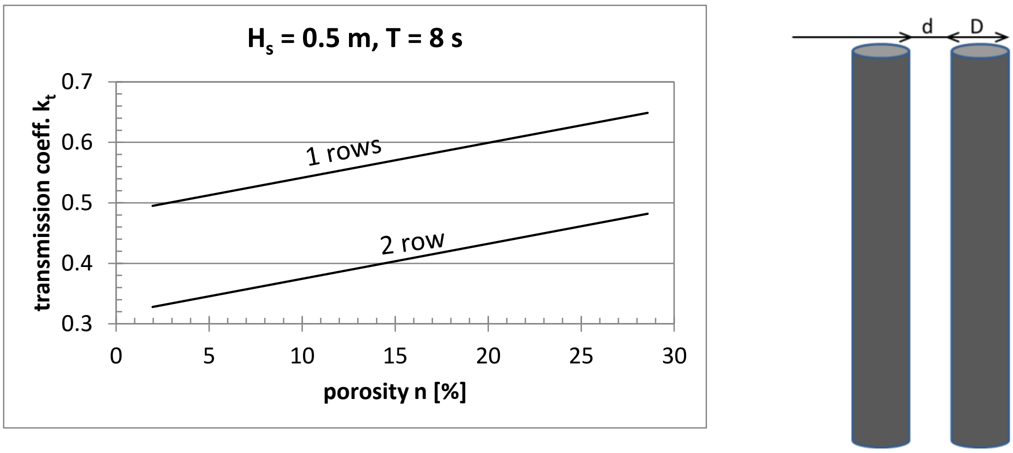


*Figure 15.1 Indicative transmission coefficient $k_t$ as function of fence porosity n for a single and double row fence and as a function of water depth h and wave height $H_s$, and definition of fence parameters (frontal view).*

The porosity is defined as:

$$n = d / (D + d) \qquad (15.2)$$

where *D* is the diameter of the poles, and *d* their spacing, see Figure 15.1. Figure 15.1 suggests that this may be achieved by a fence of one row of bamboo, with porosities not larger than about 20% ($d < 0.25D$) at a water depth *h* = 1 m, and wave height $H_s$ = 1 m. However, the transmission coefficient is rather sensitive to water depth and wave height, as shown in the figure. However, the larger wave damping is required during stormy conditions, thus larger wave height. It is therefore recommended to experiment with a double row of bamboo fences, measuring efficiency of the single and double row configuration, as a double row provides redundancy in case of damage. Such redundancy must be weighed against the extra costs.

These rows are placed at a distance of at least three diameters of the bamboo poles. Note that the curves of Figure 15.1 are based on a linear analysis and idealistic conditions, hence are indicative – the actual transmission coefficient may be smaller or larger, while not too dependent on the actual wave period (i.e. valid for 9 s as well). Further it is noted that small spacings lower than 5 – 10% porosity are not recommended because of augmented wave reflection.

STU's are placed on the intertidal:
1. In front of a mangrove fringe, such as in the case of the MBM approach. The objective is to generate as much mangrove habitat as possible in as short a time possible. Therefore, we recommend STU's as large as possible to build out fast as possible, ranging from 50×50 m$^2$. to 200×200 m$^2$. We recommend experimenting with varying the STU's size when deployed at a new site to optimize dimensions with respect to the local conditions.
2. In front an embankment such as deployment on the islands in the Essequibo River (District 2 & 3). We recommend STU's of about (50 to 100)×(50 to 100) m$^2$. We recommend experimenting with varying the STU's size when deployed at a new site to optimize dimensions.

We have indicated some other isolated locations where STU's may be used. Also in these situations, STU's of about (50 to 100)×(50 to 100) m$^2$ are recommend.

In all cases, 5 m openings must be constructed every 25 m or so in the fences to allow entrance of sediment-laden water. Stand-alone and neighboring STU's have "side walls" to prevent uneven distributions of deposition. The frontal fence, facing approaching waves may be constructed from double fences; for the side walls a single fence is likely sufficient under all conditions if properly maintained. The openings are made in the frontal fence, generally facing the incoming waves, though other configurations may be considered when practical. Figure 15.2 presents a schematic of a serial application of STU's of 50×50 m$^2$ and subsequent extension in offshore direction.

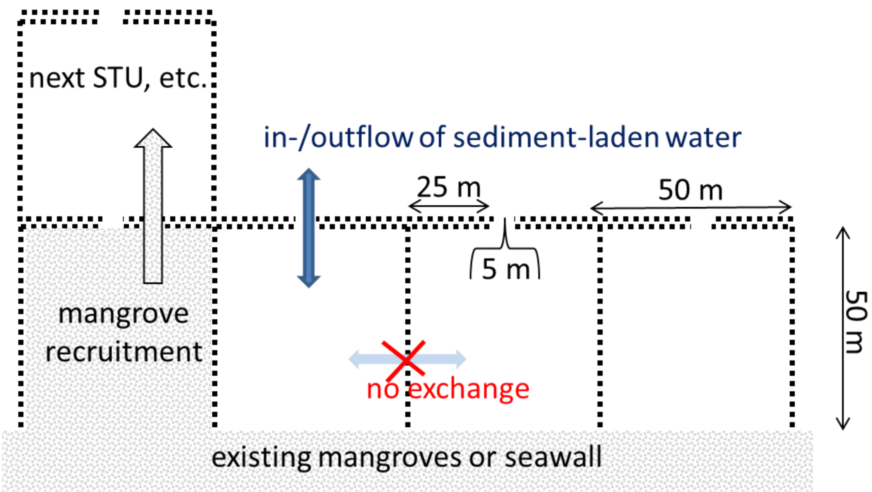


*Figure 15.2 Schematic of serial 50×50 m$^2$ STU deployment.*

After some time, a new series of STU's can be constructed in front of the previous series, when mudflat heights are sufficient, and mangrove recruitment is advanced.

## 15.2 Permeable Fences and Coastal Protection

These permeable fences are meant to protect existing mangrove fringes during post-mudbank (interbank) periods and are therefore erected around the eastern edge of mangrove fringes on mudflats, where mudflat formation stopped. They are erected 10 – 20 m in front of the mangrove fringes. These fences are constructed also with 5 m openings every 25 m with the purpose to allow some additional sedimentation from the background suspended fine sediment. As these fences will be subject to more wave action than when placed in STU's, we recommend experimenting with double fences.

The required spacing between the poles can be read from Figure 15.1.

## 15.3 Permeable Groynes and Coastal Protection

Permeable groynes are meant to lower wave loads on embankments and reduce wave reflection during interbank periods, thus inducing more favorable conditions for a next mudbank period. They are best placed along the eastern edge of a passing mudbank to reduce erosion rates of the accompanying mudbank, and along all other unprotected embankments facing the ocean.

They will experience severe wave loads during a considerable period of time (a decade or more) and must therefore be made of strong, durable materials. Their spacing can be read from Figure 15.3, assuming typical wave heights of 1 m. Again, denser spacing than 5 – 10% porosity are not recommended because of the increase in wave reflection.

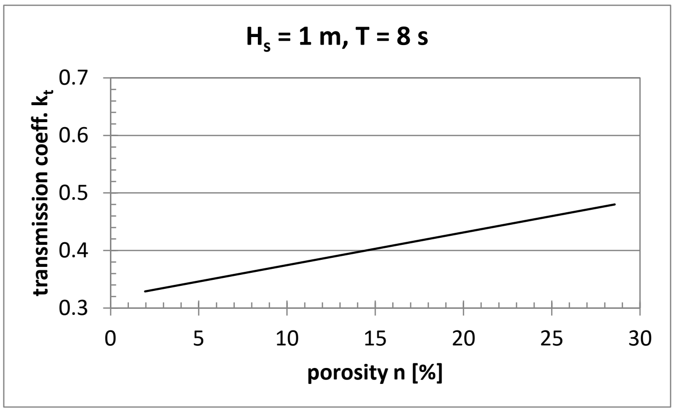


*Figure 15.3 Indicative transmission coefficient kt as function of fence porosity n for permeable groynes.*

This is an entirely new type of application of permeable structures, and we recommend small scale pilot(s) to test and evaluate them. Note that common foundation piles have the proper consistency and diameter to serve as permeable groynes. However, these have a square cross-section, which may induce severe wave reflection when oriented wrongly. We recommend placing in a diamond configuration, as sketched in Figure 15.4. The orientation of piles with a circular cross-section is of course irrelevant – these are always low-reflective if not placed too close.

