NORTH BRAZIL SHELF MANGROVE PROJECT

REGIONAL BIOPHYSICAL REVIEW

CONSERVATION INTERNATIONAL

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GLOSSARY

Carbon stock	The total amount of organic carbon stored in an ecosystem.
Coastal Plain	Area of coastal lowlands built up on soft sediment hosting coastal swamps mangroves, and human development.
Coastal Swamp	Freshwater forested wetlands on the coastal plain.
Landform	A natural physical feature of land surface.
Mangrove	A tree, shrub, palm or ground fern, generally exceeding one-half meter in height that normally grows above mean sea level in the intertidal zone of marine coastal environments.
Mangrove Forest	An assemblage of trees tolerant of saline conditions.
Peat	A common name for a soil in which the fabric is built of dominantly organic material.
Soil	A mixture of unconsolidated organic matter, minerals, gasses and water at the Earth’s surface that together support life.
Soil Consolidation	The process by which soil changes volume gradually in response to changes in loading and pore space compression.
Soil fabric	The geometrical arrangement of individual particles in a soils including the geometrical distribution of pore spaces.
Subsidence	The motion of a land surface as it shifts downwards relative to a datum, such as sea level.
Swamps	Freshwater forested wetland.
Tidal Range	The full range of tidal elevations, typically mean low water spring tide to mean high water spring tide levels.
Tidal Swamp	Freshwater forested wetlands where water levels are influenced by tides.
Wave Climate	Distribution of wave characteristics averaged over a period of time at a particular location.

ACRONYMS / ABBREVIATIONS

Acronym	Signification
C	Carbon
CH_4	Methane
CI	Conservation International
CLME+SAP	Caribbean and North Brazil Shelf Large Marine Ecosystems Strategic Action Program
GHG	Greenhouse Gas(es)
GONINI	National Land Monitoring System of Suriname
ICM	Integrated Coastal Management
ka	kilo annum
km	Kilometer(s)
l	Liter
LME	Large Marine Ecosystems
m	Meter(s)
mg	Milligram
mm	Millimeter(s)
mMSL	Meters Mean Sea Level
NBS	North Brazil Shelf
SRTM	Shuttle Radar Topography Mission
tC	Metric tons carbon

1 Executive Summary

This report synthesizes the current understanding of the physical processes and hydrodynamic mechanisms that support mangrove development across the North Brazil Shelf Large Marine Ecosystem (NBS-LME), specifically in Guyana and Suriname, and is intended as a key technical input to orientate planning and awareness building for mangrove conservation and restoration measures and to explore development options that conserve natural processes. The dynamic NBS-LME coastal plain is driven by migration of enormous mud banks that flow northwest as slow-moving waves along the shore from the Amazon river, Brazil to the Orinoco river, Venezuela. Mangroves grow seaward as mud banks pass and erode as the mudflat migrates. Landward from the coastline, the coastal plain has existed in relative stability. Conversion for agriculture and settlement is most intense in Guyana, progressively decreasing through Suriname, French Guiana and Brazil. Drained lands are below sea level, requiring drainage channels and protection by levees from river and tidal flooding. Extensive areas of farmland have been abandoned due to flooding and effects of acidic soils. Ongoing discussion about management of the coastal plain recognizes the importance of ecological conservation, the demand for land conversion to agriculture and settlement, and the growing frequency and scale of flooding from sea level rise.

Mangroves (saline tidal forested wetlands) and coastal swamps (freshwater forested wetlands) are interconnected components of the coastal plain landscape that are at, or just above, sea level. Over thousands of years, organic soils built up in the coastal swamps, while soils are more mineral along the shore. The presence of vegetation both helps to buffer wave energy that drives erosion and to bind soft sediment, although the capacity for mangroves to bind sediments is limited to the upper reaches of the tidal range. As such, mangroves are subject to periods of erosion and accretion with the passage of mud waves. Infrastructure built within the dynamic fringe of the mangroves is subject to periodic erosion threats as passing mud wave troughs lower the shore, and levees further exacerbate erosion by enhancing wave energy and hindering sedimentation on adjacent mudflats. Setting back of infrastructure can help create the space to sustain a mangrove area that responds resiliently to dynamic coastal changes and act to attenuate wave energy.

The existing NBS-LME shoreline is unlikely to be maintained as sea level rises. Rather, the shoreline is likely to retreat, the magnitude of which is dependent on sea level rise. There is likely sufficient sediment for mangroves to build vertically with high rates of sea level rise, but they will likely retreat landwards or shoreline. Where hard coastal flood protection measures exist, however, mangrove migration will be squeezed between rising waters and hard infrastructure. Mangrove afforestation on dynamic mudflats with brushwood fencing will be under increasing erosion pressures as sea level rises. With planning, there is potential to include mangrove restoration on abandoned lands as part of nature-based solutions for climate adaptation, flood risk reduction, and for ecosystem survival.

2 Introduction

2.1 Project Background

The project entitled “Setting the foundations for zero net loss of the mangroves that underpin human wellbeing in the North Brazil Shelf LME (NBS-LME)” (from here on the “NBS Mangrove Project”), is a one-year primer project to help establish a shared and multi-national process for an Integrated Coastal Management (ICM) in the NBS. The project recognizes the prevalence, socio-ecological importance and connectivity of mangroves in the retention and generation of key ecosystem services (fisheries, coastal protection and defenses, water quality, blue carbon etc.) from which communities in the NBS countries are beneficiaries. This project builds on, and supports, the antecedents and key elements of the regional agreement established within the CLME+SAP for the NBS region.

The objectives of the NBS Mangrove Project are:

1. To generate the necessary baseline knowledge and technical assessments as inputs towards a collaborative vision and a coordinated well-informed management of NBS mangrove systems, with emphasis on the information needs of Guyana and Suriname.
2. To support development of transboundary coordination mechanism(s) between the countries of Guyana, Suriname, French Guiana, and Brazil (state of Amapá) towards the improved integrated coastal management of the extensive, ecologically connected yet vulnerable mangrove habitat of the NBS region.

2.2 Report Objectives

This report provides a synthesis of current understanding of the physical processes and hydrodynamic mechanisms that support mangrove development across the NBS. This synthesis is intended as a key technical input to orientate planning and awareness building for conservation and restoration measures across the mangrove forests of the NBS region and as a means to explore development options in the region that conserve (vs disrupt) natural processes. It aims to ensure the sustainable use and providence of critical ecosystem goods and services (e.g. natural heritage, fisheries, carbon storage and coastal defenses to local communities). The focal area is Guyana and Suriname, with reference to the neighboring and connected mangrove systems of Brazil (Amapá State) and French Guiana. Specific objectives are to describe:

1. Factors that shape mangrove environments
2. Hydrodynamic and physical processes essential to mangrove environments
3. Feedback processes that maintain mangrove environments

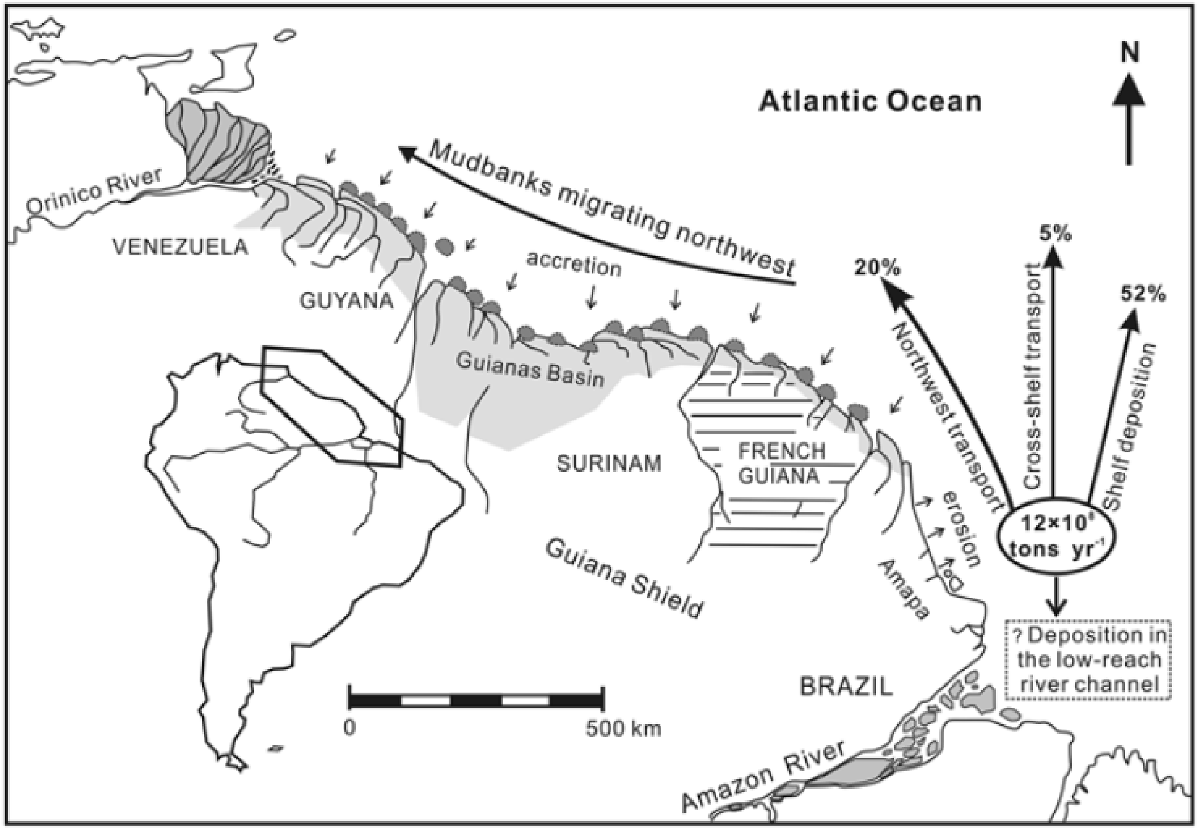
3 Geographic Setting

3.1 Key Messages

- The coastal plain and adjacent nearshore of the NBS-LME comprise one of the world's great muddy shorelines. Over thousands of years the accumulating coastal plain has formed expansive coastal swamps (freshwater forested wetlands) and, at the saline margin, mangroves (saline forested wetlands). The shoreline edge and nearshore is very dynamic, driven by migration of enormous deposits of intertidal and subtidal mud that flow as slow-moving waves northwest along the shore from the Amazon river to the Orinoco river. As mud waves pass by mangroves advance seaward the mud wave crest and retreat as the mudflat lowers with the wave trough. Away from the coastline, the coastal plain has existed in relative stability.
- The ecology of the coastal plain is a rich mosaic of diverse communities of freshwater swamp forest, upland forests on higher sandy deposits, and beach ridges (cheniers), mangrove and marsh areas. Deep peat soils, at, and just above, tidal elevations, are found sporadically along the inner coastal plain where saturation by freshwater has encouraged organic matter accumulation. Towards the coast, the soils become increasingly rich in minerals.
- Land conversion on the coastal plain for agriculture and settlement is most intense in Guyana, progressively decreasing through Suriname, French Guiana and into Brazil. Drained, subsided lands are below sea level, requiring drainage channels and protection by levees from river and tidal flooding.
- Extensive areas of reclaimed farmland have been abandoned likely due to flooding and effects of acidic soils. In a few locations, failure of levees has reflooding lands with tidal waters, reintroducing tidal environments.
- Ongoing discussion about management of the coastal plain recognizes the importance of ecological conservation, the demand for land conversion to agriculture and settlement, and the growing frequency and scale of flooding from sea level rise.
- Substantial research has been, and continues to be, undertaken along the coastline of the NBS-LME, focused largely on understanding mangrove-mud bank interactions and dynamics (Appendix 1). The consequences of levee construction along the shore have been identified as a driver of mudflat erosion (Winterwerp et al., 2013). Mangrove planting, along with experimental brushwood fencing to encourage sedimentation and shoreline stability, is being trialed. The consequences and impacts of sea level rise have not yet been explicitly addressed in these studies.

3.2 Landscape Context

The coast between the mouth of the Amazon and the Orinoco rivers is one of the world's most extensive muddy shorelines (Figure 1). Over thousands of years, muds accumulated here, building an expansive intertidal coastal plain which is still linked to a highly dynamic nearshore environment of migrating mudbanks (Anthony et al. 2013). Extensive and ecologically diverse forests remain on the coastal plain, ranging from ancient freshwater peatland swamp forests to younger mangroves, which erode and accrete in response to the passage of mud waves.



Source: Fan 2012

Figure 1. Map of the NBS-LME and associated sediment pathways, mud bank locations and bounding rivers.

The coastal plain has been subject to varying degrees in land use change, with the highest clearance for agriculture and settlement in Guyana and progressively decreasing through Suriname, French Guiana and northern Brazil (Anthony et al. 2010, Nijbroek 2014, Anthony 2016). Though populations of these countries and states are relatively low, much of the populations congregate along the coastal plain and the agricultural sector along the coast is an important contributor to the national income (Table 1; Government of Guyana 2013, Government of Suriname 2017). These lands are maintained below sea level, behind levees that keep out the tide and surrounded by a network of ditches and channels that deliver freshwater for irrigation and aid in flood management.

The quality of soils on the coastal plain is a factor both in the conversion of wetlands to agriculture and likely the subsequent abandonment of large areas of those lands. Soil productivity, even though higher than on upland sands and on the granites of the Guiana Shield, is relatively low. Where peat soils are drained, acid sulfate soils may form, releasing sulfuric acid and heavy metals and rendering the soil inhospitable for nearly all plant life (Brinkman and Pons 1968, Masulili et al. 2010). Extensive areas of abandoned farmland exist (Bruiner et al. 2019). In Suriname, 100,267 ha of former wetland, now agricultural land, are recognized as being in production and while an area almost double is size, 186,677 ha, is described as abandoned agriculture (GONINI data portal[1]).

Table 1. Population, agriculture, and coastal elevation data in Guyana and Suriname (ND = data are not currently available)

Country	Guyana	Suriname
Population (2019)[2]	787,000	573,000
Population along coast (%)	90[3]	80[4]
National income from coastal agriculture (%)		20[4]
Average elevation of coastal agricultural land (m)	ND	ND
Agriculture on former peat swamp and mangroves (ha)	ND	ND
Abandoned agriculture on former peat swamp and mangroves (ha)	ND	ND

Because coastal wetlands soils subside when drained infrastructure and communities on the coastal plain are below sea level and at risk to both nuisance and catastrophic flooding from rivers and the

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[1] www.gonini.org, accessed June 2019

[2] Source: https://databank.worldbank.org/, accessed June 2019

[3] Da Silva 2015

[4] UNDP 2016

ocean. Over time, with sea level rise, these risks increase, along with impacts of rising groundwater and salinization of soils. How to balance land use and land use change on the coastal plain, with the consequences of climate change, is an ongoing discussion (Government of Guyana 2013, Government of Suriname 2017). Development plans call out the importance of strengthening economies, growth and diversification, social progress and utilizing and protecting the environment (Government of Guyana 2013, Government of Suriname 2017). Mangrove forests, the ecosystem of primary focus of this report, are vulnerable to decisions on land use, infrastructure construction and the consequences of sea level rise. Unless space is maintained or provided, mangroves will be 'squeezed' between rising seas and hard flood protection levees (Figure 2). Factoring in conservation and restoration of mangroves as part of development and climate adaptation and mitigation planning will be critical to maintaining these ecosystems and the services they provide. Mangrove ecosystem services can take many forms, including supporting (nutrient cycling, carbon storage, primary production), provisioning (wood, fuel, food), regulating (climate and flood regulation, water purification), and cultural (recreation, spiritual, aesthetic, education) services (Vo et al. 2012, Lee et al. 2014).

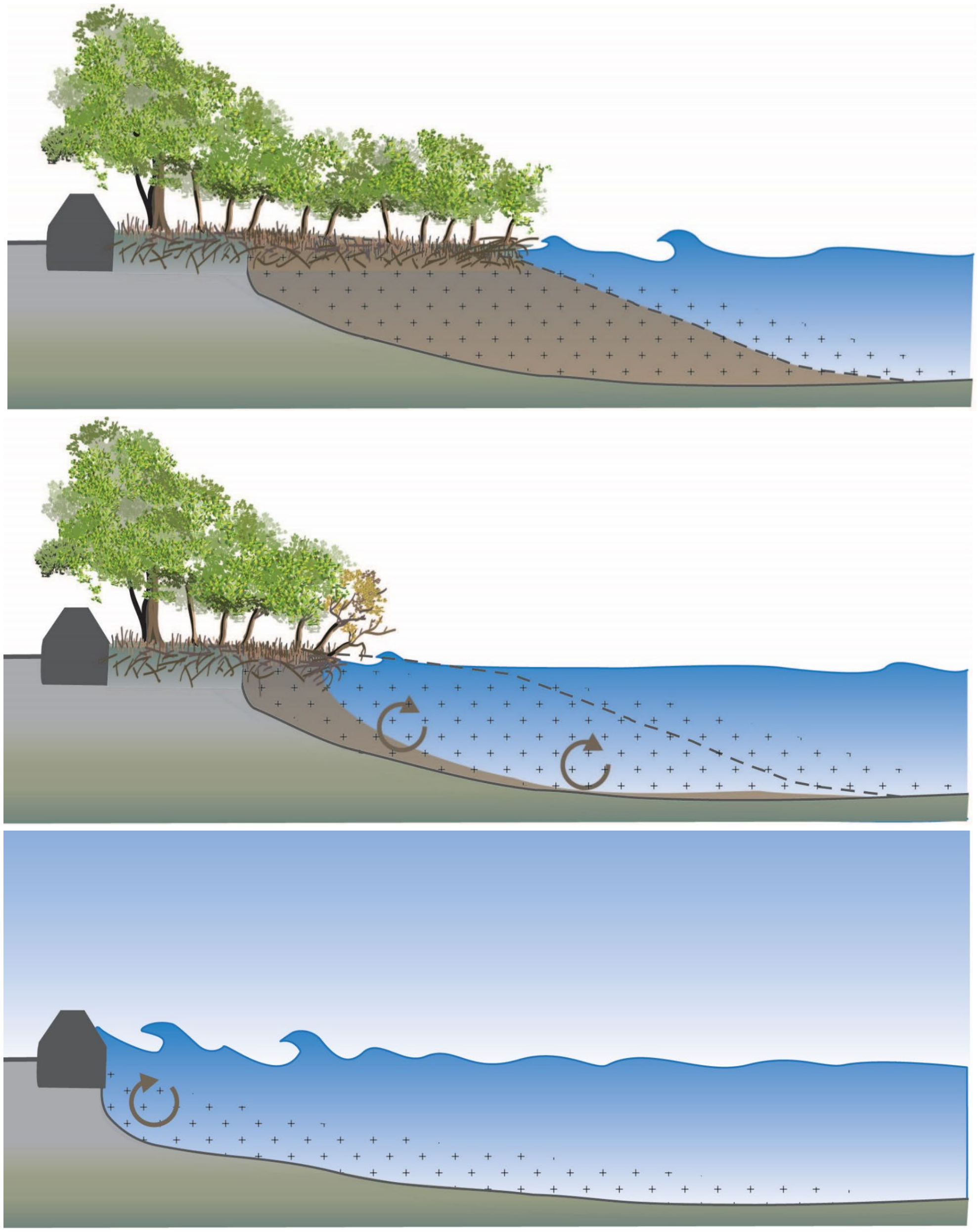
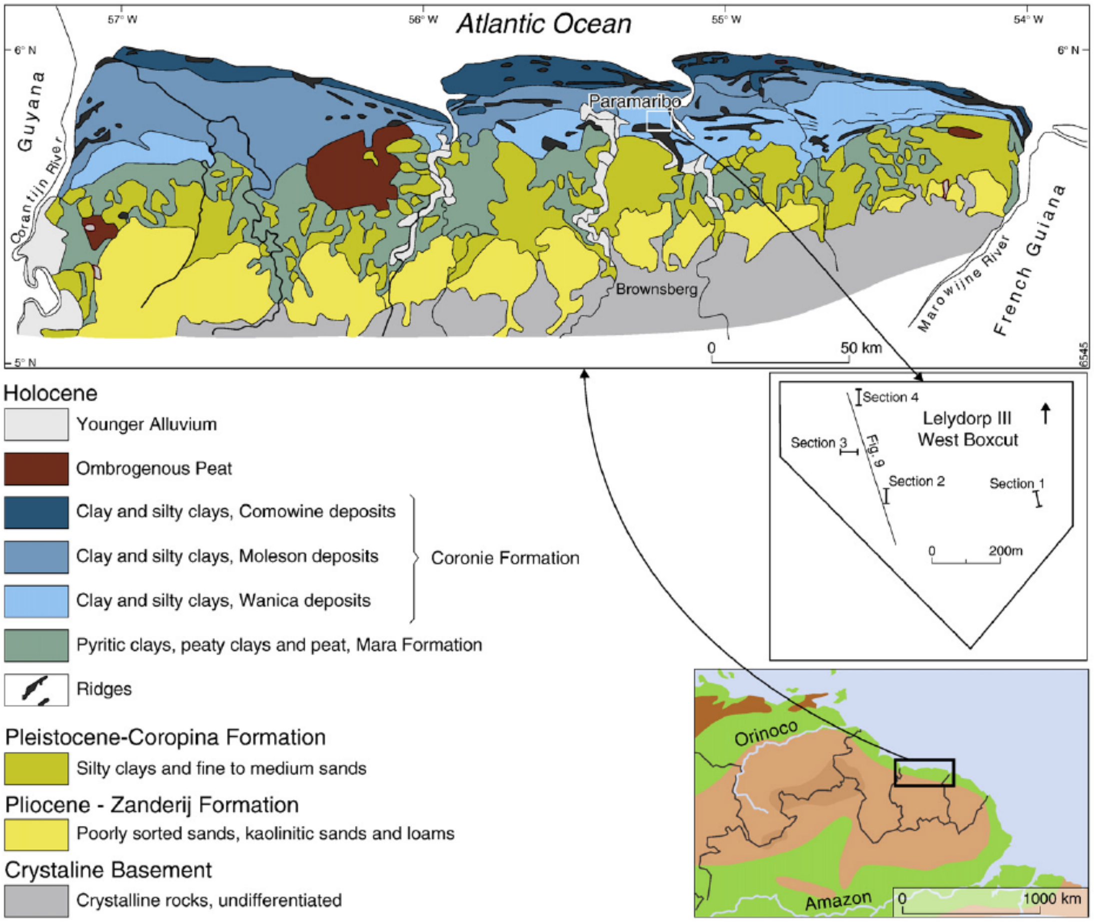