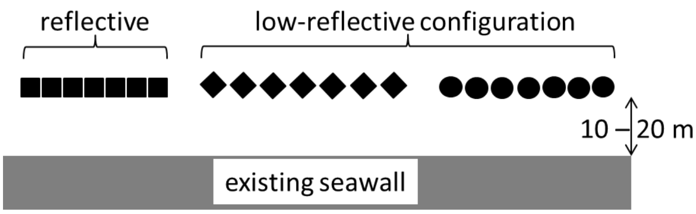


*Figure 15.4 Schematic of placement of the elements of permeable groynes.*

## 15.4 Coast-Perpendicular Groynes for Muddy Environments

Coast-perpendicular groynes are meant to block/reduce/trap alongshore transport of fines, forming intertidal mudflats in between them. Length and spacing of the groynes are interrelated determining the efficiency of this configuration as a function of the environmental conditions, of which flow velocity, tidal range, local wave conditions and suspended sediment concentration are the more important ones. This requires site-specific designs which are best informed by a hydro-sedimentological mathematical model study of the local conditions, and some local surveys to measure the relevant hydro-sedimentological parameters. This type of modelling is not very difficult and can optimize the groyne design largely, saving considerable construction and maintenance costs. As too site-specific, we cannot provide further guidelines.

As explained before, these groynes are generally not permeable, certainly not after some time when the pores in between the groyne's elements are expected to be filled with sediment.

## 15.5 Coast-Perpendicular Groynes for Sandy Environments

This configuration is likely uniquely deployed along the sandy beaches in front of Georgetown to protect the city and its seawall. Again, length and spacing of the groynes are interrelated determining the efficiency of this configuration as a function of the environmental conditions, of which flow velocity, tidal range, local wave conditions and expected sand fluxes are the more important ones. Its design requires a hydro-sedimentological mathematical model study of the local conditions, and some local surveys to measure the relevant parameters. The groynes, also those made of rubble mound, are expected to be impermeable sometime after their construction.

Given the scarcity of sand in the coastal system and the importance of the hinterland (Guyana's capital), such modelling and the subsequent conceptual design should be done with priority.

# 16 Construction of Permeable Fences and Groynes

As explained before, we strongly recommend using fences made of vertical (bamboo) poles instead of the classical brushwood dams:

1. Fences from vertical poles can be as efficient as brushwood dams with respect to wave damping,
2. The proper placement of brushwood in between supporting vertical poles is difficult and expensive, and requires substantial skill,
3. Brushwood is lost easily, and its application requires much maintenance,
4. When loose, flow creeps under the brushwood, inducing local scour, further loosening the brushwood bundles.

This section contains the lessons-learned on constructing permeable dams in Demak, Indonesia, partly based on the experience gained in Vietnam by GIZ (Von Lieberman, 2012). This section is based on the more comprehensive "Technical Guidelines Permeable Structures" (Wilms et al., 2018) developed on the basis of the Building with Nature works in Indonesia. The dams in Indonesia and Vietnam consist of the classical brushwood dams, i.e. horizontally placed brushwood, which mainly damp the waves, and vertical poles to hold the brushwood. However, the issues addressed are directly applicable to the fences proposed for Guyana. The permeable dams need to stay in place long enough for mangroves to take over, which period is determined by the sediment accretion rate (in Guyana estimated at 1 – 3 years) and rate of mangrove recovery (in Guyana estimated at 2 – 4 years).

The fences are constructed of bamboo poles, with diameter of 0.12 – 0.15 m; their spacing is addressed in Chapter 15. They are placed on the intertidal, thus totally emerging at least part of the time during low water. The top of the fence is above MHW – some overtopping is no problem.

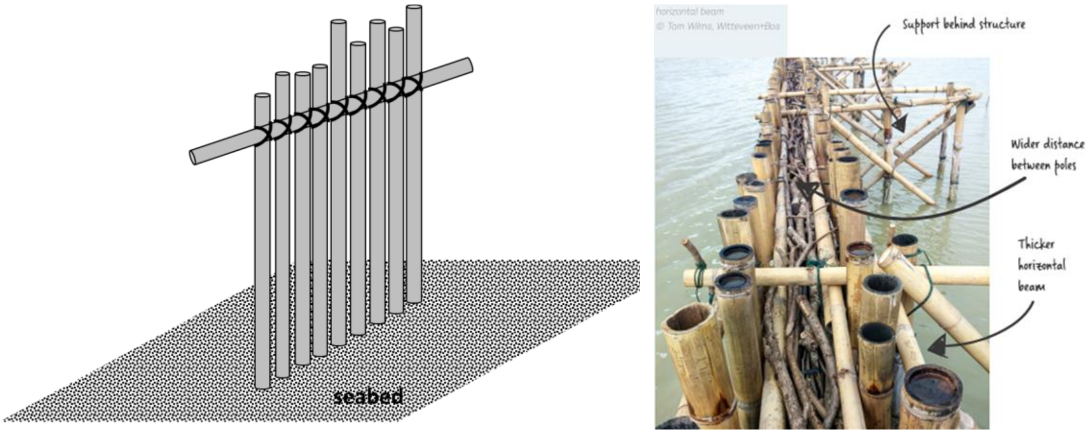


*Figure 16.1 Left panel: fence with horizontal stabilizing bar and right panel: brushwood dam with additional support when deployed as permeable groyne (Demak, Indonesia).*

The fences applied in STU's are mechanically stabilized with a horizontal bar, in particular the frontal fences that are subject to wave loading (wave loading on the "side walls" of the STU's is small), as sketched in Figure 16.1 (left panel). When deployed as permeable groyne during interbank periods, wave loading can be large and additional mechanical support is recommended as applied in Demak, Indonesia – see Figure 16.1, right panel. Note that bars and poles must be connected by wire, nailing damages the bamboo, reducing their lifetime considerably. The use of long wires is convenient, but these are valuable and were frequently stolen in Demak. Therefore, short, less valuable ropes are used, which however imply more construction work, thus higher costs. On the other hand, shorter ropes are easier to retighten, thereby lowering maintenance costs.

The bamboo poles are hammered into the soft soil to a depth of about 2 m. Experience in Vietnam and Indonesia have proven that a hammer team of about 10 persons can do this efficiently, taking about 10 – 15 minutes per pole (Figure 16.2). Use of sledgehammers, etc. is not practical and not safe to operate in these shallow waters, and may damage the bamboo.

To build ownership, it is recommended to involve local stakeholders in the construction and maintenance of the fences, supervised by experienced staff from the ministries and/or contractors. In Indonesia this was organized through the so-called Bio Rights program, providing funds for local communities in return for construction and maintenance works (van Eijk and Kumar, 2009). This would lead to a construction cycle, as deployed in Indonesia:

1. Based on the Master Plan and Spatial Planning, a spatial design and time schedules are made for the work to be carried out in the next construction cycle.
2. Ongoing stakeholder engagement to explain progress and plans for the rest of the year.
3. Discussions of the plans with local communities to guarantee stakeholder participation. Past experience with previous structures (if any) and physical or social constraints at the proposed locations should be incorporated. Site inspection is a necessity for a detailed design, obtaining up-to-date data on depth, physical obstacles, etc. Markers for the actual construction are set to facilitate the execution of the work.
4. Permits may need to be obtained for construction in the coastal zone – compliance and application of these permits should continuously be checked during the execution of the work.
5. Tender for supervision: prepare documents and allocate budget. When possible, involve the supervisor in the tender for construction.
6. Tender for construction: prepare documents, drawings and allocate budget, also for maintenance. When ordering materials, provisions should be made for losses due to sub-standard quality.
7. Training for construction, maintenance, and monitoring.
8. Construction and supervision accounting for delays and unworkable weather.
9. Monitoring and maintenance start during the construction work and continues.

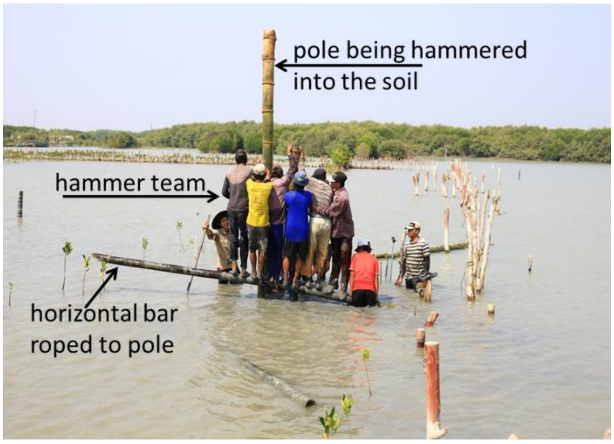


*Figure 16.2 Hammer team at work to place bamboo pole, Bogorame, Demak, Indonesia.*

Transport of the fence material to the building site is done with barges, constructed from the bamboo itself that is going to be used. Because of the shallowness of the area, other means of transport are not efficient.