Figure 2. Mangroves abutting hardened structures without the ability to migrate inland are likely to be lost with sea level rise.

3.3 Geomorphology

Much of the landmass of the NBS-LME consists of Precambrian igneous rocks of the Guiana Shield, eroded in a hilly landscape covered by tropical rainforest. These rocks dip to the north where they are overlain by coastal plain deposits of Pleistocene, Holocene, and contemporary ages (Figure 3; Brinkman and Pons 1968, Wong et al. 2009).



Source: Wong et al. 2009

Figure 3. Geologic map along the coast of Suriname.

The coastal plain extends the full length of the 1,500 km shore between the Amazon and Orinoco rivers. The source of the sediment is predominantly from the Amazon river, providing a mix of clays and very fine sands that are transported westwards towards the Orinoco River in Venezuela. Sediment and freshwater are also supplied from local rivers (Anthony 2010). During glacial periods, low sea levels exposed the continental shelf and sediment from the Amazon was directed to the deep ocean. As sea levels rose, sediments were deposited along the shore to build the coastal plain.

A report by the Netherlands Soil Survey Institute provides a comprehensive synthesis of the soil geomorphology of the coastal plain of the NBS-LME (Brinkman and Pons 1968). This is helpful to review to understand the distribution of habitats on the plain:

- *Beach ridges (cheniers)*: parallel to the shoreline, discontinuous ridges of sand and shell material, the tops reaching 2-4 m above mean sea level. Where the coast is eroded, ridges form at the edge of the mudflat. In Suriname there are two series of well-developed chenier bundles, denoting two periods of coastal erosion during the Coronie Formation (6,000 years ago). These two hiatuses among three sedimentation phases of the Wanica, Moleson and Comowine coincide with slight falls in sea level.

- *Marine tidal clay flats and mangroves*[5]: Mangroves develop during accretion from uncovered mudbanks by salt tolerant *Rhizophora* and *Avicennia*. Behind the mangroves, where freshwater conditions dominate, saline forests give way to freshwater forests and grass swamps with a thin "pegasse" (peat) surface soil layer.
- *Natural levees of the rivers and estuaries*: These occur in broad to narrow bands parallel to the rivers, have mainly silty clay textures, are 'silted up' to above mean high tide level and support evergreen seasonal forest.
- *[Forested] peat swamps*: In the bank swamps, 'eustatic' peat is formed on the top of tidal clay flats under conditions prevailing during a relative rise in sea level. Very poor drainage conditions in large areas led to the formation of ombrogenous[6] peats with strong acidic conditions with swamp vegetation.

The coastal plain of the NBS-LME consists of a series of these geomorphological landscapes, sometimes incomplete marking where periods of erosion have occurred.

The coastal plain is divided onto two main geomorphological units: the Old Coastal Plain of predominantly Pleistocene deposits, and seaward the Younger Coastal Plain of Holocene age (Figure 3; Brinkman and Pons 1968, Wong et al. 2009). The clay and silty clay deposits shown in shades of blue in Figure 3 depict the Younger Coastal Plain while the Old Coastal Plain is shown in shades of yellow.

The Old Coastal Plain lies at an elevation of between 4 – 11 m above mean sea level and consists of a discontinuous belt of dissected Pleistocene sandy ridges and clay flats, remnants of former beaches, cheniers and mangroves. Both are now covered with rain forest. These higher landscape elements are interspersed with Holocene clay and peat soils with freshwater herbaceous swamps, alternating swamp scrub, swamp wood and swamp forest (Teunissen 2000).

The Young Coastal Plain lies at elevations slightly above mean sea level (Roeleveld and van Loon 1979), with the exception of drained areas which now lie below the elevation of high tides. The plain consists of extensive Holocene clay flats, and belts of mangrove forest, saline to brackish lagoons and brackish herbaceous swamps. At its landward margin, rainwater drives salt from the soils, supporting freshwater herbaceous swamps alternating with swamp scrub, swamp wood and swamp forest. These northern

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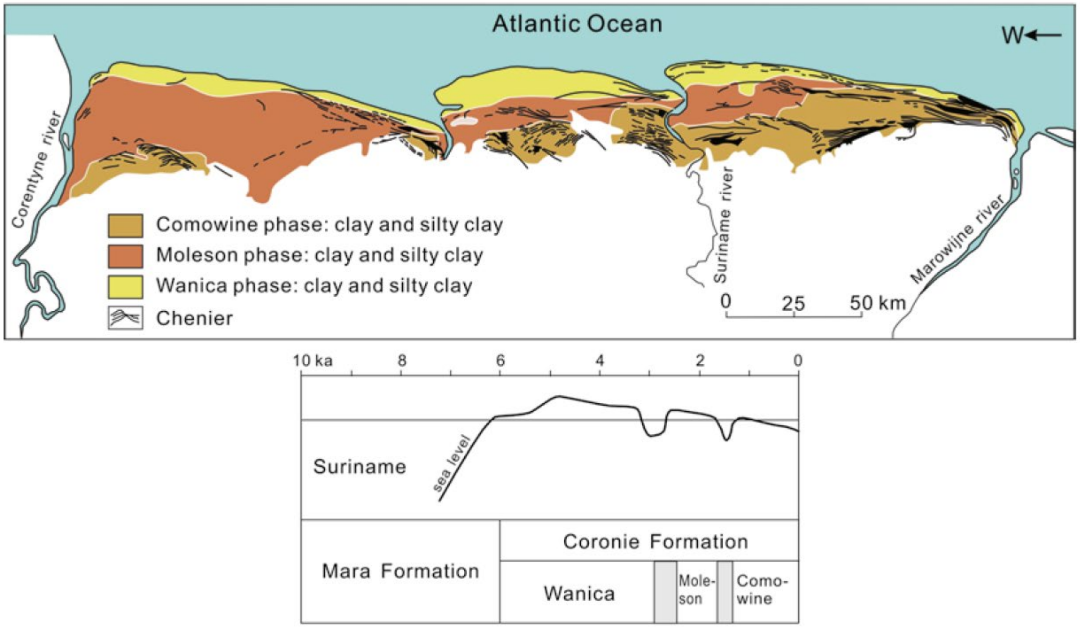
[5] Brinkman and Pons (1968) refer to mangroves as marshes.

[6] The resulting lack of dissolved bases gives strongly acidic conditions only specialized vegetation, predominantly bog mosses, will grow.

freshwater swamps store and supply freshwater to maintain brackish conditions in the coastal swamps, lagoons and swamp forest (Teunissen 2000).

The distribution of landforms also reflects a complex evolution of a mosaic of mineral soils and peats. Soils of the Young Coastal Plain are divided into those older than 6,000 years (Mara and Pegasse Formations) and those younger (Figure 4; Coronie Formation; Wong et al. 2009). In Suriname, the Mara formation covers large areas mainly west of the Commewijne rivers and in western and eastern French Guiana and penetrates onto the erosion gullies of the older landscape (Brinkman and Pons 1968). The Mara Formation and Pegasse Formation in neighboring Guyana consist of deep deposits of pyritic clays and pyritic peats that built during the early Holocene. Pollen analysis identifies the deposits as being from brackish *Rhizophora* mangrove that accumulated peats that may be 4 to 8.5 m deep (Brinkman and Pons 1968). West of the Essequibo river in Guyana, the distribution of pyrite clay and peats is more complex, in places mixed with younger deposits and occurring at elevations up to 3 m above mean sea level. When drained, these deposits give rise to 'cat clays' or acid sulphate soils (Brinkman and Pons 1968), which can make them unusable for agricultural land use.



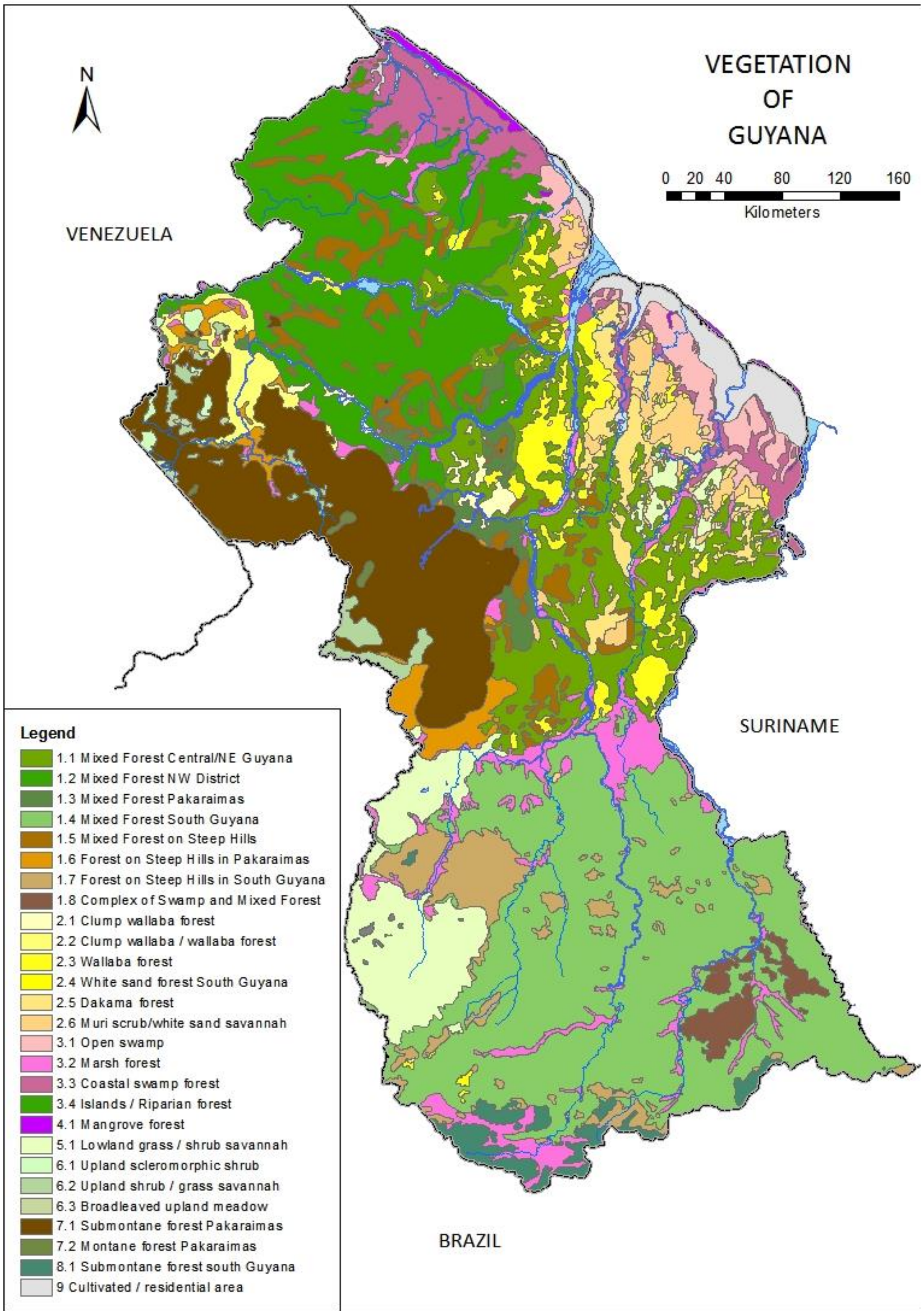
Source: Fan 2012

Figure 4. Three-phase sedimentation units along the Suriname coastal plain, and the relationship between accretion and erosion phases with sea level fluctuations.

3.4 Landscape Ecology

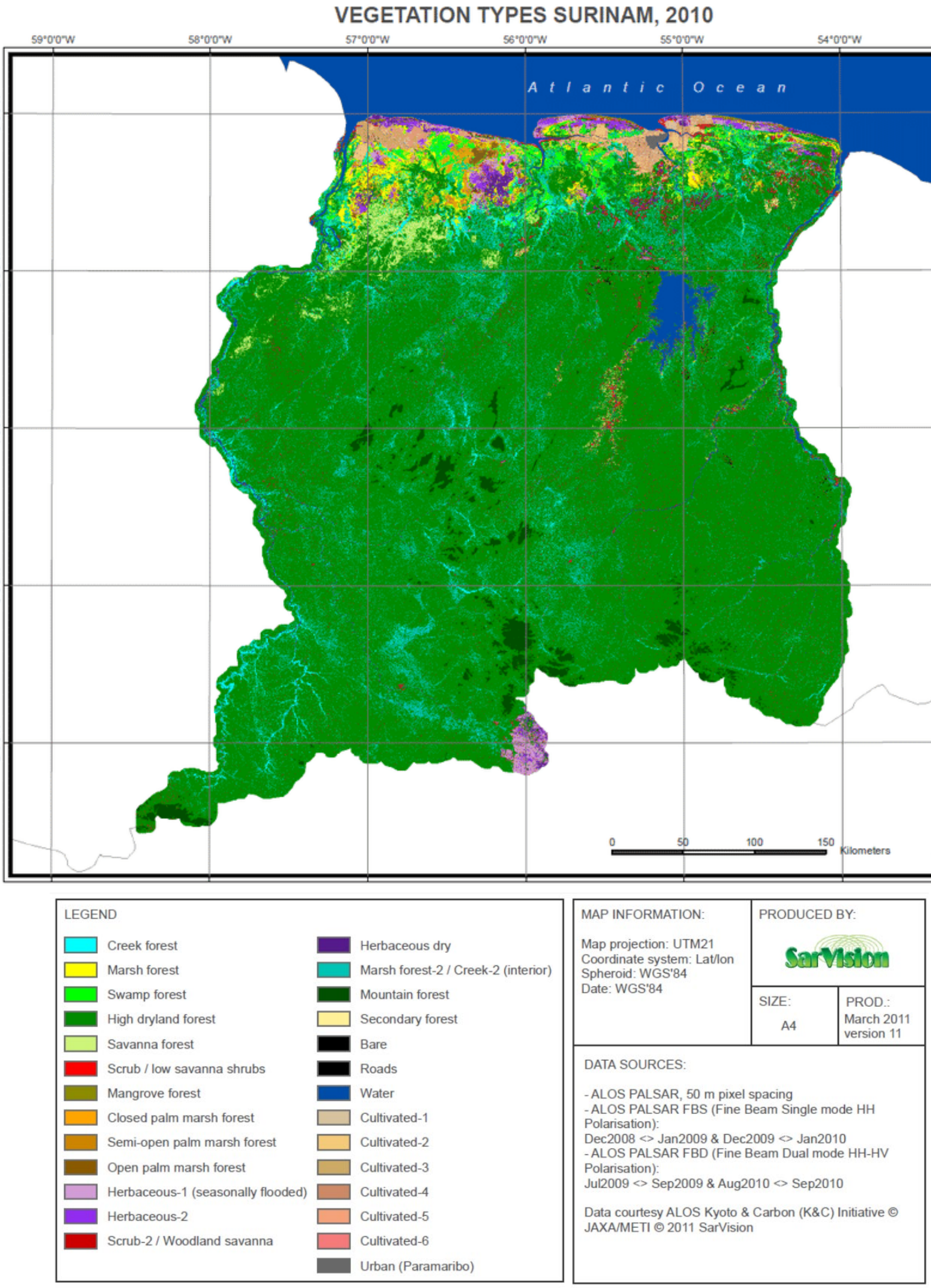
In addition to the geomorphology, understanding the ecologic relations and benefits of its ecosystem services is equally important to this review. The coastline of the NBS-LME hosts a rich diversity of coastal swamp forests (Figures 5 and 6). Both the hydroperiod (flooding frequency and duration) as well as water chemistry and acidity (in addition to the nature of soil substrate) act together to influence floristic diversity (van Andel 2003). The diversity in ecology is described in the range of forest types that have been mapped. While this study is focused on the mangrove areas, certain forest types are key components of a linked ecological mosaic on the coastal plain.

Mangrove systems along the NBS are comprised of three genera: *Avicennia germinans* (also accounts of *A. schaueriana* in Suriname; black mangrove, parwa, courida), *Rhizophora mangle* (also accounts of *R. racemosa* and *R. harrisonii* (hybrid); red mangrove, mango, red mango), and *Laguncularia racemosa* (white mangrove, akira). Black mangroves are the dominant species along the North Atlantic Ocean and have the potential to withstand high soil salinities, upwards of 60 PSU (Marchand et al. 2004). Growth is very rapid once seedlings establish and trees can reach 30 m in height once mature. Red mangroves are more abundant inshore of coasts in riverine zones and along the edges of swamp forests, where fluctuations in water salinity are common. These species can also reach heights upwards of 30 m. White mangroves, reaching heights of 6 m, are not as common as black mangroves but can colonize along with them on the ocean-front and are most often found at the landward edge of mangrove stands in areas that are inundated mainly by spring tides. At the landward side of the mangrove band, marsh forests occur, composed of *Symphonia globulifera*, *Ficus* spp., *Virola surinamensis*, *Euterpe oleracea*, which can be mixed with old *A. germinans* stands (Lee et al. 2014).



Source: Van der Hout (2015)

Figure 5. Vegetation map of Guyana. Coastal swamps are denoted in rose and light pink and mangroves are denoted in purple.



Source: Arets et al. (2011)

Figure 6. Vegetation map of Suriname. Coastal swamps are denoted in shades of brown and mangroves are denoted in olive.

Coastal swamps are described by Prance (1979) who recognized variation in ecology associated with topography and hydrology. Mora Forest is classified as a seasonal vārea, a forest flooded by regular annual cycles of river flow. A manicole swamp represents a tidal vārea, inundated and drained twice daily by tidal freshwaters. A quackal forest is a permanent swamp forest, occurring in depressional areas behind river levees that stay saturated through most dry seasons. In Guyana, the quackal forest is flooded by rainwater and black water from the Moruca River and shows some traits similar to Amazonian igapő forest as well as nutrient-poor white sands forest (van Andel 2003). Each of these forest types hosts different plant species (Prance 1979), the diversity of which illustrates the sensitivity of the landscape to hydrological conditions and modifications.

These forests occur on soil types that transition from organic and acidic to organic interbedded with muds to mud deposits with interstitial organics from the land to the shore. In the context of carbon management, soil type influences the scale of potential emissions, with organic soils potentially exhibiting heightened and more long-term emissions than mineral soils.

Coastal swamps also play an important role in sustaining seafood, as is recognized in the Coastal Management Plan for the North Coronie Area in Suriname (Teunissen 2000) that lists the following ecosystem services and benefits:

- *"Seafood abundance is directly related to the extent of the local mangroves.*
- *Up to 90% of marine fish and shrimp species are found in and near mangrove areas during one or more periods of their life cycle.*
- *Offshore industrial fisheries largely depend on mangrove forests: including large-scale industrial deep-sea fisheries which benefit from the nursery function of these ecosystems.*
- *High production of seafood is also found in the nearshore habitats where small-scale fisheries are practiced: in the shallow sea, the river estuaries, tidal creeks, lagoons and brackish swamps. These ecosystems provide the local market with foodfish, shrimp and mangrove-honey."*

4 Mangroves and Coastal Swamps

4.1 Key Messages

- Mangroves and coastal swamps are interconnected components of the coastal plain landscape. The nature and extent of these habitats are defined by how sediments, water and plants interact. The health and biodiversity of these habitats are sensitive to hydrology, how it is changed by people as well as changes in climate.

- The mosaic of habitats reflects the prevailing hydrology of freshwater and saline flows, soils building to maintain lands at, or just above, sea level, and rhythmic tidal flooding, as well as disturbance events of droughts and floods.
- Over thousands of years organic soils built up at the inland and more stable reaches of the coastal plain. Towards the shore where natural physical disturbance is more common soils are more mineral. As long as soils are maintained wet and undisturbed they remain sinks for long term carbon storage.
- The presence of vegetation both helps to buffer wave energy that drives erosion and also to bind soft sediment that increases resistance to erosion. Mangroves do not grow at elevations lower than mean sea level and as such their capacity to bind sediments is limited to the upper reaches of the tidal range. As such, the mangrove edge is subject to periods of erosion and accretion with the passage of mud waves that build and lower the shore, modifying the wave climate.
- Infrastructure built within the dynamic fringe of the mangroves is subject to periodic erosion threats as passing mud wave troughs lower the shore. The presence of levees further acts to exacerbate erosion by enhancing wave energy and hindering sedimentation on adjacent mudflats.
- Setting back infrastructure can help create the space to sustain a mangrove area that responds resiliently to dynamic coastal changes with passing mud waves and act to attenuate wave energy.
- On abandoned lands reconnected to tides, some impairment to mangrove recovery has been observed as a result of high wave energy. Measures to temporarily reduce wave energy on restoration sites may be required to promote and accelerate mangrove recovery.

4.2 Hydrology and Physical Processes that Determine the Coastal Forest Environment

The ecology and extent of the coastal plain are defined by hydrology and how both sediments and plants interact with water flows and quality. Beard's (1955) pioneering work surveying the coastal landscape of Suriname in the 1940s and 1950s remains today broadly representative of conditions that apply across the study area. Swamp and woodlands are found near creeks, where drainage conditions and lines of moving water create better aerated conditions. He postulated that soil conditions drove a distinction between swamp and unforested lands, with swamps occurring where flow of freshwater maintained aerated soil conditions and unforested wetlands where impeded flows favored herbaceous cover.

At the shore, the ecology is increasingly influenced by salinity and freshwater / brackish water tolerant forest species give way to mangroves. Even amongst mangrove species, there are differences in capacity to withstand flooding and salinity. Black mangrove (*Avicennia* spp.) are the most salt tolerant and are found on the open shore but these trees may also die back under conditions of impaired drainage and hyper-salinization. Red (*Rhizophora* spp.) and white mangroves (*Laguncularia racemosa*) tend to be found in less saline settings.

Disruption to freshwater flows from rivers and seeping from coastal swamps can significantly impact coastal ecology. The free flow of freshwater has been obstructed by several infrastructure projects over the past 50 years including major road construction and development projects. In one case, the construction of small dams to sustain large-scale mechanized rice farms were cited by the Members of the Committee for the Rehabilitation of the Northern Coronie Polder to limit freshwater flow to the coast, causing mangrove die off and exacerbating coastal erosion (Figure 7; Nijbroek 2014).

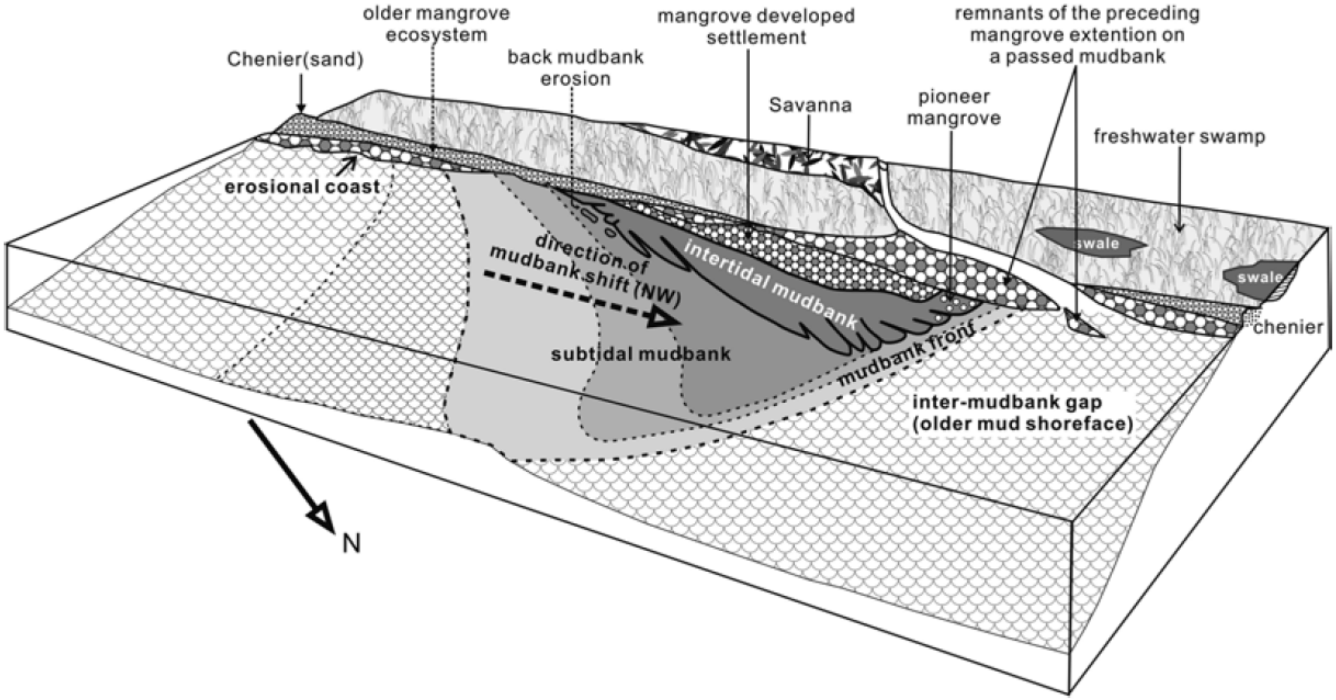
Source: Toorman et al. 2018

Figure 7. Example of mangrove die-off due to impaired tidal connection in Coronie, Suriname.

4.3 Feedback Processes that Maintain the Coastal Forest Environment

In addition to the direct impact of water flow and quality on the ecology of the coastal plain, hydrology and sediment supply also influence soil building. The structure or fabric of soil consists of two components: organic and mineral material. Organic material is derived dominantly from in-situ plant production but also material brought in by flooding waters. Under low oxygen availability occurring in wetland soils, decomposition of organic matter is substantially curtailed leading to accumulation of organic soils and peats (Krauss et al. 2014). This accumulation rate is relatively slow but continuous over centuries, with soils functioning as a carbon sink as long as they stay saturated and protected from erosion.

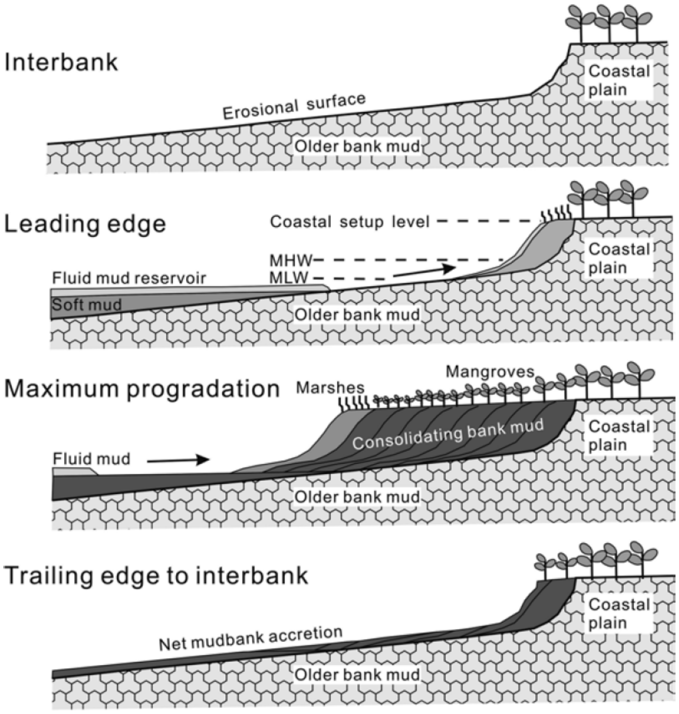
The mineral component of soils is largely derived from sources beyond the site that are transported mostly with waterflow (Figure 8). Across the coastal plain of the NBS-LME, the mineral soils are found dominantly along mangrove-covered outer edges and along channel margins, whereas the organic content of soils increases towards the inland areas of the Young Coastal Plain. This distribution reflects a combination of soil maturity, distance from the dynamic coastline edge, distance from sediment supply and delivery of freshwater flows.



Source: Fan 2012

Figure 8. Mud bank zonation and shapes along the North Brazil Shelf.

The presence of vegetation acts to stabilize sediments by buffering waves and reducing direct scour (Winterwerp et al. 2013), binding the soil fabric with roots and extracting water to increase sediment packing density (Krauss et al. 2014). Through feedback processes, further vegetation establishment and soil building occurs along with succession of vegetation. Root-bound and consolidated sediments act to resist erosion disturbance events (Figure 9).



Source: Fan 2012

Figure 9. Example of shoreline evolution along the North Brazil Shelf.

On muddy coastal plains with deep soils, such as that of the NBS-LME, there is a degree of self-weight consolidation that takes place leading to ongoing soil subsidence over time (Syvitski et al. 2009, Yuill et al. 2009). The weight of accumulating material bears down on the soil column and gradually expresses the soil waters. The degree to which this occurs depends upon the thickness of the accumulating alluvium and the granular nature of the soil fabric (sands consolidating less that clays). Drainage enhanced and accelerated consolidation and subsidence by removing pore waters that hold soil grains apart. At the coast, land subsidence together with global sea level rise contribute to define rates of local relative sea level rise. There is some suggestion that subsidence is occurring in the NBS-LME, contributing to reported tide gauge measurements of sea level rise in Georgetown of 3 to 10 mm yr^{-1} between 1950 and 1979 (Mott MacDonald 2004). However, tide gauges are not currently maintained in the region and the extent of subsidence is undetermined.

In absence of mineral sediment, coastal wetlands have the capacity to build organic soils against a small amount of subsidence or sea level rise. For mangroves, Krauss estimates this to have an upper bound of 3 mm yr^{-1}, possibly 5 mm yr^{-1} (personal communication, January 2019). Mineral soil contributions greatly increase the soil building capacity beyond an organic sedimentation threshold. Under adequate sediment supply, coastal marshes in the Mississippi Delta and mangroves of the Mekong Delta, for example, kept pace with subsidence of 10 mm yr^{-1} or more (Syvitski et al. 2009). For thousands of years, organic material was buried beneath new sediments though this continued process of subsidence. The interplay between sea level rise and increases in suspended sediment from the Amazon river could even result in neutral sea level rise impacts (Toorman et al. 2018) as long as sea level rise does not outpace sediment accretion.

This also means that recovery and establishment of mangroves, even on reconnected and restored lands, can be hindered by several factors: (1) land surfaces falling below the sea elevation at which mangroves establish[7], (2) increased wave activity in exposed locations (Bruiner et al. 2019), and (3) formation of acid sulfate soils and other changes in soil properties (Luke et al. 2017). However, sedimentation of muds and sandy cheniers on former drained soil surfaces are likely to foster conditions for mangrove reestablishment.

4.4 Contemporary Coastal Processes

The coastal processes that shape the nearshore and shoreline edge of the NBS-LME have been the subject of substantial research investigations and are a global 'type-site' for understanding open coast muddy systems (Fan 2012, Toorman et al. 2018). The most recent review is provided in Appendix 1. Scientific studies describe the shoreline continuously undergoes multi-decadal periods of accretion and erosion, overlaid on a long-term trend of sea level rise and periods of shifted trade wind conditions.

These fluctuations are a result of alongshore migration of mudbanks derived from the Amazon river, 45 km in width and extending offshore ten km to a depth of 20 m. At the shore, the mud waves' height from trough to crest is 3 m and they travel at a rate of 1.5 km yr^{-1} (Figure 1; Augustinus 2004, Anthony et al. 2010).

There is some indication that multi-decadal cycle of shoreline erosion and accretion are occurring driven by changes in winds and ocean wave climate (Eisma et al. 1991, Allison et al. 2000, Augustinus 2004). Identified from aerial photographs across Suriname, a period of net shoreline erosion (1947-1966) was followed by a period of advancement (1966-1981). The current status is unclear. Coincident with the shoreline's adjustments was a change in wind direction (from NE to ENE) with stronger winds more parallel to the shore, driving sediment transport, extension of mudbanks and shoreline advancement (Augustinus 2004).

The progression of mudbanks are a manifestation of largescale fluid mud transport under waves and tidal currents. These observations highlight the dynamic nature of the shoreline and its sensitivity

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[7] Mangroves establish just above mean tide elevation.

response to changing environmental conditions, which need to be considered when planning restoration and conservation activities, especially in regards to sea level rise.

4.5 Impacts of Land Use Conversion on Shoreline Stability

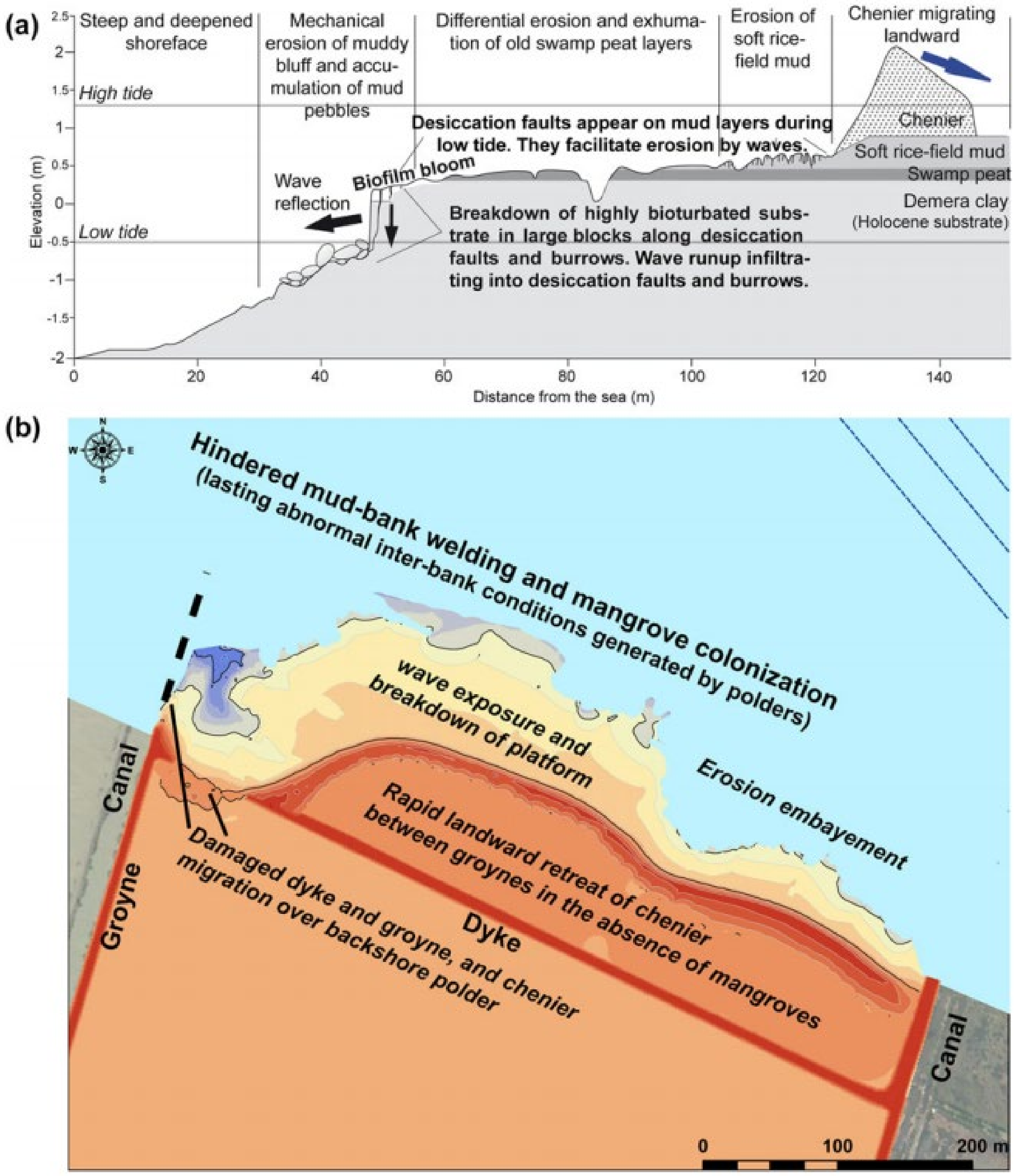
Conversion of coastal wetlands to other uses has a number of impacts. Most directly, there is a loss of habitat and associated ecosystem services. Often the land use change comes with a modification in hydrology that may impact neighboring wetlands, though this has not been studied in this region.