For the placement of permeable groynes and coast-perpendicular groynes, heavy, mechanical equipment is required, and the work must be done by experienced contractors, following common coastal engineering guidelines. These are not further elaborated upon in this report.

# 17 Monitoring and Maintenance

This section describes the monitoring and maintenance activities that are required after the first construction of Green-Grey Coastal Infrastructure measures. Note that prior to any implementation of Green-Grey Coastal Infrastructure, a survey of the local conditions and inspection of the mangrove habitat and the existing coastal defense structures must be executed (not described here). Four steps for designing and implementing an adaptive management strategy for a Green-Grey project are outlined in the Green-Grey Practical Guideline (Green-Grey Community of Practice, 2020):

Step 1: Develop a monitoring and evaluation framework;
Step 2: Define indicators, baselines, and targets;
Step 3: Operationalize the monitoring and evaluation framework in a maintenance plan;
Step 4: Use and communicate the results in an iterative process.

After the first construction of coastal interventions many follow-up activities are required, and should be included in the maintenance plan:

1. Update one's understanding of all components of the natural coastal system based on lessons-learned and the various monitoring and surveying activities,
2. Monitor the natural development of the coastal system, such as changes in bathymetry, the location and migration of mudbanks and mudflats, changes (if any) in the wind and wave conditions and mangrove recruitment,
3. Monitor the response of the coastal system to the interventions executed, in particular the development of intertidal mudflats and mangrove habitat, mangrove colonization and mudflat/mangrove development during the interbank period,
4. Inspection of the structural integrity of all permeable fences and groynes; if necessary, maintenance and/or reparations,
5. Inspection of the grey coastal defense infrastructure, i.e. the existing embankments, seawalls and dikes, maintenance and/or reparations when required,
6. Analysis and interpretation of all information collected, which form the basis for an update of one's system understanding and planning of future work; collection of all data in a data base.

Monitoring and evaluation should generate insights on what works, what doesn't work, and why. Review all project components with special attention to risk reduction effectiveness, community impact, and environmental impacts (World Bank, 2017). This process should include developments outside the project area that may influence the effectiveness of measures. Decide if the performance of Green-Grey Coastal Infrastructure meets the previously set standards and objectives. If not, decide on follow up actions, regarding maintenance or even implementation of additional interventions. Local communities can play a role in the monitoring and maintenance activities (Section 10.6).

Monitoring also strongly informs maintenance and other necessary actions. Part of the maintenance work accounts for debris management (described in Section 7.7), collecting broken poles. Prevention of debris production is often more efficient, implying the replacement of damaged poles at an early state.

For the various classes of interventions presented in Chapter 13, the following activities are recommended:

- The MudBank Motor approach requires considerable inspection, monitoring and surveying. The migration of mudbanks is key in this concept, and should therefore be monitored, at least once per year. Migration speeds are too erratic to make accurate predictions. Mudflat formation and extent must be monitored frequently as well, preferably twice per year to establish when and where new fences can be placed in front of previous ones. This is easier than the submerged part of the coastal bathymetry, as for instance airborne lidar can be used at low water. Monitoring of mangrove colonization can be done partly through remote sensing, but visual inspection by biologists/ecologists is necessary to evaluate health and biodiversity of the trees. The various STU's and permeable fences must be inspected frequently on a routine basis, preferably twice per year, and after severe storms. Damage must be restored as soon as possible, and damaged poles must be removed to prevent debris problems.

- Pilot experiments with various STU-dimensions are recommended elsewhere in these guidelines, and their performance must be monitored at an even higher frequency, dictated by wave events. The more important parameter here is the sedimentation rate. This can be established from reading the bed level variations over time from measuring poles, hammered into the soil, equipped with a measuring scale. Such poles are distributed regularly across an STU. Likely, such an array of measuring poles is placed in several STU's, while others are equipped with one reference measuring pole only.

- The eastern edge of the mangrove fringes is vulnerable to erosion when an interbank period approaches. Frequent inspection of the functioning of the permeable groynes placed to protect these mangroves is important.

- Inspection of STU's along the more riverine dominated parts of the coast need to be frequently inspected as well, again preferably twice per year on a routine basis. Sedimentation, i.e. the formation of mangrove habitat within the STU's and subsequent mangrove colonization must be monitored to establish when seaward extension is possible. Likely, wave loading is limited in most cases, as these STU's are located in more sheltered areas.

- The permeable groynes to lower wave loading on existing grey infrastructure and reduce wave reflection during interbank periods are likely constructed of durable material (armoured concrete). Yearly inspection, in conjunction with the common inspection of the seawalls themselves seems sufficient.

- The mechanical stability of the coast-perpendicular groynes (both for sandy and muddy applications) proposed likely requires also once per year inspection, as these are assumed to be solid structures. However, their hydro-sedimentological performance is recommended to be monitored more frequently collecting information for better informed designs in the future.

# 18 Cost Estimates for Green and Grey Measures

This chapter provides an overview of the cost estimates for Green and Grey Coastal Infrastructure measures based on global data and average costs of previous construction works along the coast of Guyana.

## 18.1 Global Cost Estimates

For grey measures, costs were estimated based on worldwide levee cost prices. According to Lenk et al. (2017), levee cost prices are well described by a (linear) unit cost price per kilometre per metre crest height (Lenk et al, 2017). Ward et al. (2017) proposed a unit investment cost price of USD 7.0 million per km per m for the Netherlands and for the US. This figure includes all investments costs (including groundwork, construction, engineering costs, property or land acquisition, environmental compensation, and project management) and is based on based on the construction costs from several studies (Bos, 2008; De Grave & Baarse, 2011; Aerts et al., 2013; Jonkman et al., 2013). Van Zelst et al. (in press) adjusted these cost estimates for other countries by applying construction index multipliers (based on civil engineering construction costs), to account for differences in construction costs across countries. Costs were converted using GDP deflators from the World Bank (https://data.worldbank.org/), and annual average market exchange rates. For Guyana this would result in a levee unit cost price of USD 0.94 million per kilometre per metre crest height (or USD 940 per linear metre per metre crest height). Assuming a levee crest height between 2.0 and 3.0 m, the unit cost price would be between 1800 and 2800 USD per linear metre, which is in line with the estimated 2200 USD per linear metre from Planet (2016).

Winterwerp et al. (2020) provide unit cost price for construction and maintenance of permeable dams and bamboo fences in Demak (Indonesia), Vietnam and Thailand (Table 18.1). Construction costs vary largely, between a minimum of 16 USD/m for bamboo fences and a maximum of 160 USD/m for permeable dams, but are an order of magnitude smaller than construction costs for concrete seawalls or levees. Maintenance costs are defined per maintenance cycle and were between 20 USD/m and 80 USD/m (unavailable for Thailand).

*Table 18.2 Ranges in construction and maintenance costs (per maintenance cycle) per unit meter permeable dam in USD; Thailand: bamboo fences, maintenance costs unavailable.*

| | **Construction in USD/m** | | | **Maintenance in USD/m** | | |
|---|---|---|---|---|---|---|
| Location | Material | Labor | Total | Material | Labor | Total |
| Demak | 60-120 | 20-40 | 80-160 | 38-60 | 12-20 | 50-80 |
| Vietnam | 40-70 | 10-20 | 50-90 | 10-40 | 10-20 | 20-60 |
| Thailand | 12-85 | 4-17 | 16-110 | - | - | - |

## 18.2 Cost Estimates for Guyana

This section provides an overview of the average costs for Green and Grey Coastal Infrastructure measures implemented along the coast of Guyana and at other sites worldwide. These figures reflect a summation of the costs period from 2013 to 2020, and as such inflation of material prices should be considered for future applications. Further, the costs provided do not include for expenditures such as personnel, transportation, geotechnical and topographic surveys and other secondary inputs.

For restoration measures, temporary nurseries are established in close proximity to planting sites at the rate of GYD $100 (USD 48 cents) per seedling. With this venture, community involvement and training are key to increase nursery areas as well as the awareness about the practical function of the mangroves which serve to minimize the flooding of the coastal hinterland.

Table 18.2 presents a summary of the costs for the restoration measures implemented by the Guyana Restoration and Management Department, NAREI. These costs reflect the variation in the density and coverage of the mangrove seedlings. The exact dimensions for the planting sites have not been provided. There has only been one hydrological restoration project conducted to date.

Monitoring and maintenance works are necessary follow-up components after the completion of any Green-Grey measure. The costs are quantified using a daily work rate and, the density of the forest will impact the number of working days and the overall monitoring costs. As such, a mature forest will require a higher expenditure for the monitoring measures. With a capital expenditure of GYD $ 178,853,966 from 2010 to 2018, the monitoring costs (GYD $ 6,142,381) reflected 3% of the capital costs during that period.

In addition, low-crest, low-cost structures are used as alternative to rigid ‘hard’ coastal protection measures and are positioned parallel to the shore. These structures function as wave breakers and promote the accretion of the intertidal area while the mangrove root structure stabilizes the deposited sediments. These low crested structures include bamboo brushwood groynes and geotube groynes. Table 18.2, provides the costs for both the low-crest structures and the traditional options (concrete seawalls and rip-rap structures).

The costs presented in Table 18.2 do not include for expenditures such as personnel, transportation costs, geotechnical and topographic surveys and other secondary inputs. Guyana’s poor sub-surface soil (e.g. compressive strength and bearing capacity), along the coast makes this zone prone to settlement. Therefore, consideration should be given to factors such as the soil conditions and the rate of subsidence, which is amplified by sea level rise. These factors, as discussed in Chapter 3, are key when determining the design elevation and conditions to guarantee a certain level of safety and the associated costs for any grey- green approach. Additionally, they also limit the possible types of structures built, ease or practicality of construction as well as their design dimensions.

*Table 18.3 Summary of the average costs reported for the green and grey measures implemented by the Guyana Restoration and Management Department, NAREI.*

| Interventions | Minimum Cost (USD) | Average Cost (USD) | Maximum Cost (USD) | Minimum Cost (GYD) | Average Cost (GYD) | Maximum Cost (GYD) |
|---|---|---|---|---|---|---|
| **Mangrove Restoration (Seedling Planting)** | $ 4,000 | $ 20,000 | $ 43,000 | $ 800,000 | $ 4,000,000 | $ 8,600,000 |
| **Hydrological Restoration (per 100 m of channel length)** | | $ 21,000 | | | $ 4,200,000 | |
| **Sediment Trapping per 100 m (Bamboo Brushwood Groynes)** | $ 17,000 | $ 23,000 | $ 31,000 | $ 3, 300,000 | $ 4,500,000 | $ 6,300,000 |
| **Concrete Sea Defences per 100 m** | | $ 500,000 - $ 600,000 | | | $ 104,300,000 - $ 125,200,000 | |
| **Rip Rap Armored Structure per 100 m** | | $ 239,000 | | | $ 47,800,000 | |
| **Geotube Groynes per 100 m** | $ 69,000 | $ 81,000 | $ 93,000 | $ 13,900,000 | $ 16,200,000 | $ 18,600,000 |
| **Rubble Mound Groynes per 100 m** | | $ 158,000 | | | $ 31,600,000 | |
| **Monitoring & Maintenance per site (2010 – 2018)** | $ 400 | $ 2,000 | $ 9,000 | $ 100,000 | $ 500,000 | $1,800,000 |

# 19 Scope of Future Work

This chapter summarizes a few of the most urgent developments in tools, equipment and software required to carry out the Green-Grey Coastal Infrastructure interventions proposed in this report.

## 19.1 Bathymetry and Surveying

As explained in chapters 3-5 of this report, the variability in mudbank size and migration speed are large. Frequent surveying is therefore mandatory, as the bathymetry forms the primary information for designing interventions to develop Green-Grey Coastal Infrastructure. Because of the event-driven migration of the mudbanks and formation of the mudflats, surveying is recommended twice per year. The relevant bathymetry consists of three parts:

1. the mudbanks
2. the intertidal mudflats
3. the interbank regions

Classical surveying is done by boat, which is time consuming, thus expensive. Today, remote sensing techniques are well-developed, accessible, relatively cheap, and accurate. These techniques are therefore recommended. The intertidal mudflats emerge during low water (LW), and can thus be surveyed directly by e.g. lidar, operated from airplane and/or drone. Though highly accurate, some ground truthing is recommended, and spatial reference points are necessary to calibrate/validate positioning, i.e. the GPS-system.

The submerged parts of the coastal zone, i.e. interbank areas and mudbanks can be measured indirectly from monitoring wave pattens. The waves along the Guianas coastal system are long (80 – 100 m) and long-crested and come from almost one direction (ENE – NNE). The celerity (phase speed $c$) of these waves in the shallow Guianas foreshore is affected by the water depth *h*, approximately by its root $\left(c \approx \sqrt{gh}\right)$. Hence, time-lapse recordings of wave propagation give indirect information on water depth. Over the slopes of the mudbanks, some refraction of the waves (a few $10^o$) is expected, which can also be monitored by remote sensing. The degree of refraction is governed by gradients in water depth and is thus complementary to the observation obtained from wave propagation.

The lidar technique is state-of-the-art and can be deployed readily. Assessment of the intertidal mudflat bathymetry is highest priority in deployment of Building with Nature structures to restore sediment dynamics.

The assessment of bathymetry from wave patterns and celerity is not state-of-the-art and needs technological development and validation. Software needs to be developed to read the images and convert into water depth. As this information is relevant for the management of the entire Guianas coastal system, it is recommended to explore collaboration with Suriname and French Guiana.

## 19.2 Hydrodynamic Data

Tidal ranges and predictions are required for referencing bathymetrical data and as input to the numerical modelling recommended below. In the vicinity of Georgetown, data from the local tidal station can be used. Further East or West, additional data are required to determine the local tidal phase with respect to the Georgetown signal. This can be a one-time dedicated action.

Wave data, i.e. height, period and direction drive the migration of mudbanks, the formation of mudflats and the erosion of the coast, and need therefore to be monitored permanently. Offshore wave heights form the boundary conditions for the nearshore conditions, amongst which the design conditions, and can be measured with one or more wave buoys at deeper water. It is recommended to study whether the offshore wave conditions can be assessed from world-wide wave models, such as Wave Watch III – this would make continuous deployment of offshore wave buoys superfluous. However, near-shore wave data are required to analyse the performance of the Green-Grey Coastal Infrastructure and the of the Building with Nature structures to direct the sediment dynamics. The nearshore wave conditions are quite variable, owing to the migratory nature of the mudbanks complexes. Today, small, cheap wave buoys are available, accurate and reliable. Their positioning depends on the locations and phase of Green-Grey Coastal Infrastructure works deployed.

Velocity measurements are required for the design of mudflat development using Coast-Perpendicular Groins (CPG). These are dedicated, project-related measurements, and there is no need for permanent measurements. These can be carried out with state-of-the-art instruments, which are commercially available.

Sensors (Optical Back Scatter, etc.) to measure suspended sediment concentrations are also state-of-the-art and commercially available. Such data are required to determine time scales for managed realignment interventions (see below).

Assessment of types of mangroves, biodiversity and possibly biomass can be made with standard techniques, and no developments are foreseen. For larger areas, remote sensing techniques may be practical. Quantification of mangrove characteristics with remote sensing techniques is not yet state-of-the-art and some development for operational use is required, in conjunction with ground truthing.

Other data, such as the (physical) properties of the sediment, are to be collected within dedicated research and/or engineering projects. Their measurements should be defined within the framework of such projects.

## 19.3 Numerical Modelling

We do not recommend setting up numerical models for simulating the large-scale sediment dynamics in the coastal zone, including the migration of the mudbanks and the subsequent formation of mudflats and their colonization with mangroves, for three reasons:

1. The relevant information for the application of Green-Grey Coastal Infrastructure must be collected from surveys anyway, and modelling would not add too much additional information,
2. As cited above, the variability in mudbank size and migration speed are large. It is doubtful if that variability can be predicted with numerical models. The future location of mudbanks can follow from a data-driven conceptual model,
3. Finally, the formation of the mudbanks themselves and their persistent shape during migration are not yet understood. Moreover, long-term morphodynamic modelling of muddy sedimentary systems is still in its infancy. It is therefore not cost-efficient to try and model the migration of mudbanks and the subsequent formation of mudflats, and its numerical modelling should therefore be considered as a research effort.

Modelling on smaller spatial and temporal scales is, however, very useful and often mandatory. The two major applications are:

1. Determine the infill-rates of TOP polders (see section 8.4), temporary setbacks, etc. These infill rates determine the relevant time scales for the management of such interventions.
2. Determine the development of intertidal area in between Coast-Perpendicular Groins, as a function of their alongshore spacing and cross-shore length.