At the shoreline edge, replacing the mangroves with a hard structure set in motion a phase of sustained coastal erosion (Toorman et al. 2018). Winterwerp et al. (2013) reviewed the mechanics of these processes. Under natural conditions, mangroves stabilize sediments, buffer waves and foster sediment accumulation on adjacent mudflats. These processes are important precursors for the "attachment" of passing mud waves and the associated phase of mangrove advancement. Replacing the mangrove edge with a levee both disrupts tidal flows and also increases wave reflection on adjacent mudflats, so reducing sedimentation. Conditions that prevent mangrove establishment are set in place and leads to a cycle of increased scour at the base of the levee, which may then itself be undermined (see Appendix 3 for examples).

With levee failure the land behind rejoin the intertidal zone and becomes a component of the adjusting shore profile seeking a form in balance with the wave climate and sediment delivery. Reconnection brings the opportunity for sediment accumulation, rebuilding of mudflats and, in time, recovery of mangrove forests. Such recovery may be hindered on subside lands as larger wave in deeper water propagate across the site but over time, given adequate space, a stable shoreline will recover.

Brunier et al. (2019) provide a geomorphic assessment of shoreline response to levee failure and reflooding of a rice field in French Guiana. With prior construction of the rice field, levees were built at the very seaward edge of the mangroves. In this vulnerable location the constructed levee eventually failed, likely through the processes described by Winterwerp et al. (2013). Now tidally reconnected the shoreline is undergoing a period of prolonged recovery. Wave erosion continues to erode the shoreline both through cliff erosion of the seaward edge and also scouring the surface soils on the rice field hindering mangrove seedling reestablishment. In response, natural wave breaks in the form of shelly cheniers are forming on the rice field surface (Figure 10). In time, and given sufficient space, the shore is likely to go through a phase of sustained erosion and then stabilization. Further inland from its present location, a new stable shoreline profile may develop, and, if unhindered by further human actions, could reestablish a dynamic mangrove edge there. Over the decades investigated by Brunier and colleagues (2019), this dynamically stable form had not yet been achieved at the site.

Collectively, prior studies within the region highlight not only the impact of levee construction on shoreline stability but also indicate a phase of continued erosion with uncontrolled levee failure. The management implications for mangrove recovery are to either allow the shoreline to continue to adjust to these conditions or enact measures that will stabilize the eroding edge and reduce wave activity on the exposed soil surface. Labor and cost of such adaptation measures need to be factored into overall planning considerations.



Source: Brunier et al. 2019

Figure 10. Erosional processes once mangroves are removed, viewed (a) as a cross section and (b) at the scale of a polder plot.

5 Response of the Coastline to Sea Level Rise

5.1 Key Messages

- In review of existing studies on the coastline of the NBS-LME, no evidence to was found to support a hypothesis that the existing position of the shoreline will be maintained as sea level rises. Rather, depending on the magnitude of sea level rise in coming decades and centuries the shoreline is most likely to retreat. This is consistent with studies elsewhere.
- There is likely sufficient sediment for mangroves to build vertically with high rates of sea level rise, but at the same time they will very likely retreat landwards. Given sufficient space mangroves on the coastal plain will be very resilient to sea level rise.
- Preservation success of mangroves will depend on room for landward migration. Where hard coastal flood protection measures exist the migration of mangroves will be squeezed between rising waters and hard infrastructure.
- Mangroves built on the dynamic coastal fringe through artificial means (e.g. sediment trapping approaches) will be under increasing erosion pressures as sea level rises. These approaches can be used to aid mangrove recovery on abandoned lands where levees have been set back instead of building into the foreshore.
- Potential salinization of brackish and freshwater systems may occur changing the ecology of coastal swamps.
- With sufficient planning there is potential to include mangrove restoration as part of nature-based solutions for climate adaptation, flood risk reduction, and for ecosystem survival

5.2 General Concepts on Coastal Response to Sea Level Rise

Rising sea level drives a spatial shift in coastal geomorphology, manifested through the redistribution of the coastal landform comprising subtidal bedforms; intertidal flats, beaches, chenier ridges, mangroves and coastal forests (Pethick 1984, Pethick and Crooks 2000, Wolinsky and Murray 2009). This impacts the quality and quantity of associated habitats, the nature of ecosystem linkages, and the level of vulnerability of wildlife, but also the people and infrastructure in coastal areas.

When considering coastal processes, there are broad geomorphic principles that apply in all coastal settings that should to be considered in the context of the local coastal setting. While day-to-day responses, particularly to individual events, may be difficult to predict with specificity (although they may be planned for using risk management approaches), broader trend changes can be incorporated into landscape scale planning.

Many soft sediment shorelines tend to evolve towards a dynamic equilibrium state around which they oscillate with disturbance (Pritchard et al. 2002). If an equilibrium form is attained, an increase in sediment supply (such with the passage of a mud wave) or reduction in wave energy may lead to an advance in the shore. Shoreline retreat occurs when major storms pass through or sediment supply deminishes. The capacity for the shore to recover its equilibrium form depends upon the scale of the disturbance event and whether the recovery time is shorter than the frequency of disturbances (Pethick and Crooks 2000). And, if there is a long-term change, such as sea level rise, or cut-off of sediment supply, then these oscillations continue to occur but with the additional trend of ongoing landward erosion.

A key question when assessing the response of a shore to sea level rise is whether it has attained its dynamic equilibrium form. A shoreline that is still building through sediment supply may have additional capacity to resist retreat with sea level rise. Conversely, a shoreline that has had its sediment supply reduced or destabilized through impacts of infrastructure may already be inherently more vulnerable and may see a sustained or sudden (with infrastructure failure) landward adjustment with sea level rise.

5.3 Past Sea Level Change and Shoreline Response

Projecting future response of the shoreline to sea level rise can also be informed by understanding past changes over the scale of thousands to hundreds of years. Caribbean-wide trends in Holocene sea level change are summarized by Khan et al. (2017). In Suriname and Guyana, like elsewhere in the world, early Holocene sea level rise was rapid (8.4 ± 1.1 mm yr^{-1}) before slowing during the mid to late Holocene. In the region, mean sea level attained an elevation higher than present with a highstand above present day of 0.4 ± 1.2 m by 7.2 ka and 0.9 ± 1.0 m at 4.7 ka. From this, peak sea level fell gradually (0.1 ± 0.3 mm yr^{-1}) reaching 0.6 ± 1.4 m by 1.0 ka. Sea level therefore has been higher than present for over seven thousand years (see Figure 4). Such conditions of gradual falling sea level are conducive to shoreline advancement.

Changes in the shoreline over recent millennia where investigated by Pujos et al. (1996) who examined the configuration of soil units and chenier sand ridges along the coastline of the NBS-LME. Based upon radiometric dating and mineralogy, they summarized the sequence of soil units was indicating gradual advancement of the muddy shoreline punctuated by climate-induced erosion events during which sand deposits lined the shore. The periods of erosion were interpreted to reflect dryer conditions in the Amazon that lead to reduced sediment delivery, with no opinion offered on climatic changes in trade wind strength or direction. Most of the coastal plain, away from the dynamic edge that is subject to passing mud waves, is comprised of sediments older than one thousand years, reflecting relatively a shift to dynamically stable conditions in that timeframe.

Looking at more recent times, using maps dating back to the 18th century of the French Guiana coastline, Plaziat and Augustinus (2004) found the shoreline to have occupied a relatively stable position, neither advancing nor retreating beyond small scale edge fluctuations with mud wave migration and possibly with changes in Tradewinds. This is suggestive that the shoreline of French Guiana at least has attained a dynamic equilibrium over past centuries with no ongoing seaward advancement of the coastal plain.

Overall, the balance of evidence suggests that the period of human occupation across the NBS-LME coincides with a time of relative stability of coastal position lasting several centuries. Consequently, a period of sea level rise is likely to drive a seaward retreat of the shoreline edge and readjustment in the habitat mosaic.

5.4 Projecting Coastal Response to Future Sea Level Rise

A critical limitation in assessing coastal response to future sea level rise is the absence of direct measurements of water level regionally, beyond a temporary station in Georgetown that reportedly recorded rates of sea level rise at rates greater than global rates (Mott MacDonald 2004).

Globally, ongoing and future sea level rise will force shorelines to retreat landwards. There are no indications from the considerable body of science undertaken along the coastline of the NBS-LME to suggest a process to counter that trend. Given this knowledge, what will be the fate of coastal mangroves (and infrastructure placed on the shoreline)? And what can be said for the magnitude of coastal retreat? The response of the coastal plain to sea level rise can be divided into three interacting categories: (1) lateral retreat of the mangrove edge; (2) vertical soil building with increased tidal flooding and sedimentation; and (3) adjustments in habitat mosaic in response to salinity changes (also potentially impacted by any changes in rainfall patterns associated with climate change). At this stage, it is possible to apply calculations based on geomorphic principles, to explore the lateral retreat of the shoreline and capacity of coastal forest to build with sea level rise. There is insufficient information to determine how salinity changes will influence habitat mosaic into the future.

To frame a discussion on the magnitude of coastal retreat and whether mangroves will migrate and can be established further inland, a simple geometric model is applied in this report. It is based upon a hypothetical 2-dimensional mangrove – mudflat shore profile (described in Appendices 2 and 3). The model can be adjusted for a range of parameters including geometry of the shore profile (mudflat slope, mangrove cliff height, mangrove width, slope of hinterland), tidal range, land subsidence, mineral and organic sedimentation rates, and sea level rise rate projection. The model can be set to examine retreat either unhindered by infrastructure or influenced by it.

The model is based upon several assumptions: (1) that the slope of the mudflat is in equilibrium with wave energy; (2) changes in water depth with sea level rise drive erosion to extend that slope; and (3) mineral sediment will be supplied to the mangrove surface with sea level rise and contribute to soil building. At this stage, the model has yet to be calibrated for the NBS region and is thus configured with scenarios that are likely more conservative than necessary. Data needed include: 1) measurement of sea level change at locations across the region (currently there is an absence of primary tide gauges) and 2) shore profile topography / bathymetry.

Key interpretations from applying the simple geometric model:

1) There is enough mineral sediment in circulation to maintain mangrove soil building under existing and future higher rates of sea level rise. Previous studies suggest that a time averaged concentration of sediment in the water column delivered to a coastal wetlands of 300 mg l^{-1} is required to sustain soil building against rates of sea level rise of at up to 10 mm yr^{-1} (Orr et al. 2003, Stralberg et al. 2011, Morris et al. 2012, Kirwan and Megonigal 2013, Lovelock et al. 2015). Sediment availability to the mangroves of the NBS-LME far exceeds that threshold.
2) The relatively high tidal range along the coast (spring tide range 2-2.5 m across the region), is a positive attribute to support mangrove resilience to sea level rise over coming decades (Morris et al. 2012). Mature tidal wetlands build towards an elevation around mean high water spring tide elevation. At a location with a tidal range of 2 m, mature mangroves at mean high water spring tide elevation will have approximately 1 m of elevation capital in term of sea level rise (in absence of any soil building) before water elevations attain the level of drowning the forest (an elevation just above mean sea level). This follows the rule that in locations with higher tidal range the magnitude of elevation capital increases.
3) Applying the high sea level rise curve (RCP8.5 Max, IPCC 2014), the model calculates retreat of the mangrove edge of 46 m by year 2050, 102 m by year 2075, and 174 m by year 2100. While the calculations are not yet precisely calibrated for the local region, they are informative in terms of the scale of erosion that will very likely result from sea level rise.

In locations where mangroves are backed by swamp forest, they will likely transgress into those swamps. In places where infrastructure is maintained behind mangroves, the forest will be progressively lost with erosion at the seaward margin and prevention of landward migration. Where the erosional edge abuts infrastructure, those structures will come under increasing wave attack and risk of failure.

5.5 Including Natural Infrastructure in Coastal Resilience and Risk Reduction

The terms “green” or “natural” infrastructure cover a wide range of practices, but in essence refer to ecosystems that provide humans with an infrastructure service. Coastal ecosystems fulfill this definition, as they can provide substantial coastal flood defense benefits. A growing body of evidence characterizes the conditions for which these ecosystems provide wave sheltering, shoreline stabilization, and coastal storm surge reduction (e.g. Gedan et al. 2011, Shepard et al. 2011, Temmerman et al. 2013, Spalding et al. 2014, Narayan et al. 2016, Currin et al. 2017, Morris et al. 2018). Given their ability to adapt with sea level rise and provide several co-benefits, natural coastal infrastructure can provide significant benefits over traditional "hard" infrastructure. In the context of managing water resources, natural infrastructure is recognized for its role in storing, filtering and purifying water.

In terms of scale, the concept of natural infrastructure is commonly applied in small-scale projects, such as an installation of a "living shoreline" or individual wetland restoration projects. But natural infrastructure can scale across the landscape. Large scale floodplain reactivation (removing levees to allow water to reach river or coastal floodplains), the cumulative impact of multiple wetland restoration projects, and large natural reefs and wetlands are considered examples of system-scale natural infrastructure. Coordinating projects and natural systems brings benefits that accrue across the landscape such as hydrologic and ecological connectivity, habitat mosaics, species refugia, flow dissipation, sediment supply and carbon sequestration.

In the landscape context, linkages between ecosystems utilized as natural infrastructure also need to be considered. Coral reefs, for example, are highly effective in attenuating wave energy (Ferrario et al. 2014), as they provide sheltered conditions for coastal residents, mangroves and seagrass beds. Mangroves and seagrasses help stabilize sediment from upland areas, thus protecting coral reefs from harmful sedimentation. A sequence of habitats such as reefs, seagrasses and mangroves provide cumulative risk reduction benefits. These linkages and their ecosystem services of shoreline protection, food security, and climate ecosystem benefits are dependent on maintaining integrated healthy ecosystems.

Despite its many benefits, natural infrastructure can't be implemented everywhere. The appropriate use of natural infrastructure versus traditional "hard" approaches also depend on the landscape setting and planning context. While meaningful wave attenuation can occur within the first few meters of the wetland margin, large areas (km rather than m) of mangroves and coastal marshes are required to reduce surging flood water levels, with the magnitude of reduction dependent on the strength and duration of a given storm (Wamsley et al. 2009, Wamsley et al. 2010, Zhang et al. 2013). Traditional hard infrastructure typically requires a smaller footprint. Because hard infrastructure is static, fixing the shoreline in place, the shore protection benefits and limits of hard infrastructure are more readily quantifiable from an engineering perspective, which provide a level of comfort to decision-makers even when use of natural infrastructure may be more appropriate and cost-effective in the long-term. However, because of its static nature, hard infrastructure can be "brittle" when thresholds are exceeded (Gittman et al. 2014). Unlike hard infrastructure, natural systems are adaptable to highly dynamic conditions and can often recover following damage (e.g. Paling et al. 2008, Gittman et al. 2014). Over time, coastal wetlands accumulate sediments, building in elevation and thus naturally maintaining their benefits with sea level rise, unless sedimentation does not keep pace with sea level rise. For example, under high rates of sea level rise, or other forms of stress, coastal wetlands can also drown and convert from intact vegetated ecosystems to unvegetated flats and open water (Morris et al. 2012, Kirwan and Megonigal 2013). Creating space for wetlands to migrate landwards is an important resilience strategy response to sea level rise (Pethick and Crooks 2000).

In the right context, natural infrastructure can be more cost effective when directly compared to conventional hard infrastructure, such as submerged breakwaters (Narayan et al. 2016). This particularly applies when co-benefits are factored in (Costanza et al. 2014, Gittman et al. 2016). Natural systems can be combined with “hard” engineering components along a “soft-hard” or “green-gray” continuum, to provide shoreline protection with ecosystem benefits within site-specific constraints. Of course, some extreme events can overwhelm both natural and hard infrastructure. In the event of a major hurricane for example, residents behind hard infrastructure are evacuated to high ground and shelters. Such an approach will also need to be applied for communities living behind natural infrastructure.

Large and growing sources of funding are becoming available for coastal development incorporating natural infrastructure (such as green bonds, see Roth et al. 2019), but investment is often hindered by a lack of technical guidance for designing and evaluating such projects and lack of ability to adequately quantify ecological and economic benefits. Guidance is needed in: (1) identifying locations where natural infrastructure can play a significant role in coastal resilience; (2) developing the experience and standards to overcome institutional biases in favor of “proven” hard infrastructure and (3) developing institutional arrangements capable of matching available funding with the needs of individual situations (Colgan 2017).

Though the capacity to quantify all ecosystem services is often lacking and remains a considerable challenge, funds are increasingly being provided to support natural infrastructure approaches. In California in the United States, for example, the Water Quality, Supply and Infrastructure Improvement Act of 2014 (Proposition 1) authorized $1.5 billion of $7.545 billion USD ($313.79 billion of 1.58 trillion GYD / $11.19 billion of $56.27 billion SRD[8]) in general obligation bonds to fund ecosystem and watershed protection and restoration and water supply infrastructure projects, including coastal wetlands restoration. There have been several similar bond financing products, and, with a growing focus on climate resilient urban community development, the linkages are being made between land use, climate adaptation and mitigation, with requisite funding. The State of Maryland in the United States, set another example of a small scale, yet meaningful approach. It shifted the burden of proof in permit applications for shoreline protection, requiring that living shoreline (small-scale natural infrastructure) approaches be considered first, with hard infrastructure approved only where living shorelines cannot be used (Pace 2017).

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[8] Applying May 2019 USD/GYD/SRD exchange rates.

While knowledge gaps currently impede more widespread global adoption, there are a growing number of examples and reviews that can be drawn upon to inform the evaluation of natural infrastructure success (e.g. Shepard et al 2011, Temmerman et al. 2013, Spalding et al. 2014, Narayan et al. 2016, Bilkovic et al. 2017, Morris et al. 2018). The literature addresses natural and restored systems and, in some cases, compares natural infrastructure to conventional engineering approaches, such as seawalls (Gittman et al. 2014) and breakwaters (Narayan et al. 2016). Much of the data was collected quantifying the natural infrastructure benefits of blue carbon ecosystems during "everyday" conditions, and therefore data representing extreme events are sparse (Shepard et al. 2011, Narayan et al. 2016). Thus there is little data on the green infrastructure's response to high wave energy and flooding. More detailed research is needed to develop metrics that allow planners and engineers to quantify risk reduction while considering location-specific conditions (Spalding et al. 2014). And generally, more capacity is needed within the planning and engineering community to plan and design natural and integrated green-gray infrastructure solutions.

5.6 Mangrove Restoration: Opportunities and Constraints

Mangrove restoration is an important component of natural infrastructure approaches. As a primary principle, the best place to restore mangroves is in the location where they once existed, given that basic conditions of tidal influence, salinity, appropriate substrate and ecosystem connections are still present. This is not always possible because of a combination of land use, infrastructure and environmental constraints. Yet, abandoned lands, reconnected to the sea as needed, with constructed levees to protect neighbors from flooding as needed, offer a restoration opportunity that has the potential to restore a colonizing forest relatively quickly. From a mangrove restoration perspective, the coastline of the NBS-LME is blessed with a great abundance of sediment. Sediment is critical for rebuilding soils to an elevation that will support mangrove colonization. The NBS-LME also has a warm and wet climate that supports healthy mangrove tree growth once established (5-year-old trees observed to gain over 1 m yr^{-1} in height at planted mangroves in Georgetown (reported by field staff at site visit).

In conclusion, from this analysis, and experience in other settings several opportunities and some constraints for mangrove restoration projects in the NBS-LME are proposed for consideration in future planning.

5.6.1 Opportunities

1. Suriname and Guyana host substantial areas of former agricultural land abandoned due to low land productivity and salinization. Depending upon hydrology and geomorphic setting, these lands may offer sites for coastal swamp forest or mangrove recovery.