Such models are unique for a particular application at a particular site, and need to be steered with local hydro-sedimentological parameters, which have therefore to be collected. The variability in these data may follow from the sediment balance presented in Section 5.

## 19.4 Dissemination and Collaboration

After some training, local Guyanese parties (among others the University of Guyana) can setup the numerical models described above and carry out the necessary surveys to collect data.

Assessment of the bathymetry from remote sensing wave data requires some development, also with respect to the post-processing software. It is recommended to try and collaborate with the neighbouring countries. Possibly the European Union, or other agencies are willing to finance such developments.

The dynamics of the Guyana coastal system are typical for the entire Guianas coastal zone. Their conceptual understanding and management require long-term dedication by the government, executing authorities, hydraulic engineers and scientists. These demands are identical for the three neighbouring countries, ad will increase over time, given the expected climate changes and sea level rise. Therefore, we recommend exploring the possibility to setup a centre of expertise, where knowledge and lessons-learned are concentrated and can be shared with all stakeholders.

# References


Abascal-Zorrilla, N., V. Vantrepotte, N. Huybrechts, Dat Dinh Ngoc, E.J. Anthony and A. Gardel, 2020. Dynamics of the Estuarine Turbidity Maximum Zone from Landsat-8 Data: The Case of the Maroni River Estuary, French Guiana. Remote Sens., 12, 2173; doi:10.3390/rs12132173.

Abernethy, C.L. (1980): Guyana Coast, recommendations for a future sea defense strategy. Report OD 30, Hydraulics Research Station, Wallingford, England, 20 pp.

Adams, J. B., & Human, L. R. D. (2016). Investigation into the mortality of mangroves at St. Lucia Estuary. South African Journal of Botany, 107, 121-128.

Aerts, J. C. J. H., Botzen, W. J. W., de Moel, H. & Bowman, M. (2013).Cost estimates for flood resilience and protection strategies in New York City. Ann. N. Y. Acad. Sci. 1294, 1–104.

Allison, M. A., Nittrouer, C. A., & Kineke, G. C. (1995). Seasonal sediment storage on mudflats adjacent to the Amazon River. Marine Geology, 125(3-4), 303-328.

Allison, M. A., Lee, M. T., Ogston, A. S., & Aller, R. C. (2000). Origin of Amazon mudbanks along the northeastern coast of South America. Marine Geology, 163(1-4), 241-256.

Allison, M. A., & Lee, M. T. (2004). Sediment exchange between Amazon mudbanks and shore-fringing mangroves in French Guiana. Marine Geology, 208(2-4), 169-190.

Anderson, M.E., J.M. Smith, and S.K. McKay. 2011. Wave Dissipation by Vegetation. Coastal and Hydraulics Engineering Technical Note ERDC/CHL CHETN-I-82.  Vicksburg, MS: U.S. Army Engineer Research and Development Center. http://chl.erdc.usace.army.mil.chetn

Anthony, E.J., A. Gardel, F. Dolique and D. Marin, 2001. The Amazon-influenced mud-bank coast of South America: an overview of short- to long-term morphodynamics of ‘inter-bank’ areas and chenier development. Journal of Coastal Research, SI 64, pp 25 – 29

Anthony, E. J., & Dolique, F. (2004). The influence of Amazon-derived mud banks on the morphology of sandy headland-bound beaches in Cayenne, French Guiana: a short-to long-term perspective. Marine Geology, 208(2-4), 249-264.Anthony, E. J., A. Gardel, N. Gratiot, C. Proisy, M.A. Allison, F. Dolique and F. Fromard, 2010. The Amazon-influenced muddy coast of South America: A review of mud-bank–shoreline interactions. Earth-Science Reviews 103 (2010) 99–121. doi:10.1016/j.earscirev.2010.09.008

Anthony, E.J., A. Gardel, F. Dolique and D. Marin, 2011. The Amazon-influenced mud-bank coast of South America: an overview of short- to long-term morphodynamics of ‘inter-bank’ areas and chenier development. Journal of Coastal Research, SI 64, pp 25-29, ISSN 0749-0208

Anthony, E. J., Gardel, A., & Gratiot, N. (2014). Fluvial sediment supply, mud banks, cheniers and the morphodynamics of the coast of South America between the Amazon and Orinoco river mouths. Geological Society, London, Special Publications, 388(1), 533-560.

Arnold, B.C. (2011). "Chapter 7: Pareto and Generalized Pareto Distributions". In Duangkamon Chotikapanich (ed.). Modeling Distributions and Lorenz Curves. New York: Springer. ISBN 9780387727967.

Augustinus, P.G.E.F., 1978. The changing shoreline of Suriname (South America). PhD Thesis, University of Utrecht, Netherlands, 232 pp.

Augustinus, P.G.E.F., Mees, R.P.R. and Alphen Van, J.S.L.J., (1984), “Study of Approach Channels to The Demerara and Berbice Rivers, Guyana”, Report Guychan Project 21-09-1984.

Augustinus, P.G.E.F., 1989. Cheniers and chenier plains: a general introduction. Marine Geology, 90, pp 219-229.

Augustinus, P.G.E.F., 2004. The influence of the trade winds on the coastal development of the Guianas at various scale levels: a synthesis. Mar. Geol. 208, 141–151.

Balke, T., Bouma, T. J., Horstman, E. M., Webb, E. L., Erftemeijer, P. L., & Herman, P. M. (2011). Windows of opportunity: thresholds to mangrove seedling establishment on tidal flats. Marine Ecology Progress Series, 440, 1-9.

Barbier, E.B., Hacker, S.D., Kennedy, C., Koch, E.W., Stier, A.C., Silliman, B.R., (2011). The value of estuarine and coastal ecosystem services. Ecol. Monogr. 81 (2), 169e193.

Beck M (2016) Managing Coasts with Natural Solutions: Guidelines for Measuring and Valuing the Coastal Protection Services of Mangroves and Coral Reefs.(MW Beck & G.-M. Lange, Eds.). Washington DC: The World Bank

Best ÜS (2017) Process-based modelling of the impact of sea level rise on salt marsh & mangrove fringe-mudflat morphodynamics [An assessment of the decadal triggers for morphological evolution and restoration methods]. UNESCO-IHE

Bhaskaran PK (2017) Wave attenuation in presence of mangroves: A sensitivity study for varying bottom slopes. The International Journal of Ocean and Climate Systems: 1759313117702919

Bijsterveldt, van, C. E. J., van Wesenbeeck, B. K., van der Wal, D., Afiati, N., Pribadi, R., Brown, B., & Bouma, T. J. (2020). How to restore mangroves for greenbelt creation along eroding coasts with abandoned aquaculture ponds. Estuarine, Coastal and Shelf Science, 235, 106576. https://doi.org/10.1016/j.ecss.2019.106576

Blankespoor B, Dasgupta S, Lange G-M (2017) Mangroves as a protection from storm surges in a changing climate. Ambio 46: 478-491

Bos, A. J. (2008) Optimal safety level for the New Orleans East polder; A preliminary risk analysis. (University of Amsterdam, 2008).

Brinkman, R. & L.J. Pons 1968 A pedo-geomorphological classification and map of the Holocene sediments in the coastal plain of the three Guianas - Soil Survey Papers 4. Soil Survey Inst., Wageningen, 40 pp.

Brinkman, R.M., Massel, S.R., Ridd, P.V. and Furukawa, K., 1997. Surface wave attenuation in mangrove forests. Proceedings of the Combined Australasian Coastal Engineering and Ports Conference, Christchurch, 941-946.

Brunier, G., E.J. Anthony, N. Gratiot and A. Gardel, 2019. Exceptional rates and mechanisms of muddy shoreline retreat following mangrove removal. Earth Surf. Process. Landforms 44, 1559–1571, DOI: 10.1002/esp.4593.

Bovell O. (2019) Setting the foundations for zero net loss of the mangroves that underpin human wellbeing in the North Brazil Shelf LME: Review of the effectiveness of existing coastal restoration efforts in Guyana. Report by Conservation International and the National Agricultural Research and Extension Institute.

Caires, S. and A. Sterl, 2003, On the estimation of return values of significant wave height data from the reanalysis of the European Centre for Medium-range Weather Forecasts, in Safety and Reliability, eds. T. Bedford and P. H. A. J. M. van Gelder, Lisse Swets and Zeitlinger, pp. 353–361

Caires, S. and A. Sterl, 2005, 100-year return value estimates for ocean wind speeds and significant wave height from the ERA-40 data, J. Climate, 18, 1032–1048

Castillo, E., 1988, Extreme Value Theory in Engineering, Boston, MA, Academic Press, Inc., 389 pp.