2. Connecting mangrove restoration sites to abundant sediment supply from the nearshore will accelerate the restoration process.
3. Setting back mangrove restoration from the active coastal edge offers potential to restore mature mangrove forest, build space to accommodate erosion of the coastal edge with sea level rise, as well as create a buffer for dynamic edge processes.
4. Mangrove restoration planning design may include green and green-gray infrastructure approaches to facilitate flood risk reduction; including maintaining scour / reducing sedimentation flood conveyance channels and attenuating wave action.
5. Mangrove restoration and coastal swamp forest may be planned and designed to provide habitat and transport corridors for fisherfolk.
6. Mangrove and coastal swamp forest restoration may be planned and designed to include areas for public access and recreation as well as sites of low disturbance for biodiversity.
7. Mangrove and coastal swamp forest restoration may be planned to reduce landscape fragmentation and connectivity between habitats, as well as hydrological connectivity necessary to support a mosaic of biodiverse wetlands.
8. Mangrove and coastal forest restoration may be planned and designed to accommodate sea level rise adaptation, recognizing that the shoreline will respond dynamically to changing water levels and the need for space.
9. Construction of structures to reduce erosion of the mangrove edge will be less costly as pre-restoration activity on dry land than a restoration activity on soft muds in the intertidal shore. Mangrove restoration approaches on abandoned lands might be planned in coordination with sedimentation fields constructed on the dynamic open shore.
10. Rewetting soils can arrest development or worsening of acid sulphate soil conditions on drained wetlands containing organic soils.

5.6.2 Constraints

1. Space, measured in hundreds of meters, is required for mangrove restoration, particularly in areas set back from the dynamic mudflat edge.
2. A set-back buffer (c.200-500m) to accommodate sea level rise will also be required to sustain mangroves. There are challenges in quantifying the extent of the set-back distance required.
3. Levees may be needed to protect neighboring properties from flooding. Construction of levees increases the cost of projects and fragments the landscape but are often necessary.
4. Wave energy and possible acid sulphate soil conditions on abandoned lands set-back for mangrove restoration and to provide a flood protection buffer should be taken into consideration as part of the mangrove or coastal forest restoration planning process.

6 Relevance to the NBS

In this study, the extensive and long-term science investigating the dynamic shoreline of the NBS-LME has been summarized and built upon. Prior studies have clearly articulated the interactions between mangroves and mudflats and the impact of hard infrastructure on shoreline processes (Appendix 1). Focus was particularly placed on the likely fate of the coastal plain under conditions of sea level rise. In reviewing the literature, data were purposefully sought that might test an argument that the shoreline could hold its current position as sea level rises. While periods of short term (multi-decadal) advance on the shoreline have been observed, the drivers to these have been hypothesized to be related to changes in trade wind strength and duration, and do not reflect a long-term trend. As such, as with other coastlines of the world, the shoreline of the NBS-LME is very likely to respond to sea level rise by retreating landward. This will place pressure from erosion on natural and built infrastructure at the edge of the coastal plain. Further work is required to quantify the magnitude of coastal retreat and how this will vary spatially along the coast.

While in many other parts of the world coastal wetlands are at risk of drowning with sea level rise, the vast amounts of mud in coastal waters will support mangrove building as they retreat landwards. Given adequate space for retreat there is every likelihood that Guyana, Suriname and French Guiana can maintain the ecology and ecosystem services provided by mangroves.

Adopting a financial and risk-based management approach, decisions will need to be made as to which areas of the of the coastal plain will be maintained in place by hard engineering and which will be considered for retreat (see parallel report on nature-based approaches).

Finally, while this report focuses on mangrove ecosystems, attention should be brought to highlight the importance of the value of coastal swamp forest. Coastal swamp forests occupy an area five or more times greater than that of mangroves but are under particular pressure from land use change. These ecosystems form an ecological and geomorphic continuum and together provide a wide range of ecosystem benefits and services.

7 Data Gaps and Recommended Next Steps

7.1 Data Gaps

1. There is a need for a regional network of primary tide stations to provide data relative sea level rise and water levels for the calibration of sea level rise projections and models.

2. A combined topography for intertidal regions and bathymetry for nearshore would assist modeling and planning. Current elevation data, such as Shuttle Radar Topography Mission (SRTM) data, is not corrected for vegetation, which overestimates the ground surface elevation.
3. A map of forest types across the coastal plain with consistently defined vegetation classes would assist in interpretation of hydrology – ecology interactions. A detailed map has been created for Guyana but has not been updated since its creation in 2001 (ter Steege and Zondervan 2001).
4. More data needs to be collected in coastal freshwater forests, both in their species distributions and tree and soil carbon stocks. Currently, very few data are available along the NBS-LME.

7.2 Recommended Next Steps

1. Continue research into shoreline response to sea level rise.
2. Consider risks of building infrastructure on the coastal plain.
3. Consider planning that focuses on building infrastructure on upland areas above the coastal plain.
4. Establish a data platform for sharing of regional land use and other environmental data layers,.. Much of this information was unavailable to this study. Provision of data on an accessible data archive would assist analysis and planning.
5. Assess reasons for agricultural land abandonment.
6. Review opportunities and constraints for mangrove and swamp restoration across the region including an investigation to the set-back buffer needed to address sea level rise impacts.
7. Explore restoration strategies for example sites in representative geomorphic settings (e.g. open coast, riverbank, rural and semi urban settings).
8. Undertake restoration projects through setback of levees including approaches for reducing wave energy encouraging sedimentation and stabilizing the shoreline.
9. More detailed research is needed to develop metrics that allow planners and engineers to quantify risk reduction while considering location-specific conditions.

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20 Interaction of mangroves, coastal hydrodynamics and morphodynamics along the coastal fringes of the Guianas

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Abstract The mangrove belt along the coast of the three Guianas, South America, forms a unique ecosystem and acts efficiently as a natural soft coastal defence structure. The general mechanisms have been studied for over four decades and the processes governing the coastal morphodynamics are now understood, at least qualitatively. They consist of an interaction between mangroves, hydrodynamics and sediment mechanics. 20% of the mud discharged by the Amazon in the Atlantic Ocean is transported to the west along the coast by waves and currents in discrete mud banks of a few 10s of km length which travel at a speed of the order of 2 km/year. During the presence of a mud bank waves are damped, mud is trapped and colonized by mangroves. Once a mud bank has passed, the waves can attack the shore again. This results in a cycle of land accretion and erosion, with an average net gain of 1 m coast per cycle of roughly 30 years. However, in locations where too many mangroves have been removed, the coast has lost its natural resilience and the settlements and fields are prone to flooding, a concern that increases with climate change and predicted sea level rise (SLR). Hard coastal defence structures, such as those in Guyana, are expensive and not sustainable. Based on many lessons learnt, pilot projects on mangrove rehabilitation have started. At the same time research efforts are undertaken to allow making quantitative estimates of the potential risks for the coastal communities. For this purpose, numerical prediction models are developed which can compute currents, wave action and sediment transport along the coast of the Guianas. Different climate change scenarios can be investigated. These models can serve in the near future as decision support tool for the local authorities for the management of the coastal zone.

Keywords: Black mangroves, Amazon River mud, sea level rise, morphodynamic response, mangrove rehabilitation, Guianas coast.

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20.1 Introduction

Most mangroves are found in coastal lagoons and in estuaries, sheltered from waves. There are very few places around the world where they form a protecting belt along the coast itself, where they are subject to direct wave action.

20.1.1 The Guianas coast

Probably the most remarkable mangrove coastal fringe is found along the Guianas coast, stretching from the mouth of the Amazon River in northern Brazil all the way west to the mouth of the Orinoco river in Venezuela, a stretch of roughly 1600 km (**Figure 20.1**). Unfortunately, the mangrove belt has been reduced or removed in many places, making place for other land use (mainly agriculture, aquaculture and urban expansion), creating many vulnerable spots where hard coastal protection structures had to be built to protect the hinterland against flooding.

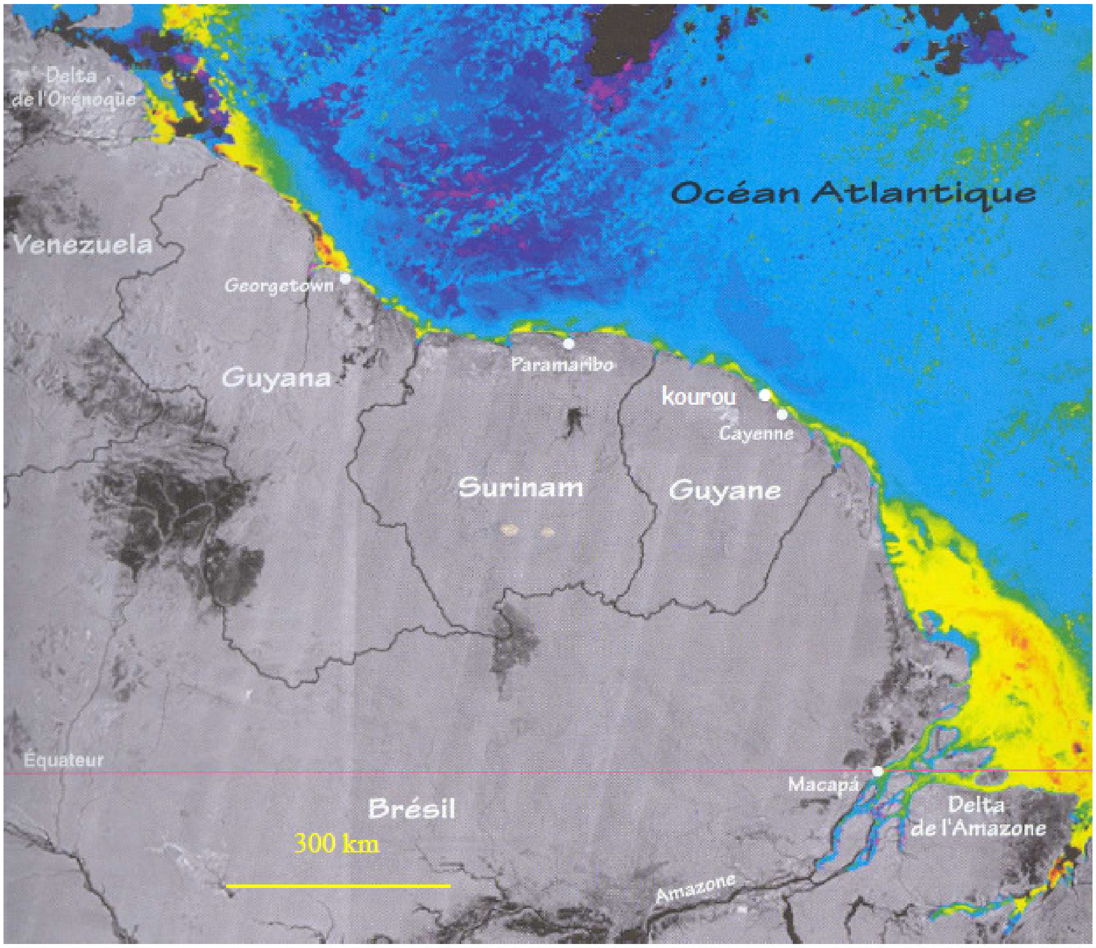

Figure 20.1 Situation of the study area. Satellite image (processed), showing the turbidity along the north-eastern coastline of South-America (NOAA images, October 1999; Laboratoire Regional de Télédétection, CNRS – after Gratiot 2011)

The investment and subsequent maintenance costs of these dikes are extremely high. This is especially problematic for Guyana, where mangroves have been replaced by a sea defence wall along about 40% of the coastline in order to protect the polders which are used for agriculture. Pelling (1999) presents an analysis of the vulnerability of the Guyana coast from the perspective of political ecology, starting with a historical review which traces its roots. The estimated yearly maintenance cost for Guyana is very high. A cost/benefit analysis by Odle and Arjoon (1971) indicates that too little has been invested in the maintenance of the sea wall. The Guyana Ministry of Finance (1996) estimated the approximate annual cost to maintain and rehabilitate sea defence works over the short term to about 7.5 million USD annually, 5 million USD over the medium term and 2.5 million USD over the long term. Eventually, under the 10th European Development Fund framework from 2007 to 2013, the EU–Guyana cooperation focussed a.o. on sea defences. This resulted in a Coastal Engineering Design Manual for the Guyana Sea an River Defences, compiled by four consultants, which was handed over in July 2016 by the EU, together with funding of 10 million USD to get the necessary actions started (Guyana Government Information Agency 2016).

Moreover, hard sea defence walls too close to the high-water line, as build in Guyana, prove to increase the problem of mangrove establishment, because the reflection of waves on the hard structure enhances the resuspension of sediments (Anthony and Gratiot 2012). By fluidizing the mud flat, the waves weaken the erosion resistance. Fluidized mud on the bottom may start to flow down the intertidal flat to deeper water offshore. By generating more turbulence, cohesive sediment flocs break up into even finer particles that more easily wash away.

The damage is much less in Suriname and French Guiana (Guyane Française). In Suriname, only a few kilometres of dike are constructed in Nickerie and recently in Coronie. By building the Coronie dike a bit further from the high-water line, behind a remnant of mangroves, waves will not directly impact with the hard structure and reflection of waves on the wall is reduced. In the meantime, the construction has been temporized because during the operations a new mud bank arrived, which has rapidly been colonized by mangroves. This decreased the necessity and changed the priorities.

In French Guiana only dozens meters of riprap have been constructed in urban places in Cayenne and Montjoly. In the Anse district of Kourou city a 900 m long sandy dune has been erected in 2016 to protect houses from erosion and submersion. Local authorities opted for this temporary solution awaiting to find a more long-lasting soft solution.

Over the past years, a growing awareness has risen among policy makers and the population that integrated coastal zone management requires a more sustainable coastal defence strategy, certainly in the light of climate change and associated sea level rise (SLR) in particular. Thanks to increasing understanding over the past years of the natural processes controlling the interaction between morphodynamics and vegetation and their potential to create natural barriers to stabilize beaches and shores, the concept of soft shore protection has become an interesting design strategy for shore management. This chapter gives an overview of how this concept is currently under investigation for the Guianas mangrove coast.

20.1.2 Mangroves along the Guianas coast

20.1.1.1 Species

Mangroves are trees with unique adaptations which allow them to survive on anaerobic, soft muddy soils in relatively high saline environments. This explains why they are found in coastal areas, where they are not competed away by other species.

Unlike other coasts, the Atlantic coast of the Americas knows only a few species of mangroves. The coastal fringe in the Guyanas is dominated by the black mangrove (*Avicennia germinans*) with prop roots (**Figure 20.2**). Red mangroves (predominantly *Rhizophora mangle*), with stilt roots, occur along the borders of tidal rivers and creeks. They are rarely found along the coast itself (**Figure 20.3**).

White mangroves (*Laguncularia racemosa*) are less common; they occur on somewhat higher, more sandy soils, e.g. creek levees. They also have prop roots.

Figure 20.2 Black mangrove (*Avicennia germinans*), with its well-developed pneumatophores (prop roots). (Credit: P. Augustinus)

Figure 20.3 A remarkable sight: a lonely, persisting Red mangrove (*Rhizophora mangle*) that refuses to be washed away along the eroded coast in front of Weg naar Zee, Suriname. (Credit: E. Toorman)

20.1.1.2 Mangrove degradation

Mangroves have adapted to grow in saline environments. Under hypersaline conditions however, even *Avicennia germinans* cannot survive. In the Guianas, these conditions may develop under natural circumstances, e.g. when a mangrove forest is closed from the sea by a new forming chenier (**Figure 20.4**), impeding the natural in- and outflow of water. Especially in the dry season, the salinity of the stagnant water can rise quickly, due to evaporation, causing the sudden death of the mangroves. During the next wet season, the salinity will be lowered, and through a transition phase with saline herbs, the mangrove vegetation can restore itself again in the course of time (**Figure 20.5**).

Sometimes however, the degradation of mangroves is due to human impact, such as in Coronie (Suriname), where the freshwater inflow from the coastal swamps is cut off by the main coastal road. The sea water evaporates and leaves behind extreme high-saline pools, in which the mangroves cannot survive (**Figure 20.6**). In these cases, the degradation usually has a more permanent character.

Figure 20.4 Dead mangroves (*Avicennia germinans*) in a hypersaline environment behind an actual chenier in East Suriname (Credit: P. Augustinus).

Figure 20.5 Recovering saltmarsh vegetation in a former hypersaline environment behind an actual chenier in East Suriname (Credit: P. Augustinus).

Figure 20.6 Dead trees in hypersaline water in Coronie, Suriname, cut off from the inland fresh-water marshes by the main east-west road. (Credit: E. Toorman)

20.2 Morphodynamics of the Guianas Coast

20.2.1 Mud bank migration

The Guianas coast has been studied for a long time, with the work by Augustinus (1978) as the main pioneering physical research. These studies have revealed the major processes that explain the formation of the Holocene coastal plain over the past 6000 years, which has gradually accreted at a mean rate of the order of 2 meter per century (Rine 1980). This can be summarized as follows (Allison 2000; Augustinus 2004).

About 20% of the continuous flux of sediments by the Amazon river into the Atlantic Ocean is transported westward along the North coast of South America. Some 150×10^6 tons is transported yearly as suspension load, another 100×10^6 tons per year in the form of huge mud banks, which travel at an average speed of roughly 2 km/year in westerly direction. Waves are the driving force behind this migration (Nedeco 1972, Allison and Lee 2004). The question why an important part of the mud transport takes place in discrete banks of roughly 30 km length is still not well understood.

In the classic model, mud banks are shore face attached (e.g. Delft Hydraulics Laboratory 1962, Allersma 1971, Augustinus 1978, Wells and Coleman 1981; Rine and Ginsburg 1985). This is shown in **Figure 20.7A**. The migration of the mud banks is caused by erosion of their trailing edge (East side) and the deposition, mainly of fluid mud, at their leading edge (West side).

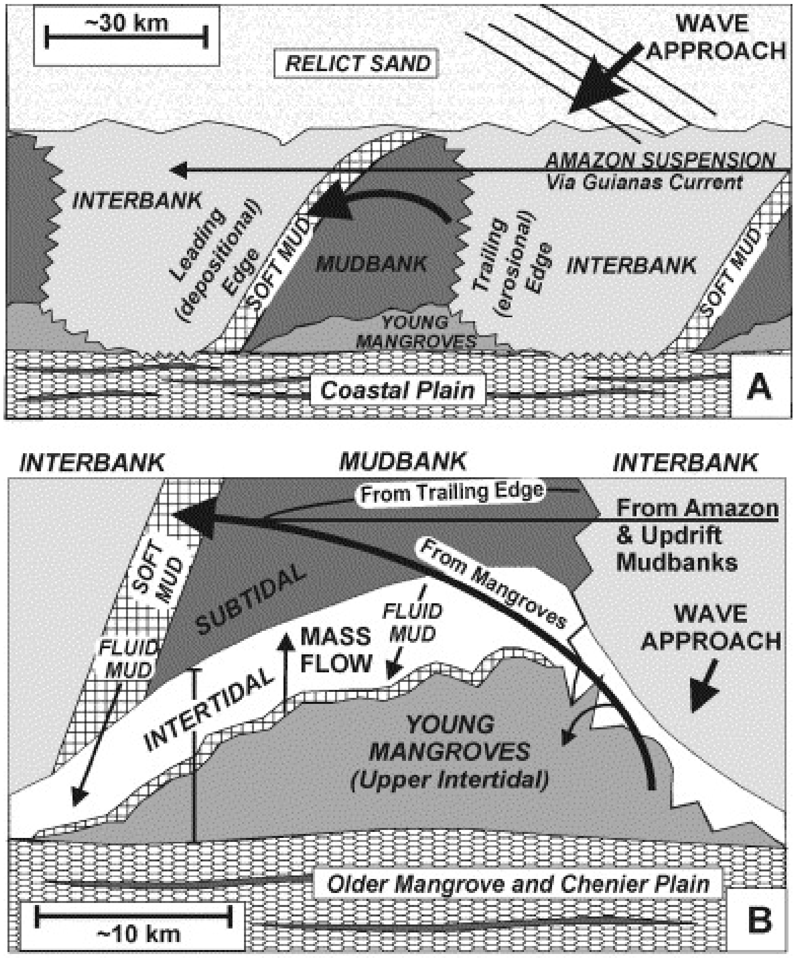

Figure 20.7 The classic model for mud bank migration (A) and mud bank dynamics (B). (Allison and Lee 2004)

Figure 20.7B shows the mud bank dynamics according to Allison and Lee (2004). In their hypothesis the mud bank is disconnected from the coast. During flood, fluid muds are driven shoreward over the mud bank, filling the upper intertidal area between the mud bank and the coast. The fluid mud originates from the transported suspension load as well as from erosion of the trailing edge of the mud bank. If the concentration of silt particles in the water exceeds the point of hindered settling, fluid mud is formed. It is so soft, that it absorbs the energy of surpassing waves by visco-plastic deformation (i.e. friction between the sediment particles). This means that waves running into an area with fluid mud are strongly attenuated and even may disappear (**Figure 20.8**). As a result, deposition is further enhanced.

In the course of time, the mud consolidates and becomes more compact. A hydrographic pattern develops and mangroves start to grow (**Figure 20.9**). Mangrove roots give rigidity to the soil and further its compaction by extracting water (**Figure 20.10**).

Moreover, the complex system of above-ground prop roots, branches and stems act as an increased surface roughness for incoming waves and currents, which therefore lose energy. So vital mangroves capture sediments, resulting in coastal accretion in the quiet zone between the mud bank and the shore. New mangrove propagules will colonize the new land, stabilize its soil enhancing further accretion. However, with ongoing consolidation (i.e. self-weight compaction; Toorman 1996) towards the east, the mud matures into a young clay, which can be eroded.

Therefore, when the mud bank has passed (after roughly 30 years), the waves will break without significant attenuation on the shore, washing away sediments between the mangrove roots and eventually uprooting the trees: the shore will erode. The uprooted trees may pile up against the living trees, forming extensive accumulations of stems and branches (**Figure 20.11**). These act as an increased bottom roughness, slowing down erosion.

When, after some 30 years, in which a mud bank and the adjacent interbank area has been completely migrated westward, a new mud bank settles in front of the mangrove forest under erosion, a new cycle begins.

If the width of the vital mangrove forest has been sufficient large, the coast may have accreted. However, the opposite is also possible. In the period 1947-1966 the coast of Suriname shows net erosion over its full length. From 1966 onwards, net coastal accretion takes place (**Table 1**). This net accretion can (at least partially) be explained by the observed increase of the sediment discharge of the Amazon river. A recent study by Martinez et al. (2009), based on the analysis of an extensive time series of field data (10-day sampling) and satellite data show an increase of the yearly-averaged sediment discharge from 1995 to 2007 by 20%, which is not correlated to the nearly unchanged annual river discharge. The increase may be attributed to stronger erosion caused either by climate change (intensification of rainfall) or by land cover changes resulting from deforestation (Callede et al. 2008). Since another study (Filizola and Guyot 2009) indicates that 90% of the sediment load originates from the Andes, the deforestation of the lowland rainforest of the Brazilian shield most likely is not the main contributor.

Table 1 The net erosion (-) or accretion (+) in tons per year, for the coast of Suriname, deduced from a comparison of aerial photographs and satellite images from different years.

Period		
Interval	Number of years	Net amount of sediment x10^6 tons/year
2001– 2007	6	+59.44
1992 – 2001	9	+29.07
1981 – 1992	11	+48.43
1970 – 1981	11	+7.61
1966 – 1970	4	+2.18
1957 – 1966	9	- 1.00
1947 – 1957	10	- 0.82

Remarks: The coastline in 1981 has been drawn using aerial photographs. For 1992, satellite images with a lower resolution are used. The amount of sediment in the intermediate period is therefore less accurate (probably too high), compared to the other intervals.

Figure 20.8 To the left one notices the sudden disappearance of waves running over fluid mud. (Credit: P. Augustinus)

Figure 20.9 A vital mangrove vegetation growing on relatively young clay. (Credit: P. Augustinus)

Figure 20.10 Eroded coast with protruding mud, protected by roots of *Avicennia germinans*. (Credit: P. Augustinus)

Figure 20.11 Accumulation of uprooted mangrove trees against the living trees in Coronie, Suriname. (Credit: P. Augustinus).

This large scale coastal behaviour is probably caused by a (cyclic) shifting of wind frequencies. In the sixties and seventies of the former century, winds from an east-north-eastern direction steadily increase and so does the wind strength. Waves generated by winds from that direction approach the shore under a smaller angle. Therefore, the component of the wave energy flux parallel to the coast (P_2a) becomes more important, compared to the component of the wave energy flux perpendicular to the coast (P_2o) (**Figure 20.12**). So sediment transport is furthered and erosion is diminished. This must lead to a growth in length of the mud banks, which is indeed the case (**Figure 20.13**).

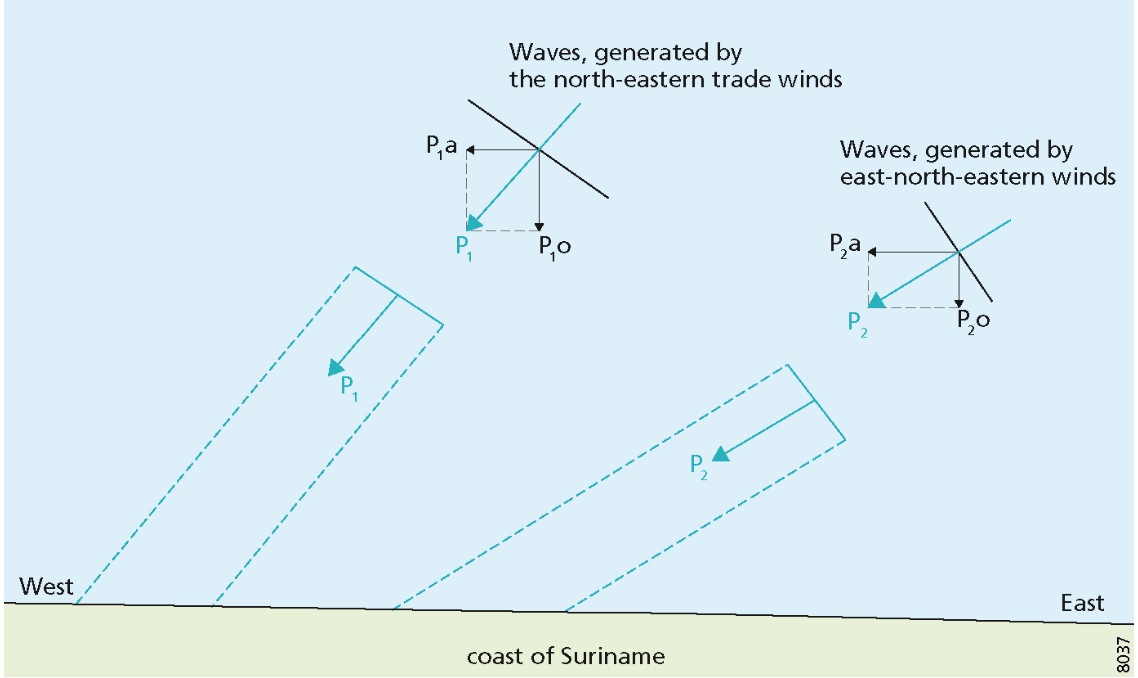

Figure 20.12 The influence of the difference in the angle of approach of waves, generated by the north-eastern trade winds (**P_1**) and waves generated by east-north-eastern winds (**P_2**). Energy flux **P** is defined as the transport of energy through a vertical plane, parallel to the wave crests, per unit crest length. **Po** is the landward directed component of the wave energy flux, **Pa** is the component parallel to the coast. (after Wong et al. 2017)

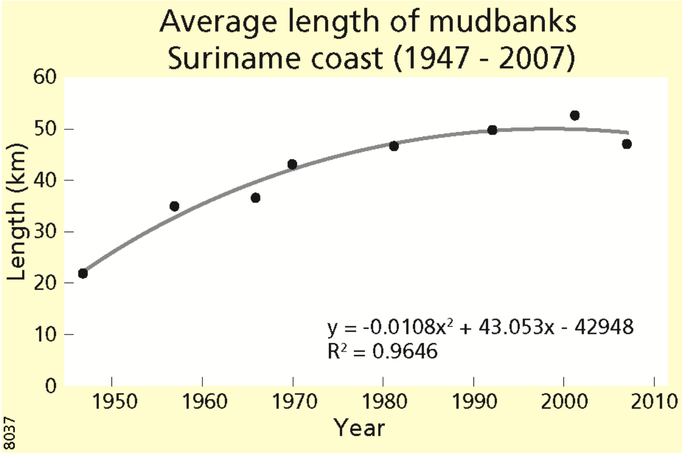

Figure 20.13 Average length of the mud banks in Suriname, deduced from aerial photographs and satellite images. (after Wong et al. 2017)

Since 2001 the average length of the mud banks is slightly decreasing. This could indicate the beginning of an increase in the frequency of more northern (or north-north-eastern) wind directions. In addition, the El Niño and the La Niña events also have impact on wind and rainfall. Sometimes even hurricane influences are noticed, even though the Guianas coast lies outside the hurricane area. To our knowledge, these possible effects on the mud bank migration have rarely been studied (Van Ledden et al. 2009).

20.2.2 Coastal erosion analysis

Erosion of the muddy coast of the Guianas begins with the development of small pits in the bare mud surface in front of the mangrove vegetation. The slightly consolidated mud in front of the *Avicennia germinans* vegetation has a brownish colour due to the presence of diatoms. The small erosion pits are filled in afterwards with lighter coloured fresh mud, which makes them easily recognizable (**Figure 20.14**).

Figure 20.14 Erosion pits in the mud surface in front of vital black mangroves (*Avicennia germinans*) in Suriname. They are filled in afterwards by lighter coloured fresh mud, which contrasts with the brownish colour of the mud surface, due to the presence of diatoms. (Credit: P. Augustinus)

With increasing degree of consolidation, the erosion depressions become larger and more elongated. They develop in the direction of wave attack (**Figure 20.15**). During ebbtide, when exposed to the sun, the walls desiccate, the clay shrinks and cracks appear parallel to the walls. With the next rising tide, rotational sliding along the sheer faces occur, resulting in a widening of the depressions. In areas where many of these depressions are concentrated the original clay surface is more lowered than elsewhere. In this way, an indented erosion coasts develops (**Figure 20.16**).

Figure 20.15 Coastal erosion in Coronie, Suriname, in 1972. (Credit: P. Augustinus)

Erosion is dominant in the interbank area. The incoming waves erode the clay surface and cheniers are formed. If sand is available from a local source, e.g. the Marowijne River or the Corentyne River, it is transported in the coastal zone by longshore drift and beach drift. The cheniers develop at or just above mean high tide level. During higher water levels, sand is washed over the top of the chenier to its backside. This causes the chenier to migrate landward (**Figure 20.17**). In the mean time they may grow in height and therefore progressively counteract coastal erosion.

If there is no sand available from local sources, sand can be winnowed from the mud. The muddy sediment contains approximately 2% very fine sand, which originates from the Amazon River. Due to the continuous alternation of compression and decompression caused by the waves, the clay can be stirred up. The fine particles are transported to the west by weak currents, the sand grains settle down again. In this manner sand is concentrated at the surface. Chenier formation under these circumstances begins at about low water level. Due to the very fine grainsize of the sand, the cheniers are much flatter and they show ripples on the foreshore (**Figure 20.18**).

In periods of severe erosion, coastal retreat can go so far that an old chenier is reached, which starts to function as a local sand source. Under these circumstances a sand accretionary coast will develop. A number of chenier ridges is formed, one after another, in seaward direction. Beyond backward bending parts of the coast, spits develop, e.g. at Braamspunt. These beaches often show rhythmic features like beach cusps (**Figure 20.19**).

Figure 20.16 Indented erosion coast in East Suriname in 1972. (Credit: J. Schulz)

Figure 20.17 A landward migrating chenier along the coast of Commewijne, Suriname. (Credit: P. Augustinus)

Figure 20.18 Fine sandy chenier in Coronie, Suriname, in 1972. The development of this type of chenier starts at low water level. Note the ripples on the foreshore. (Credit: P. Augustinus)

Figure 20.19 Seaward extending beach near Diane Creek, Commewijne, Suriname, with rows of beach cusps. (Credit: P. Augustinus)

20.3 Mangroves as sustainable coastal defence

It has been claimed that mangroves provide protection against waves (Mazda et al. 1997; McIvor et al. 2012), storm surges (Zhang et al. 2012) and tsunamis (Danielsen et al. 2005). This is correct in the sense that they absorb energy from these floods. But they will be uprooted and washed away nonetheless when subjected to repeatedly breaking waves (**Figure 20.20**) or to a single violent flood, leaving a more vulnerable coast for the next decades. Of course, the piles of uprooted trees on the shore themselves also form a hindering for waves and currents and contribute to coastal protection (**Figures 11 and 20b**).

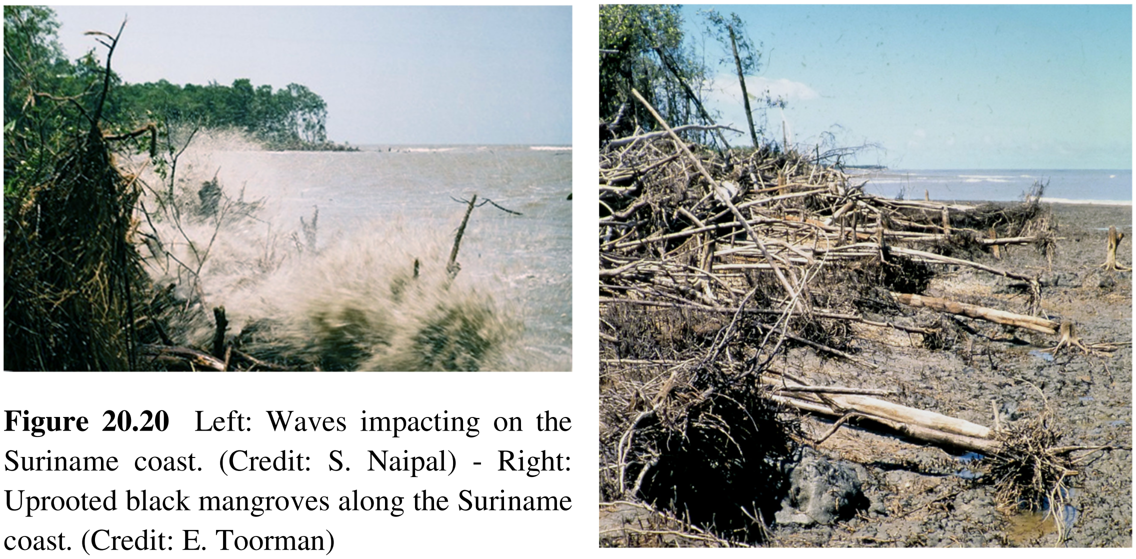

Figure 20.20 Left: Waves impacting on the Suriname coast. (Credit: S. Naipal) - Right: Uprooted black mangroves along the Suriname coast. (Credit: E. Toorman)

The 2004 Indian Ocean tsunami in particular raised a discussion on the effectiveness of mangroves, mainly resulting from interpretations of the data which did not account for all factors. Eventually this debate was settled with a common publication (Feagin et al. 2010). However, the important role of the sediments has not been considered.

20.3.1 The physical functioning

To understand how mangroves can act as coastal defence, it is necessary to look at the interaction between three key players: the trees, the sediment and the hydrodynamic forcing. The functioning can only be understood by considering the interaction between each of these three and their combined effects.

20.3.1.1 Interaction between mangroves and hydrodynamics

Many studies exist on how vegetation reduces the energy from currents and waves (Mazda et al. 1997; McIvor et al. 2012). In the case of mangroves, the vegetation can be considered rigid. Energy is dissipated by friction with the stems and, in the case of *Avicennia*, the pneumatophores, which implies conversion of hydrodynamic energy into turbulence which eventually in its turn is dissipated by viscosity into heat. It is then evident that the degree of dissipation depends on the density of the trees and their size.

20.3.1.2 Interaction between mangroves and sediment

Like all trees, mangroves find their stability by developing an appropriate root system in the soil in which they grow and from which they extract their nutrients. Mangroves typically grow on mud deposits, to which they are adapted.

Mud usually refers to a dense sediment-water mixture dominated by clay particles. Such sediment is referred to as cohesive sediment (Mehta 2014). Clay particles in water hardly occur as individual primary particles, since they tend to aggregate and form flocs. When these flocs settle they form a so-called soil skeleton where the "particles" (i.e. flocs) are stacked and support each other, whereas the open spaces between the particles (the pores) are filled with water.

A mud deposit is sometimes compared to a card house structure or a sponge structure: a low volume of solids and a large volume of voids filled with water. But due to accumulation of depositing sediment flocs, the skeleton is subject to an increasing load of particles and the network may deform and bonds between particles broken, such that the card house collapses. The latter goes very slowly, because the pore water needs to escape, but due to the small size of the pores, and the hydrophilic nature of the clay particles, the pore water experiences a lot of capillary flow resistance. This compaction is called self-weight consolidation (Toorman 1996; Mehta 2014).

Black mangrove propagules can develop their roots very easily in the soft top soil of these mud banks. With the growth of the tree, the tree becomes heavier, but it manages to divide its weight over a larger area by spreading the roots in the horizontal direction. The roots do not grow deeply, because due to the low permeability of the mud, the compacting mud becomes deoxidized very quickly at 5-10 cm depths. This explains the more the adaptation of the root system.

Furthermore, the mangroves-sediment entity forms an ecosystem of high biodiversity. The growth of plants and the activity of animals alter the composition, by adding organic material to the sediments, and subsequently the structure of the sediments. From studies elsewhere, it is known that organic matter increases the strength and thus the erosion resistance of sediments (Grabowski et al. 2011).

20.3.1.3 Interaction between hydrodynamics and sediment

Realizing the cohesive nature of the sediments, one can look at the interaction between marine hydrodynamics and the sediments. The sediment deposits are fed by sediments transported by tidal and wave-induced currents. But when the wave movement is more dynamic the water can also remobilize sediments that lie between the roots. When inundated and subjected to waves, the erosion resistance of the sediment may reduce due to pore pressure build up (i.e. partial fluidization), making the sediment even more prone to erosion. Hence, mangrove trees at the seaside edge of the fringe that are most subject to waves in interbank areas are most prone to sediments weakened and eventually washed away between the roots (**Figure 20.21**), which may destabilize the tree. Indeed, it is seen that many mangroves simply tip over on the eroded shore (**Figure 20.22**).

Figure 20.21 *Avicennia* roots exposed due to hydrodynamic forcing which washes away the sediments at high water. (Credit: E. Toorman)

Figure 20.22 *Avicennia* tree about to tip over. (Credit: S. Naipal)

Figure 20.23 Cliff erosion by waves. (Credit: S. Naipal)

Where there is persistent erosion, as seen for instance at the outlet of some drainage channels in Coronie (Suriname), cliff erosion can occur, which washes away even the older sediments beneath the root system (**Figures 20.10** and **20.23**).