Church, J. A., Gregory, J. M., Huybrechts, P., Kuhn, M., Lambeck, K., Nhuan, M. T., Qin, D. and Woodworth, P. L. (2001). "Changes in sea level". In: J. T. Houghton, Y. Ding, D. J. Griggs et al (Eds.). Third assessment report: climate change 2001, the scientific basis. Cambridge University Press, UK, Intergovernmental Panel on Climate Change: 639-693.

Cintron-Molero, G., 1992. Restoring mangrove systems. In: Thayer, G.W. (Ed.), Restoring the Nation’s Marine Environment. Maryland Seagrant Program, College Park, Maryland, pp. 223–277.

CIRIA, CUR, CETMEF (2007). *The Rock Manual. The use of rock in hydraulic engineering (2nd edition).* C683, CIRIA, London

Clarke, P.J., 1993. Dispersal of grey mangrove (Avicennia marina) propagules in south-eastern Australia. Aquatic Botany, 45, 195-204.

Clough, B. F. (1993). Primary productivity and growth of mangrove forests. Coastal and estuarine studies, 225-225.

Coles, S., 2001, An Introduction to Statistical Modeling of Extreme Values, London, Springer-Verlag, 208 pp.

Dalrymple, R. A., Kirby, J. T., & Hwang, P. A. (1984). Wave diffraction due to areas of energy dissipation. Journal of waterway, port, coastal, and ocean engineering, 110(1), 67-79.

Dalrymple, O. K., & Pulwarty, R. S. (2006, June). Sea-level rise implications for the coast of Guyana: Sea walls and muddy coasts. In Breaking Frontiers and Barriers in Engineering: Education, Research and Practice. Fourth LACCEI International Latin American and Caribbean Conference for Engineering and Technology (LACCET 2006) Conference Proceedings (pp. 21-23).

Daniel, J. R. K. (1988). Sea defense strategies and their impact on a coast subject to a cyclic pattern of erosion and accretion. Ocean and Shoreline Management, 11(2), 159-175.

Dasgupta S, Islam M, Huq M, Khan ZH, Hasib M (2017) Mangroves as protection from storm surges in Bangladesh

Doody, J.P., 2004. 'Coastal squeeze' - an historical perspective. Journal of Coastal Conservation 10 (1-2), 129-138.

Douglas, B. C., 1995. Global Sea Level Change: determination and interpretation, in: Review of Geophysics, Supplement US National Report to International Union of Geodesy and Geophysics 1991-1994, page 1425-1432

Duarte, C.M., Losada, J., Hendriks, E., Mazarrasa, , Marba, N., (2013). The role of coastal plant communities for climate change mitigation and adaptation. Nat. Clim. Change 3 (11), 961e968.

Duivendijk, J. van and J.R. Pieters, 1983. Design and construction of the sea defences of Guyana. In: Proceedings International Symposium 'Polders of the World'. International Institute for Land Reclamation and Improvement, Wageningen, the Netherlands.

Eijk, van, P. and R. Kumar, 2009. Bio-rights in theory and practice A financing mechanism for linking poverty alleviation and environmental conservation. Wetlands International (see also https://www.wetlands.org/publications/biorights-in-theory-and-practice/).

Eisma, D. (1967). Oceanographic observations on the Surinam shelf. Hydr. Newsletter Spec. Publ.5, 21-53.

Eisma, D. and H.W. Van der Marel, 1971. Marine muds along the Guiana coast and their origin from the Amazon Basin. Contributions to Mineralogy and Petrology 31, 321– 334.

Eisma, D., P.G.E.F. Augustinus and C.A. Alexander, 1991. Recent and subrecent changes in the dispersal of Amazon mud. Netherlands Journal of Sea Research 28, 181–192.

Ellison, A.M., 2000. Mangrove restoration: do we know enough? Rest. Ecol. 8 (3), 219–229.

ENGINEERS-USACE, U. A. C. O. (1984). Shore protection manual. US Army Corps of Engineers Research and Development Center, Coastal and Hydraulics Laboratory, Vicksburg.Froidefond, J.M., Pujos, M., Andre, X., 1988. Migration of mud-banks and changing coastline in French Guiana. Mar. Geol. 84, 19–30.

the EurOtop Team (2007). *Eurotop Overtopping manual*.

FAO (2007) The world's mangroves 1980–2005. FAO Forestry Paper 153, Rome, 89 pp

Feagin RA, Mukherjee N, Shanker K, Baird AH, Cinner J, Kerr AM, Koedam N, Sridhar A, Arthur R, Jayatissa LP (2010) Shelter from the storm? Use and misuse of coastal vegetation bioshields for managing natural disasters. Conservation Letters 3: 1-11

Ferreira, J. A. and C. G. Soares, 1998, An application of the peaks over threshold method to predict extremes of significant wave height, J. Offshore Mechanics and Arctic Engineering, ASME, 120, 165–176

Field, C.D. (Ed.), 1996. Restoration of Mangrove Ecosystems. International Society for Mangrove Ecosystems, Okinawa, Japan.

Field, C.D., 1998. Rehabilitation of mangrove ecosystems: an overview. Mar. Pollut. Bull. 37 (8–12), 383–392.

Froidefond, J.M., F. Lahet, C. Hu, D. Doxaran, D. Guiral, M.T. Prost and J.-F. Ternon, 2004. Mudflats and mud suspension observed from satellite data in French Guiana. Marine Geology 208, 153–168.

Gade, H.G., 1958. Effects of a non-rigid, impermeable bottom on plane surface waves in shallow water. Journal of Marine Research 16 (2), 61–82.

Gardel, A., Gratiot, N., 2005. A satellite image-based method for estimating rates of mud bank migration, French Guiana, South America. J. Coast. Res. 21, 720–728.

Gelder, van, P. H. A. J. M. and J. K. Vrijling, 1999, On the distribution function of the maximum wave height in front of reflecting structures, Proc. Conf. Coastal Structures, ed. J. Losada, 1, pp. 37–46

Gijón Mancheño, A., W.J. Jansen, J.C. Winterwerp and W.S.J. Uijttewaal, 2021a. Predictive model of bulk drag coefficient for a nature-based structure exposed to currents, Scientific Reports, 11:3517, https://doi.org/10.1038/s41598-021-83035-0

Gijón Mancheño, A., W.J. Jansen, W.S.J. Uijttewaal, A.J.H.M Reniers, A. van Rooijen, T. Suzuki, V. Etminan and J.C. Winterwerp, 2021b. Wave transmission and drag coefficients through dense cylinder arrays: implications for designing nature-based structures, Ecological Engineering, 165:106231, https://doi.org/10.1016/j.ecoleng.2021.106231.

Goda, Y., 1985. Random seas and design of maritime structures. Tokyo: University of Tokyo Press.

Goda, Y., 1992, Uncertainty of design parameters from viewpoint of extreme statistics, J. Offshore Mechanics and Arctic Engineering, ASME, 114, 76–82

Granek EF, Ruttenberg BI (2007) Protective capacity of mangroves during tropical storms: a case study from 'Wilma'and 'Gamma'in Belize. Marine Ecology Progress Series 343: 101-105

Gratiot, N. and E.J. Anthony, 2016. Role of flocculation and settling processes in development of the mangrove-colonized, Amazon-influenced mud-bank coast of South America. Marine Geology 373, 1–10.

Grave, de, P. & Baarse, G. (2011). Kosten van maatregelen. Informatie ten behoeve van het project Waterveiligheid 21e eeuw.

Green-Grey Community of Practice. (2020). Practical Guide to Implementing Green-Grey Infrastructure.

Gumbel, E. J., 1958, Statistics of Extremes, New York, Columbia University Press,
375 pp.

Hendry, M. (1993). "Sea-level movements and shoreline changes". In: G. A. Maul (Ed.). Climate Change in the Intra-Americas Sea. Arnold, London.: 115-161

Holthuijsen, L. (2007). Waves in oceanic and coastal waters. Cambridge University Press.

Horstman E, Dohmen-Janssen CM, Narra P, Van den Berg N, Siemerink M, Hulscher SJ (2014) Wave attenuation in mangroves: A quantitative approach to field observations. Coastal engineering 94: 47-62

Horstman, E.M., 2014. The mangrove tangle – short-term bio-physical interactions in coastal mangroves, PhD-thesis, University of Twente, The Netherlands.