When waves move over a mud bank, the pores are subjected to an oscillating pressure field. This tends to induce pore water flow within the soil skeleton, but due to the capillary resistance, it cannot follow the frequency of the wave. This lag leads to pore pressure build-up. The resulting normal stresses counteract the effective stress due to self-weight consolidation. If the excess pore pressure becomes higher than the submerged weight of the overlying sediment (i.e. the effective stress), the bed is fluidized: the particles are pushed aside, bonds are broken and they can move relative to each other (similar to quick-sand).

At the other hand the cycle of expansion and compression of the pore pressure results in a net elasto-plastic deformation of the skeleton. The mechanical friction between the particles as well as the pore water flow induce energy loss. Since this energy originates from the wave motion transferred to the pore water, it therefore results in damping of the waves, when they travel over a mud bank.

Fluid mud on a slope may tend to move downhill as a visco-plastic fluid. Gratiot et al. (2007) hypothesize that this is counteracted by wave-induced drag in the wave direction (usually towards the shore). This balance may explain the cross-shore profile of a mud bank. The highest thickness is expected to occur where the waves have lost their energy.

Thus far, wave-mud interaction had been studied with an elastic description of the deformation of the mud layer (reviewed by Mehta et al. 1994). But this is only valid for very small deformations. In this case one can compute the motion of the fluid mud layer even analytically for idealized homogeneous mud layers. These results were successfully compared to laboratory experiments (Sakakiyama and Bijker 1989).

Over a soft fluidized mud layer, the deformation results in visco-plastic flow and its non-Newtonian behaviour can be represented by a (non-ideal) Bingham rheological model (Toorman 1997). The rheological parameters change in time due to break-up and restoration of interparticle bonds. This thixotropic behaviour can be modelled with an additional kinetic equation which describes the break-up under shear and recovery of the soil skeleton structure at rest. The corresponding rheological closure (Toorman 1997), implemented into a CFD software, has been demonstrated to be able to simulate the damping by waves (Toorman 2008; Villaroel 2009). It proved to be necessary to account for an increase in resistance with self-weight compaction, i.e. the effective viscosity increasing with depth and density, in order to obtain realistic velocity profiles, as observed in laboratory experiments (Villaroel 2009).

Therefore, mangroves need shelter, which is provided along the Guianas coast by the mud banks. Waves are damped and do not reach the shore. Moreover, the mud deposit forms a low berm which canalizes the runoff from land into a creek running in front of the mangroves (**Figure 20.24**). The berm itself is also slowly colonized by propagules that get stuck on these slightly higher elevations, where optimal conditions for seedling trapping occurs (Proissy et al. 2009).

Figure 20.24 Head of a mud bank at low water, deflecting the runoff from land and providing shelter for the mangroves. (Credit: S. Naipal)

20.4 Ecological engineering: mangrove restoration

Efforts have been made in Guyana and Suriname to restore mangrove woods along the coast at places where the natural belt has disappeared or became too narrow to be sufficiently resilient to survive a cycle of mud bank migration. Initially, mangroves have been planted only in the swamps behind the former coastline, where the vegetation had been degraded (Augustinus, pers. comm.). Rehabilitation on the intertidal mud flats, where the plants are subject to the forces of waves and currents has only recently been tried, with mixed success.

Worldwide, a lot of mangrove restoration projects have failed, often by lack of understanding the proper conditions for development and growth (Ellison 2000; Winterwerp et al. 2013).

Local ecological experts expressed their low confidence in the success of mangrove rehabilitation along the Guianas coast, simply because there are sufficient propagules and the necessary dispersion by currents and waves is favourable, distributing them along the entire coast (Erftemeijer and Teunissen 2009). They concluded that if natural regeneration does not occur in certain places, it implies that the local conditions are unfavourable and one should not expect that planted mangroves will survive. Therefore, the first key to mangrove restoration is to understand the local conditions. Once the unfavourable conditions are understood, one can try to design a methodology to change the local conditions to favourable ones.

20.4.1 General principles

Consultation of various international experts and lessons learnt from other restoration projects elsewhere in the world eventually helped to develop a general strategy (Field 1999; Lewis III 2009; Winterwerp et al. 2013).

Prior to the design of a suitable rehabilitation strategy, a study has to be made in order to understanding the ecology of the local mangrove species, i.e. reproduction patterns, propagule distribution and conditions for seedling establishment and growth. A model for the dynamics for the Guianese mangroves has been proposed by Fromard et al. (2004) – **Figure 20.25**. Next, one has to understand which conditions prevent the natural regeneration of mangroves in the problematic areas.

To rehabilitate a target area, first the optimal natural conditions have to be restored. This involves measures to improve the hydrological conditions (i.e. ensuring fresh water runoff and restoring tidal creeks) and the onshore sediment fluxes. Secondly, it requires a large enough buffer zone to give sufficient flexibility to overcome periods of degradation during storms or of absence of soft mud banks (interbank periods). Since sufficient propagules are available along the Guianas coast, actual planting then should no longer be necessary.

The main challenge along the Guianas coast is to provide conditions that allow mangrove regeneration during interbank periods in areas where the minimal width of the mangrove fringe is below the critical size, which is estimated to be of the order of 1 km, while the width of a resilient coastal fringe should be of the order 5 km (Anthony and Gratiot 2012). Since there is no shelter provided by an onshore mud bank during this period, artificial shelter has to be provided which allows entrapment of sediments and reduces wave action (by reducing wave heights by damping and reducing wave reflection).

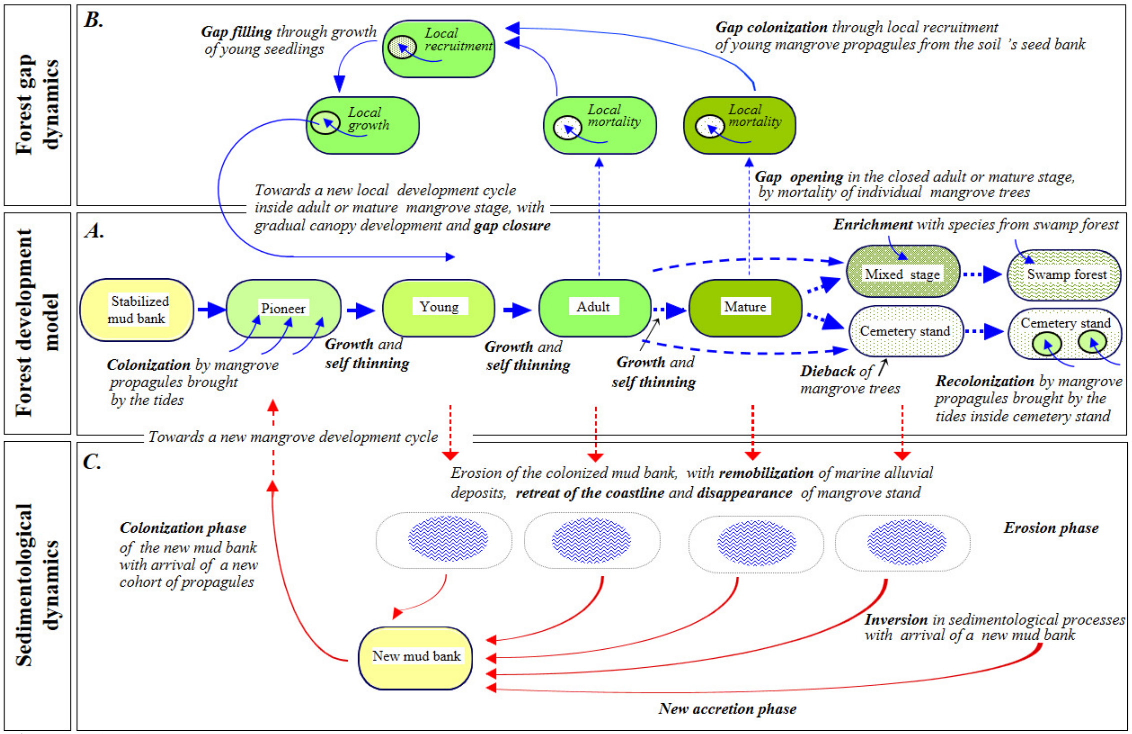

Figure 20.25 A combined model of Guianese mangrove dynamics. (A): Forest development model, mainly based on growth and self-thinning processes. (B): Forest gaps dynamics, brought about by local decaying and death of individual mangrove trees (adapted from Duke 2001). (C): Sedimentological dynamics, the major driving force along the coastal area under Amazonian influence. (Fromard et al. 2004)

Sediment entrapment areas are well know from saltmarsh works (Winterwerp et al. 2013). The latter type is based on its successful use centuries ago for the creations of polders in the Netherlands. They consist of areas enclosed at both cross-shore boundaries, reducing longshore currents within the unit, and seaside boundary, reducing wave action and tidal currents. Fine sediments can settle and deposit more easily under these quieter conditions. Moreover, cohesive sediments can form larger flocs, which settle faster (Mehta 2014).

20.4.2 Guyana Mangrove Restoration Project

The Guyana Mangrove Restoration Project (GMRP - www.mangrovesgy.org) commenced in 2010 and was co-financed by the Government of Guyana and the European Union under the Global Climate Change Alliance. The Project was implemented by the National Agriculture Research and Extension Institute (NAREI) with support from a multi-agency oversight committee known as the Mangrove Action Committee. Following the completion of the project phase in 2013, the Government of Guyana committed to continued mangrove restoration and management, and the Project Unit was integrated into the NAREI structure (NAREI 2014).

GMRP adopted a multidisciplinary approach to mangrove restoration, protection and management. This included restoration through the use of coastal engineering structures and seedlings, enforcement by rangers, community development and alternative livelihoods, research and development and public awareness and education.

20.4.2.1 Mangrove restoration interventions implemented under GMRP

Guyana adopted the principles of Ecological Mangrove Restoration (EMR) (Lewis III 2004) to design and implement its mangrove restoration program following failed attempts at restoration primarily through seedling plantations at the beginning of the project.

A range of interventions aimed at restoring degraded coastal mangroves and creating a suitable environment for mangrove to colonize the coastline were implemented as part of the mangrove restoration programme. These interventions included:

- Mangrove seedling planting
- Construction of coastal infrastructure such as groins and breakwaters
- Spartina grass planting
- Construction of restrictive gates and fences to reduce the impact of anthropogenic activities

204.2.1.1 Mangrove seedling planting

Seedling planting is only possible in areas or sites that have a suitable mud elevation. Based on the most successful sites and comparison of natural forest, NAREI has established a suggested guideline range for planting *Avicennia germinans* based at 2.3m – 2.7m above chart datum (Landell Mills Limited 2013). Only the *Avicennia germinans* species is planted based on the natural zonation pattern in Guyana.

From 2010-2016 over 500,000 mangrove seedlings were produced in community nurseries and planted in sixteen villages along the coastline (**Figure 20.26**).

Figure 20.26 *Avicennia germinans* seedlings planted along the Better Hope coastline, East Coast Demerara (Guyana), August 2016. (Credit: R. Adams, NAREI)

Initial efforts of restoration were unsuccessful due to limited local expertise. The success rate increased during the second year of project implementation following the fielding of technical experts and training of local project team. Detailed site assessments where introduced and pre-planting surveys and surveys of the topography of both successful and unsuccessful planting areas showed that surface elevations of unvegetated mudflats needed to be in the range of +2.0m - +2.5m MSL in order to support planted mangroves (Landell Mills Limited 2013). Following the guiding principles of EMR, seedling planting was only utilized to increase recovery time of a site that met the necessary criteria to support restoration.

Field monitoring of planted restoration sites (**Figures 20.27-20.30**) facilitated a comprehensive statistical analysis for survival and growth rates. Assessments completed (Machin and Lewis III 2013; Adams 2014) indicated that survival rates and growth varied among restoration sites and can be grouped into three scenarios:

1. Fast growing and high survival (Wellington Park, Village #6-8, Chateau Margot, Success, Lima, Better Hope). Mud elevation 2.13 – 2.49cm above CD;
2. Slower growing and high survival (Greenfield, Hope Beach, Le Ressouvenir, Felicity). Mud elevation 1.61 – 2.37cm above CD;
3. Low or no survival (Hope, Greenfield, Victoria, Section C Enterprise, Mon Repos, LBI/Triumph, Buxton, Nooten Zuil, Lusignan). Mud elevation 1.9 to 2.4m above CD.

Research completed by Robertson (2014) on the protective capacity of the restored Chateau Margot/Success restoration site indicated that a three year old black mangrove forest with a bandwidth of 50m can reduce a 0.43m wave at open sea to 0.001m at the coast. Modelled wave heights prove that a 50m mangrove forest can reduce a 0.43 m wave to approximately 0.2 m (Robertson 2014).

Figure 20.27 Planted black mangrove seedlings along the foreshore of Village #6-8, West Coast Berbice (Guyana), Region 5. The site was planted in 2011 and 2012. (Credit: K. Moseley, NAREI)

Figure 20.28 2016 aerial of Village #6-8, West Coast Berbice (Guyana), planted in 2011 and 2012. Successful planting of black mangrove seedlings resulted in extensive natural regeneration. (Credit: C. Gittens, WSG)

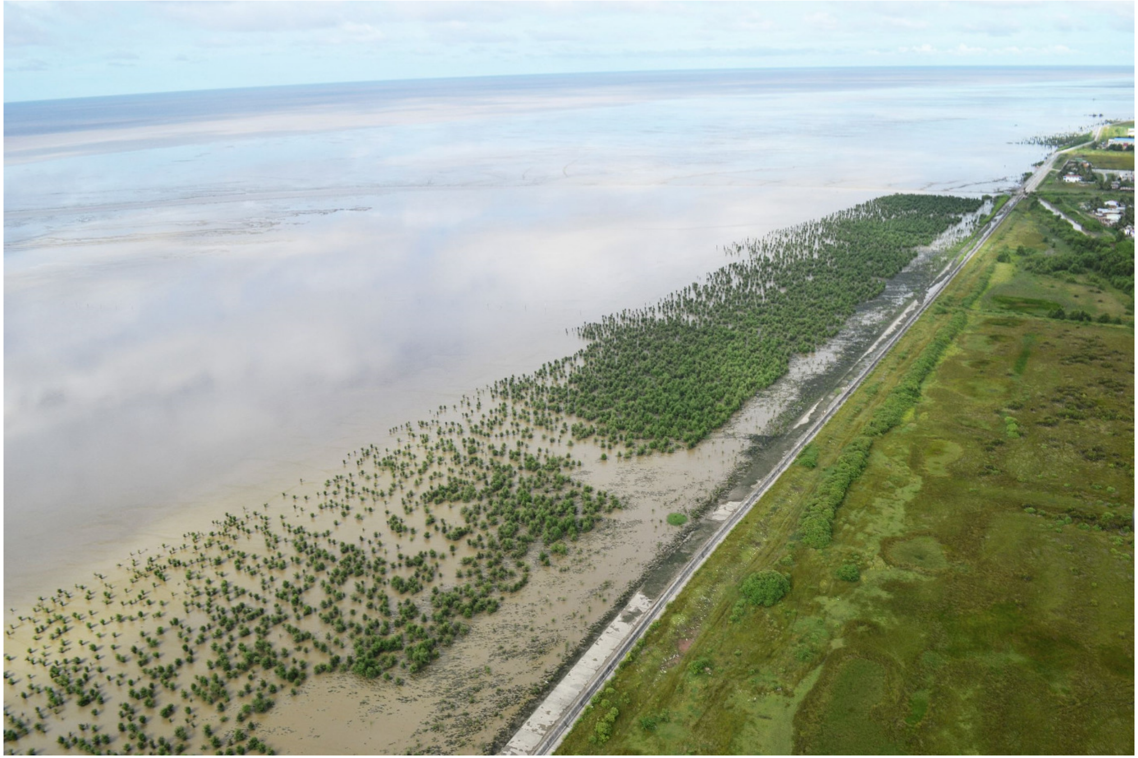

Figure 20.29 2012 aerial of planted black mangroves along the coastline Felicity to Chateau Margot (East Coast Demerara, Guyana), Region #4. Site was planted in 2011 and 2012. (Credit: I. Brierley, CATS)

Figure 20.30 2015 aerial of restored black mangrove with extensive natural regeneration along the coastline Felicity to Chateau Margot (East Coast Demerara, Guyana), Region #4. (Credit: I. Brierley, CATS)

20.4.2.1.2 Coastal engineering interventions

Coastal engineering interventions were implemented at sites along the coast to encourage accretion. These interventions aim to create a suitable environment that will encourage mangrove restoration by increasing shoreline elevation**.**

Following collaboration with the Guyana Sea and River Defence Division, three options for construction of low-cost coastal structures was developed using the following technologies: geotextile tubes, brushwood dams and rubble mounts.

Geotextile tube technology was implemented at two sites to form a detached offshore breakwater and a groin. Two geotextile tube projects were completed at Devonshire Castle in Regions #2 and Victoria in Region #4. *Spartina* grass was introduced at both sites following completion of the structures to support soil consolidation.

Brushwood dams were constructed using locally available building material i.e. bamboos (**Figure 20.31**). The brushwood dams were designed to mimic the mangrove roots by trapping sediments thus increasing shoreline elevation. Brushwood dams were constructed at three locations in Region #2 and Region #4 in 2013 2015 and 2016. Iron bamboos were used as piles ranging from 10 to 15 cm in diameter and having lengths between 7 to 9 m. Brushwood dams were filled with bundles of bamboos of the same size to that of the bamboo piles to complete the system.

Figure 20.31 Brushwood dam constructed at Walton Hall (Essequibo Coast, Guyana), Region #2 in 2015. (Credit: L. Jack, NAREI)

The result of the impact of coastal structures on mangrove regeneration is expected to be a continuous long term study. Data collected on structures are varied. Results indicate that structures placed at a site with a visible mud bank offshore and experiencing accretion, have greater potential to trap sediments and increase elevation. Critical to the success of coastal structures is the completion of geotechnical surveys to ensure design parameters are suitable for the foreshore characteristics. Geotextile groin constructed at Devonshire (**Figure 20.32**) showed the best results in relation to changes to the shoreline line conditions and rapid colonization of planted *Spartina* and mangrove seedlings. While there has been significant consolidation of the soil at this site, elevation taken at two periods showed a marginal decrease in elevation within a six month period from 2.39 m to 2.35 m above chart datum (CD). This was due to consolidation of the soil.

Figure 20.32 Site conditions following completion of a geotextile tube groyne at Devonshire Castle (Guyana), Region 22014. (Credit: L. Jack, NAREI)

20.4.2.1.3 Spartina grass planting

In 2013 the GMRP implemented a new restoration strategy for sites along the coastline where mangrove planting was not suitable due to poor mud consolidation and low elevation. The *Spartina brasiliensis* (*Raddi*) is one of the lesser known coastal salt marsh species along Guyana's coastline. The presence of *Spartina brasiliensis* beds in Guyana has been described as occurring on raised areas on nearshore mud banks where the grass quickly establishes, develops into large clumps and raises the level of the mud to form large stands. These stands are then typically colonised by *Avicennia* and *Laguncularia* mangrove species, after which they eventually disappears beneath these forests (Machin 2012).

Figure 20.33 Top: Devonshire Castle shoreline (Guyana) was planted with *Spartina* in May 2015 following construction of geotextile tube. Bottom: Rapid colonization of *Spartina* within five months. (Credit: R. Adams, NAREI)

Spartina was planted to stabilize sediments and support accretion. The use of the *Spartina* was introduced late in the project implementation as it was not a part of the original project plan and was a relatively new concept to the local project team. Following a technical mission from restoration expert Robin Lewis III this intervention was introduced and has been incorporated into the restoration program. *Spartina,* which is native to the Guyana coastline, was transplanted to nine sites along the coast which did not meet the criteria to support mangrove restoration due to poor consolidation.