Hossain, M. D., & Nuruddin, A. A. (2016). Soil and mangrove: a review. Journal of Environmental Science and Technology, 9(2), 198-207.

Hughes SA (2008) Estimation of combined wave and storm surge overtopping at earthen levees. Coastal and Hydraulics Engineering Technical Note ERDC/CHL CHETN-III-78. Vicksburg, MS: U.S. Army Engineer Research and Development Center

(ICBA), C. B. A. (2006). Guyana Sea Defenses, Bridging Programme Progress Report Block 5 Coastal Processes. G. S. D. Government of Republic of Guyana.

Jeuken, M.C.J.L., Z.B. Wang and D. Keiller, 2008. Impact of setbacks on the estuarine morphology, In Dohmen-Jansen, C.M. and S.J.M.H. Hulscher (eds.), River, Coastal and Estuarine Morphodynamics, RCEM2007, Taylor & Francis, 2008, London, pp1125-1134.

Jonkman, S. N., Hillen, M. M., Nicholls, R. J., Kanning, W. & van Ledden, M. (2013). Costs of Adapting Coastal Defences to Sea-Level Rise— New Estimates and Their Implications. J. Coast. Res. 29, 1212–1226.

Kamali, B., & Hashim, R. (2011). Mangrove restoration without planting. Ecological Engineering, 37(2), 387–391.

Kineke, G. C., & Sternberg, R. W. (1995). Distribution of fluid muds on the Amazon continental shelf. Marine Geology, 125(3-4), 193-233.

Kineke, G. C., Sternberg, R. W., Trowbridge, J. H., & Geyer, W. R. (1996). Fluid-mud processes on the Amazon continental shelf. Continental shelf research, 16(5-6), 667-696.

Kirwan M.L., Megonigal J.P. (2013) Tidal wetland stability in the face of human impacts and sea-level rise. Nature 504(7478):53–60

Kit LW (2016) Wave attenuation function of mangroves along Singapore's northern coast.

Kobayashi N, Raichle AW, Asano T (1993) Wave attenuation by vegetation. Journal of waterway, port, coastal, and ocean engineering 119: 30-48

Lees, D., Wernerus, F.M.J., Simpson, M.C., 2009. Strategic environmental assessment of the sea defenses sector policy in Guyana, letter of contract no. 2008/150593.

Lenk, S., Rybski, D., Heidrich, O., Dawson, R. J. & Kropp, J. P. (2017). Costs of sea dikes – regressions and uncertainty estimates. Nat. Hazards Earth Syst. Sci. 17, 765–779.

Lewis, R.R., 1977. Impacts of dredging in the Tampa Bay estuary 1876–1976. In: Pruitt, E.L. (Ed.), Proceedings of the Second Annual Conference of the Coastal Society—Time-stressed Environments: Assessment and Future Actions. The Coastal Society, Arlington, Virginia, pp. 31–55.

Lewis, R.R., 1982. Mangrove forests. In: Lewis, R.R. (Ed.), Creation and Restoration of Coastal Plant Communities. CRC Press, Boca Raton, Florida, pp. 153–172.

Lewis, R.R., 1994. Enhancement, restoration and creation of coastal wetlands. In: Kent, D.M. (Ed.), Applied Wetlands Science and Technology. Lewis Publishers, Inc., Boca Raton, Florida, pp. 167–191.

Lewis, R. R., Streever, W., 2000. Restoration of Mangrove Habitat. Tech Note ERDC TN-WRP-VN-RS-3. US Army, Corps of Engineers, Waterways Experiment Station, Vicksburg, Mississippi.

Lewis, Roy R. (2001). Mangrove Restoration - Costs and Benefits of Successful Ecological Restoration. Mangrove Valuation Workshoop, 4–8. Retrieved from http://www.fao.org/forestry/10560-0fe87b-898806287615fceb95a76f613cf.pdf

Lewis III, R. R. (2005). Ecological engineering for successful management and restoration of mangrove forests. *Ecological engineering*, *24*(4), 403-418.

Lewis, Roy R. & Gilmore, R.G. (2007). Important considerations to achieve successful mangrove forest restoration with optimum fish habitat.

Lieberman, Von, 2012. Management of Natural Resources in the Coastal Zone of Soc Trang Province, Vietnam, Von Lieberman, Hamburg, project report 13775-01.

Marchand M (2009) Modelling coastal vulnerability: design and evaluation of a vulnerability model for tropical storms and floods IOS Press

Martin, L., Dominguez, J. and Bittencourt, A. (2003). "Fluctuating Holocene sea levels in eastern and southern Brazil: evidence from multiple fossil and geometric indicators". Journal of Coastal Research9(1): 101-124.

Massel S, Furukawa K, Brinkman R (1999) Surface wave propagation in mangrove forests. Fluid Dynamics Research 24: 219-249

MacDonald, M., 2006. Feasibility Study for the Sea Defences Programme financed under the 9th EDF for "The Co-operative Republic of Guyana", Feasibility Report, Croydon, 220 pages.

Maza M, Lara JL, Losada IJ (2015) Tsunami wave interaction with mangrove forests: A 3-D numerical approach. Coastal Engineering 98: 33-54

Mazda Y, Magi M, Ikeda Y, Kurokawa T, Asano T (2006) Wave reduction in a mangrove forest dominated by Sonneratia sp. Wetlands Ecology and Management 14: 365-378

McDonald, T., Jonson, J., & Dixon, K. (2016). National standards for the practice of ecological restoration in Australia (vol 24, pg S1, 2016). Restoration Ecology, 24(5), 705-705.

McIvor, A.L., Möller, , Spencer, T., Spalding, M., 2012a. Reduction of wind and swell waves by mangroves, Natural Coastal Protection Series: Report 1. Cambridge Coastal Research Unit, Cambridge ISSN 2050-7941.

McIvor A, Spencer T, Möller I, Spalding M (2012b) Storm surge reduction by mangroves The Nature Conservancy and Wetlands International.

McIvor, A.L., Möller, , Spencer, T., Spalding, M., 2013. Mangroves as a sustainable coastal defense, Proceedings of the 7th International Conference on Asian and Pacific Coasts (APAC 2013) Bali. Indonesia, September 24-26, 2013.

McKee, K.L., 1993. Soil physiochemical patterns and mangrove species distribution-reciprocal effects? J. Ecol. 81, 477–487.

McKee, K.L., 1995a. Seedling recruitment patterns in a Belizean mangrove forest: effects of establishment ability and physiochemical factors. Oecologia 101, 448–460.

McKee, K.L., Faulkner, P.L., 2000a. Restoration of biogeochemical function in mangrove forests. Rest. Ecol. 8 (3), 247–259.

McLachlan, R. L., Ogston, A. S., Asp, N. E., Fricke, A. T., Nittrouer, C. A., & Gomes, V. J. C. (2020). Impacts of tidal-channel connectivity on transport asymmetry and sediment exchange with mangrove forests. Estuarine, Coastal and Shelf Science, 233, 106524.

NEDECO, 1972, Report on sea defense studies, NEDECO, The Hague, The Netherlands.

Nickerson, N.H., Thibodeau, F.R., 1985. Associations between pore water sulfide concentrations and the distribution of mangroves. Biogeochemistry 1, 183–192.

Pachauri, R. K., Allen, M. R., Barros, V. R., Broome, J., Cramer, W., Christ, R., ... & van Ypserle, J. P. (2014). Climate change 2014: synthesis report. Contribution of Working Groups I, II and III to the fifth assessment report of the Intergovernmental Panel on Climate Change (p. 151). Ipcc.

Parizek, B. R. and Alley, R. B. R. B. (2004). "Implications of increased Greenland surface melt under global-warming scenarios: ice-sheet simulations". Quaternary Science Reviews 23(9-10): 1013-1027.

Planet, 2016. Coastal engineering design manual for Guyana sea and river defenses. FWC BENEFICIARIES 2013 EuropeAid/132633/C/SER/multi, LOT 2: Transport and Infrastructure, Contract No. 2015/362251.

Plaziat, J.-Cl. and P. G.E.F. Augustinus, 2004. Evolution of progradation/erosion along the French Guiana mangrove coast: a comparison of mapped shorelines since the 18th century with Holocene data. Marine Geology 208, 127– 143

Primavera, J. H., & Esteban, J. M. A. (2008). A review of mangrove rehabilitation in the Philippines: successes, failures and future prospects. Wetlands Ecology and Management, 16(5), 345-358.

Raper, S. C. B. and Braithwaite, R. J. (2006). "Low sea level rise projections from mountain glaciers and icecaps under global warming". Nature439(7074): 311.

Repko, A., P. H. A. J. M. van Gelder, H. G. Voortman and J. K. Vrijling, 2000, Bivariate statistical analysis of wave climates, Proc. 27th Int. Conf. Coastal Engineering (Sydney), Reston, VA, ASCE, pp. 583–596

Rull, V., Vegad-Vilarrubia, T. and De Pernia, N. E. (1999). "Palynological Record of an Early-Mid Holocene Mangrove in Eastern Venezuela. Implications for Sea-Level Rise and Disturbance History". Journal of Coastal Research15(2): 496-504.

Rupprecht, F., Möller, , Evans, B., Spencer, T. & Jensen, K. 2015. Biophysical properties of salt marsh canopies – Quantifying plant stem flexibility and above ground biomass. Coastal Engineering 100:48–57.

Saenger, P., 2002. Mangrove Ecology. In: Silviculture and Conservation. Kluwer Academic Publishers, Dordrecht, The Netherlands.

Sandilyan S, Kathiresan K (2015) Mangroves as bioshield: an undisputable fact. Ocean & Coastal Management 103: 94-96

Schiereck, G. J. (2012). Introduction to bed, bank and shore protection. VSSD, Delft.

Smith, D.E. et al., 1999. Relative sea level rise during the Main Postglacial Transgression in NE Scotland, UK Transactions of the Royal Society of Edinburgh: Earth Sciences 90, page 1-27

Spalding MD, McIvor AL, Beck MW et al (2014) Coastal ecosystems: a critical element of risk reduction. Conserv Lett 7(3):293–301

Stevenson, N.J., Lewis, R.R., Burbridge, P.R., 1999. Disused shrimp ponds and mangrove rehabilitation. In: Streever, W.J. (Ed.), An International Perspective on Wetland Rehabilitation. Kluwer Academic Publishers, The Netherlands, pp. 277–297.

Stocken, Van der, T., J. López-Portillob, N. Koedam, 2017. Seasonal release of propagules in mangroves – Assessment of current data. Aquatic Botany 138, 92–99. http://dx.doi.org/10.1016/j.aquabot.2017.02.001.

Sutton-Grier, A. E., Wowk, K., & Bamford, H. (2015). Future of our coasts: The potential for natural and hybrid infrastructure to enhance the resilience of our coastal communities, economies and ecosystems. *Environmental Science & Policy*, *51*, 137-148.

Thampanya, U., Vermaat, J. E., & Duarte, C. M. (2002). Colonization success of common Thai mangrove species as a function of shelter from water movement. *Marine Ecology Progress Series*, *237*, 111-120.

Thampanya, U. (2006). Mangroves and sediment dynamics along the coasts of southern Thailand.

Townend, H., J.R. French, R.J. Nicholls, S. Brown, S. Carpenter, D.Haigh, C.T. Hill, E. Lazarus, E.C. Penning-Rowsell, C.E.L. Thompson and E.L. Tompkins, 2021. Operationalising coastal resilience to flood and erosion hazard: A demonstration for England. Science of the Total Environment 783, 146880

Turner, R.E., Lewis, R.R., 1997. Hydrologic restoration of coastal wetlands. Wetland Ecol. Manag. 4 (2), 65–72.

Ward, P. J. et al. (2017). A global framework for future costs and benefits of river-flood protection in urban areas. Nat. Clim. Chang. 7, 642–646

Warne, A. G., Meade, R. H., White, W. A., Guevara, E. H., Gibeaut, J., Smyth, R. C., ... & Tremblay, T. (2002). Regional controls on geomorphology, hydrology, and ecosystem integrity in the Orinoco Delta, Venezuela. Geomorphology, 44(3-4), 273-307.

Warrick, R. A., Oerlemans, J., Woodworth, P. L., Meier, M. F. and le Provost, C. (1996). "Changes in sea level". In: J. T. Houghton, L. G. Meira Filho and B. A. Callander (Eds.). Climate change 1995: the science of climate change, Cambridge University Press, Cambridge: 359-405

Wells, J. T., Coleman, J. M., & Wiseman Jr, W. J. (1978). Suspension and transportation of fluid mud by solitary-like waves. In Coastal Engineering 1978 (pp. 1932-1952).

Wells, J.T. and G.P. Kemp, 1986. Interaction of surface waves and cohesive sediments: Field observations and geologic significance (Louisiana and Surinam). Estuarine cohesive sediment dynamics. Proc. workshop, Tampa, 1984.

Wesenbeeck, van, B. K., Balke, T., Van Eijk, P., Tonneijck, F., Siry, H. Y., Rudianto, M. E., & Winterwerp, J. C. (2015). Aquaculture induced erosion of tropical coastlines throws coastal communities back into poverty. Ocean & Coastal Management, 116, 466-469.

Wesenbeeck, van, B. K., de Boer, W., Narayan, S., van der Star, W. R., & de Vries, M. B. (2017). Coastal and riverine ecosystems as adaptive flood defenses under a changing climate. *Mitigation and Adaptation Strategies for Global Change*, *22*(7), 1087-1094.

Wesenbeeck, van, B.K., van Rees, F.F., Tonneijck, F., Cronin, K., Winterwerp, H. (2021a). System Understanding; Building with Nature to restore eroding tropical muddy coasts. Ecoshape technical report, Dordrecht, The Netherlands.

Wesenbeeck, van, B.K., Wolters, G., Antolínez, J.A.A., et al. (2021b) Woods versus waves: Wave attenuation through non-uniform forests under extreme conditions, 24 March 2021, PREPRINT (Version 1) available at Research Square [https://doi.org/10.21203/rs.3.rs-321272/v1]

Wilms, T., van Wesenbeeck, B.K., Tonneijck, F., 2018. Technical guidelines nr 4. Permeable Structures. Report Ecoshape, The Netherlands.

Winterwerp, J. C., Borst, W. G., & de Vries, M. B. (2005). Pilot Study on the Erosion and Rehabilitation of a Mangrove Mud Coast. Journal of Coastal Research, 212, 223–230. https://doi.org/10.2112/03-832a.1

Winterwerp, J.C., 2006. Stratification effects by fine suspended sediment at low, medium and very high concentrations, Geophysical Research, Vol. 111, C05012, pp 1-11.

Winterwerp, J.C., R.F. de Graaff, J. Groeneweg and A. Luyendijk, 2007. Modeling of wave damping at Guyana mud coast, Coastal Engineering, Vol 54, pp 249-261.

Winterwerp, J.C., T. Albers, E. J. Anthony, D. Friess, A. Gijón Mancheño, K. Moseley, A. Muhari, S. Naipal, J. Noordermeer, A. Oost, C. Saengsupavanich, S.A.J. Tas, F.H. Tonneijck, T. Wilms, C. van Bijsterveldt, P. van Eijk, E. van Lavieren and B.K. van Wesenbeeck, 2020. Managing erosion of mangrove-mud coasts with permeable dams – lessons learned, Ecological Engineering, 158, 106078, https://doi.org/10.1016/j.ecoleng.2020.106078

Winterwerp, J.C., T. van Kessel, D.M. van Maren and B.C. van Prooijen, 2021. Fine sediment in open water – from fundamentals to modeling. World Scientific, in press.

Wolters, M., A. Garbutt and J.P. Bakker, 2005. Salt-marsh restoration: evaluating the success of de-embankments in north-west Europe. Biological Conservation 123 (2005) 249–268

World Bank (2007). Republic of Guyana Conservancy Adaptation Project

World Bank (2007). Guyana Investment Climate Assessment. Available at: http://www-wds.worldbank.org/external/default/WDSContentServer/WDSP/IB/2007/10/05/000020439_20071005091246/Rendered/PDF/359511GY0V2.pdf World Health Organization (2010) www.who.int/WTTC (2011). Travel & Tourism Economic Impact 2011: Guyana. World Travel and Tourism Council

World Bank. (2017). Implementing nature-based flood protection: Principles and implementation guidance. Washington, DC: World Bank.

Zelst, van , V.T.M., et al., (In press). Cutting the costs of coastal protection by integrating vegetation in coastal defences.

Zhenchang Zhu, Vincent Vuik, Paul J. Visser, Tim Soens, Bregje van Wesenbeeck , Johan van de Koppe, Sebastiaan N. Jonkman, Stijn Temmerman and Tjeerd J. Bouma1, 2020. Historic storms and the hidden value of coastal wetlands for nature-based flood defense. Nature Sustainability | VOL 3 | October 2020 | 853–862, doi.org/10.1038/s41893-020-0556-z

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