The grasses planted have had mixed results. Grass planted at BV/Triumph, Kilmarnock and Walton Hall was affected by heavy waves, *Sargassum* and livestock grazing. However *Spartina* planted at Victoria, Village #6-8, Devonshire Castle and La Belle Alliance have been more resilient and have extended the area coverage significantly (**Figure 20.33**). Combining *Spartina brasiliensis* with structures has shown tremendous effects at sites where implemented (**Figure 20.34**). The soil consolidation at these sites also improved significantly in a short period.

Figure 20.34 Natural colonization of black mangrove seedlings within *Spartina* grass at Devonshire Castle (Guyana), December 2016. (Credit: L. Jack, NAREI)

20.4.2.1.4 Challenges

While the mangrove seedling planting program was deemed relatively successful (Topper 2012), assessments conducted revealed that there are limited sites available that are suitable for mangroves to colonize. Site assessments indicated that the elevation was either too low to support mangroves or the sediments on the shoreline was too fluid and not consolidated enough to support young seedlings.

The importance of mud bank movement along the coast of Guyana and its influence on mangrove management and restoration has been recognized and documented (Gratiot 2011;

Welage 2005). However due to limited research on the movement and mapping of mud banks along coastal Guyana, the project continues to be challenged to effectively plan restoration activities based on definitive data on the current and future location of mud banks.

20.4.3 Mangrove rehabilitation in Suriname

20.4.3.1 Experimental pilot project in Moy (Coronie district, Suriname)

From 2010 to 2013, an original pilot project by AdeKUS, mainly financed by the Suriname Conservation Foundation, was set up in Moy, along the Coronie coast to plant mangroves on a bare mudflat, the front of a newly arriving mud bank, and study the conditions. The planting and monitoring was done using mud sledges, as used by the local crab hunters. It was noticed that the small plants, grown in a nursery, where not resistant to the force of inundating water. But they were also too heavy to remain vertically upright in the upper mud layer. They tend to sink to a depth where oxygen is depleted which implies the death of the mangrove. Therefore, the young plants where fastened on a stick which was put deep enough in the mud (**Figure 20.35**). This allows the root system to develop and establish the natural equilibrium between the extend of the root system, the weight of the plant and the condition (i.e. compaction) of the sediment. This also protected the plant against being washed away.

Figure 20.35 Young black mangrove planted and stabilized by wooden sticks along the Coronie coast, Suriname, in 2010. (Credit: S. Naipal, AdeKUS)

This project continued until the natural colonization of the new mud bank overtook the experimental site. It could not be determined whether the plantation experiment had any influence on the colonization speed of the natural process. From the point of view of the abundance of propagules, one would not expect so. But the existing plantation may have speeded up the sedimentation of the migrating mud bank, allowing a faster accumulation of fresh mud at the optimal elevation for propagules to settle. It has indeed been observed that the first seedlings settled in the cracks in the by sun desiccated mud of the highest elevations of the mudflat, between the planted mangroves.

West of this pilot site, the Coronie sea defence wall is under construction. This walls blocks the free runoff of the inland fresh water, carrier of nutrients to potential new mangrove regeneration at the sea side. This water is collected in a ditch at the land side of the dike and can be flushed to the sea through a few gates in the wall. Therefore, dr. Naipal from AdeKUS proposed to design a water distribution system to disperse this water more equally through a permeable pipeline collector at the sea side along the entire dike (since a trench would silt up). This system has not yet been implemented and tested.

20.4.3.2 Sediment trapping unit pilot project in Suriname

A new pilot project (funded by Conservation International Suriname), based on the principles of sediment trapping units, inspired by the successful application in Indonesia (Tonneijck 2013; Tol 2016), has been implemented in 2015 at Weg naar Zee (Wanica district, near Paramaribo, Suriname), one of the most threatened coastal areas of Suriname. Here the choice went to brushwood walls forming an enclosed area over a seaward width of about 200 meter on the mud flat (**Figure 36**). The dam structure consists of wallaba (*Eperua falcata*) wooden poles (10 cm diameter), driven into the ground 2 meters deep (2/3 of their length), spaced 0.75 m apart in parallel lines 0.5 m apart, filled with brushwood and tightened with plasticised wire. The advantage of this type of permeable walls is the fact that the sediment-rich water can enter the enclosed area where the sediments can deposit due to the much quieter conditions. It would actually be better to reduce the permeability close to the bottom, making sure that trapped sediment will not so easily escape with ebb currents or due to gravity currents of soft liquid mud.

Figure 20.36 Construction of the sediment trapping unit at Weg naar Zee, Suriname, in September 2015. Left: top view of the dam structure (see text for details). (Credit: C. Fung-A-Loi and S. Naipal, AdeKUS)

The results of the first 16 months of monitoring of the sediment deposits in 9 locations in this unit shows a period of deposition (5-10 cm from June to December 2015, most of which during October-December), followed by a shorter period of erosion (most of which in January 2016: rapidly down to +1 cm relative to the initial level). Subsequently gradual deposition was again observed. It is hypothesized that this alternation of erosion and deposition can be related to the on average much stronger north-eastern winds in the periods December-May, compared to the weaker, more eastern directed winds in the period June-November (NOAA Global Model wind data, averaged over the period 1997-2003; Winterwerp et al. 2005). The rapid erosion in January 2016 may indicate extreme conditions.

The following months the net deposition increased to higher levels, generating mud to the high-high waterline, reached at spring tide. Since at this elevation the fresh mud is much more exposed to drying by the sun (until the next spring tide), the material becomes much more compact and cracks are formed (**Figure 20.37**). These are the ideal conditions for mangrove propagules to develop. Natural colonization of these higher elevations has indeed started.

Figure 20.37 Evolution of the mud deposit of the sediment trapping unit at Weg naar Zee: situation in April 2016 (left) and June 2017 (right). (Credit: S. Naipal)

Figure 20.38 Spontaneous colonization by mangroves of a short-lived mud deposit at the high-high-water elevation (Wanica district, Suriname). Notice the cracked surface, as well as the cliff erosion. Photo taken from a small boat, indicating that the water depth rapidly increases, too much for a stable mud deposit. (Credit: S. Naipal, AdeKUS)

The success of this STU is also explained partially by the available large sediment supply during this period, which is attributed to the approximation of a mud bank, which is crossing the Suriname river. Increased mud deposits and spontaneous mangrove colonization has been observed also a bit further to the west, but this area seems already eroding away again, indicating that the slope in front is too steep (**Figure 20.38**). Further analysis and monitoring needs to be done in order to gain better insights.

Care has to be taken that the sediment entrapment would not lead to disturbing the sediment balance at the alongshore downstream side of the entrapment unit. By trapping the sediments in a specific area, there may be shortage of sediment supply behind the unit. Furthermore, the diverted longshore currents may increase in magnitude and may cause increased erosion in front of the unit. The latter will lead to a concave profile of the tidal flat which will hinder the onshore sediment flux beyond.

20.5 Research

Many studies have been undertaken along the Guianas coast in order to understand its dynamics. The coastal erosion problems in Guyana (Delft Hydraulics 1962; Nedeco 1972) and the Surinam Transportation Study (Nedeco 1968), investigating improvement of the conditions for navigation of ocean-going vessels, triggered the need to study the physical conditions in order to design the sea defence wall and for finding solutions for optimal access to the ports in between the mud banks. The corresponding engineering study reports remain an important source of information and data for the region. Major scientific contributions were subsequently realized by Augustinus (1978), Rine (1980), Wells et al. (1981) and Wells and Coleman (1981). These studies have resulted in a good qualitative understanding of the processes. However, in view of management, it is necessary to be able to make quantitative predictions of the expected evolution of the coast, particularly in view of different climate change scenarios. Research in the 21st century therefore has been focusing on collecting more field data, remote sensing data and on the development of numerical models for morphodynamic predictions.

20.5.1 Research in French Guiana

The French Guiana coast constitutes an ideal laboratory for studying the coastal margin as a highly active interface between intense physical processes and induced ecological changes ranging from mud bank colonization by pioneer mangroves to adult mangrove forest destruction. The coast of French Guiana may be considered the most pristine of these coasts in terms of mangroves and their conservation, since no human impact on the mangrove system has been observed, thus far.

Research in French Guiana has been conducted on mud bank morphology, hydrodynamics and sediment characteristics, with emphasis on the processes involved in bank migration and destruction, both driven by waves, but also in the consolidation of the surfaces of mud banks that is a pre-requisite for colonization by mangroves. The aim of this research, the overarching aspects of which are summarized here, has been to gain a better understanding of overall mud bank and coastal dynamics at various spatial and temporal scales, and how these interact with mangrove ecology, especially how mangroves become established, function, and are destroyed in this highly changing setting.

Although there is corpus of old and generally descriptive unpublished studies on these aspects, much of the recent research on mud banks and seafront mangroves commenced in the late 1990s using an approach combining field monitoring and remote sensing. Given the size of a typical mud bank (several 10s to 100s of km^2) and the problems of accessibility in this dynamic mud setting, remote sensing, calibrated by ground truth studies, has clearly been an area where research has led to breakthroughs in understanding sediment dispersal and accumulation patterns along what is considered as the world's longest and most dynamic muddy coast.

20.5.1.1 Field work

Field studies on mud banks and mangroves involve considerable logistical difficulties, including the challenge of accessing experimental sites. In spite of these constraints, field work conducted in French Guiana has been fundamental in revealing processes of mudflat accretion and consolidation and mangrove colonization. Lefebvre et al. (2004) were the first to conduct high-resolution field topographic surveys that highlighted the marked surface variability of mud banks. Earlier, Fromard et al. (1998) identified, from field reconnaissance surveys, six stages of mangrove ecology, ranging from development through adulthood to destruction, that are strongly influenced by mud bank activity: (a) pioneer; (b) young; (c) adult; (d) mature; (e) mixed; (f) cemetery. The onshore-alongshore transport of mud by waves can create accreting intertidal mudflats of several km^2 in days to weeks, with very dense mangrove development in just two to three years.

Several other studies based on field observations and measurements, complemented by Lidar data and satellite images have further highlighted the topographic variations over the surfaces of mud banks (Gratiot et al. 2007; Anthony et al. 2008; Gensac et al. 2015). In the leading edge of a mud bank, accreted bars form a dynamic 'suture' zone with the muddy (or locally sandy) intertidal terrestrial shoreline (Anthony et al. 2008, Gardel et al. 2011). These characteristic features of the low-energy inner leading part of banks form the precursor substrate conditions for mangrove colonisation. Bars in the upper intertidal zone can become immobilized over fairly long periods of low wave energy, and, thus, progressively dry out via evaporation and dewatering (Fiot and Gratiot 2006; Gardel et al. 2009), leading to the development of mud cracks, typically during neap tides, that provide opportunities for mangrove colonization (Proisy et al.2 009). Wetting and drying cycles have been shown to vary considerably with elevation (Fiot and Gratiot 2006), while field studies have shown that very subtle elevation changes in the upper intertidal zone (order of a few centimetres) can have a strong influence on successful mangrove colonization (Anthony et al. 2008; Gardel et al. 2009; Proisy et al. 2009; Gensac et al. 2011). These studies have shown that mangrove colonization can be successfully predicted based on the definition of the geographic limits of a carefully determined elevation threshold of 2.45 m above the local datum (Fiot and Gratiot 2006; Proisy et al. 2009; Gardel et al. 2009; Gensac et al. 2011). Above this threshold, the duration of tidal emersion is sufficient to allow for mangrove propagules to take a hold on the mud bank surface. The progressive development of mud cracks, and the corresponding colonization by pioneer and then young mangroves, over a period of several months has been monitored by an innovative system of in situ time-lapse photography aimed at highlighting changes in the surface properties of a mud bank (Gardel et al. 2009). Under favourable conditions, mangrove colonization can be extremely rapid, with plant densities exceeding 30 per m². Rates of mangrove colonization vary considerably, however, as a function of available intertidal area. Following colonization, extremely rapid mangrove growth (individual plants grow by up to 2 m/year) leads to the establishment of a dense fringe of young mangroves and mud stabilization. Mangroves at all stages of establishment, from young pioneers to mature forests, can however, be destroyed by mud reworking by high-energy waves, sometimes simply through burial and asphyxia of mangrove pneumatophores (Fromard et al. 1998 2004). In some cases (i.e. Marais Sarcelle, Sinnamary) mangrove trees (*Avicennia*) can die over large areas due to hypersalinization when mangrove is cut off from the sea (formation of a new chenier in front of mangrove forest), as reported above for Suriname. The ensuing mangrove pattern may, therefore, be one of coexistence of young opportunistic rapid-growth juveniles adapted to the new substrate topography and dying and dead mangroves (cemetery stage) that are asphyxiated as mud accretion occurs. The coexistence of dead, dying, and thriving pioneer and young mangroves thus reflects active mangrove renewal that is also unique feature of the mangroves of the Guianas coast.

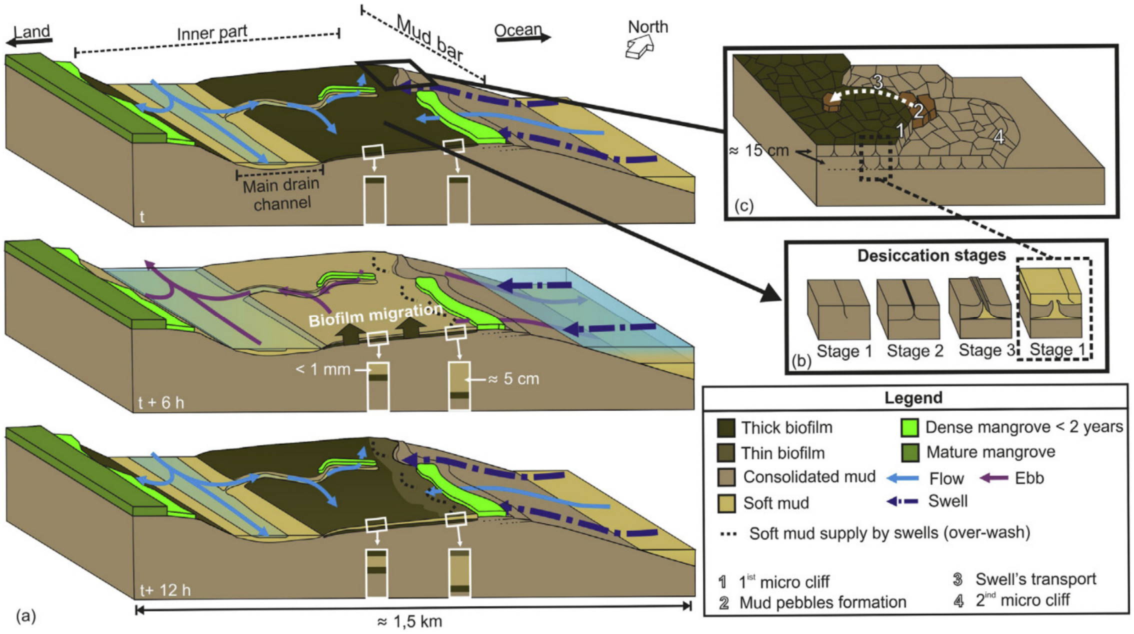

Figure 20.39 Schematic representation of the sediment dynamics on an intertidal mudflat in French Guiana during a tidal cycle (a). Desiccation (b) and erosion (c) of the consolidated mudflat are also illustrated. The time scales involved in the desiccation (b) and erosion (c) stages are longer than those in (a). (Gensac et al. 2015)

Sedimentation rates associated with wave reworking of mud have been monitored in the field (Gratiot et al. 2007; Gensac et al. 2015). The latter study carefully documented processes of wave overwash over mud bars in the course of the rising tide. A schematic representation of the sediment dynamics on an intertidal mudflat is proposed by authors (**Figure 20.39**). Mud cracking plays a determining role in the rapid and extensive colonization, by pioneer mangroves, of a mud bank undergoing consolidation (Fiot and Gratiot 2006; Gardel et al. 2009). Gratiot and Anthony (2016) have recently shown from experimental work conducted in

French Guiana that flocculation and differential settling enhance sedimentation during slack water and under low wave conditions. It can be deduced from this that enhanced settling in the leading edges of banks during such conditions is important in the temporary sedimentation that generates under-consolidated mud bars and gel-like fluid mud patches. These characteristic features of the low-energy inner leading part of banks form the precursor substrate conditions for mangrove colonization. Flocculation, hindered settling and settling by mass are all variably favoured by mangroves. In the trailing edge, old mangrove stands are uprooted and their root and trunk system favour turbulence dissipation under wave attack and the formation of mud pebbles from reworking of the bank. This reworking promotes the formation of dilute suspensions that enhance suspended concentrations. In the leading edge, young colonising mangrove stands favour wave energy dissipation, the formation of fluid mud patches, and settling by mass.

20.5.1.2 Remote sensing

20.5.1.2.1 Mud bank migration and SPM dynamics in coastal waters

Following the example of earlier work in Suriname (Augustinus 1978), Froidefond et al. (1988) used aerial photographs acquired during the late 1970s and 1980s to determine rates of mud bank migration. A mean velocity of mud bank migration of one km a year was determined from the interpretation of these aerial photographs.

The advent of moderate-to-high resolution satellite images (LANDSAT TM, SPOT) in the 1990s offered a new opportunity for the monitoring of the highly dynamic coast of French Guiana. Several studies have explored the capacity of these new sensors, initially to quantify mud bank migration (Froidefond et al. 2002 2004; Baghdadi et al. 2004; Gardel and Gratiot 2005; Gratiot et al. 2007), and, more recently, suspended particulate matter in coastal waters and in mangrove dynamics (Vantrepotte et al. 2013; Gensac et al. 2016). Froidefond et al. (2002) characterized the spectral remote sensing reflectance of coastal waters. Later, Froidefond et al. (2004) established a correspondence function between in situ optical data and concentrations of suspended particulate matter obtained from coastal surveys. This function was then applied to a set of SPOT satellite images to estimate suspended particulate matter concentrations near the sea surface at different dates.

Radar (ERS and RADARSAT) and optical (ASTER) satellite images collected from 1997 to 2001 have been used to evaluate the capacity of these types of sensors in detecting mud banks and in monitoring coastline change (Baghdadi et al. 2004). This work showed that low-angle radar is more efficient in detecting mud banks, whereas high-angle radar is more appropriate for monitoring coastline change. These results also showed that, depending on the water level on the mud bank, optical or radar satellite images were more or less accurate.

Gardel and Gratiot (2005) attempted to extract rates of mud bank migration by applying image-analysis algorithms on SPOT images covering the period 1986-2003. They showed that rates of migration have been significantly more important over the last decade (up to 2 km/year) covered by these images, possibly as a result of enhanced wind-wave activity, as suggested by wave models of the Atlantic. Gratiot et al. (2007) highlighted an increase in wave forcing over a 44-yr period (1960-2004) related to an increase in trade-wind velocities.

In more recent works using remote sensing methods of sea colour comparison of SPOT images and MODIS suspended particulate matter (SPM) maps between 2002 and 2010, Vantrepotte et al. (2013) revealed the strong spatio-temporal coupling between SPM and the dynamics of local mud banks. This study suggested that the highest MODIS SPM values (>13 g/m^3 approximately) can be significantly associated with the subtidal part of the banks as well as to the related turbid plume (**Figure 20.40**). Mud bank migration rates derived from MODIS SPM data are, on average, higher than 2 km/year, in agreement with previous studies.

Gensac et al. (2016) used MODIS satellite data over the period 2000-2013 to assess the sediment dynamics in the shallow coastal waters from the Amazon River mouth to the Capes region (northern part of the Amapa region of Brazil and eastern part of French Guiana). They determined the role of continental and oceanic forcing and the implications for coastal geomorphology and mud bank formation. This work also confirmed an average rate of mud bank migration of up to 2 km/year.

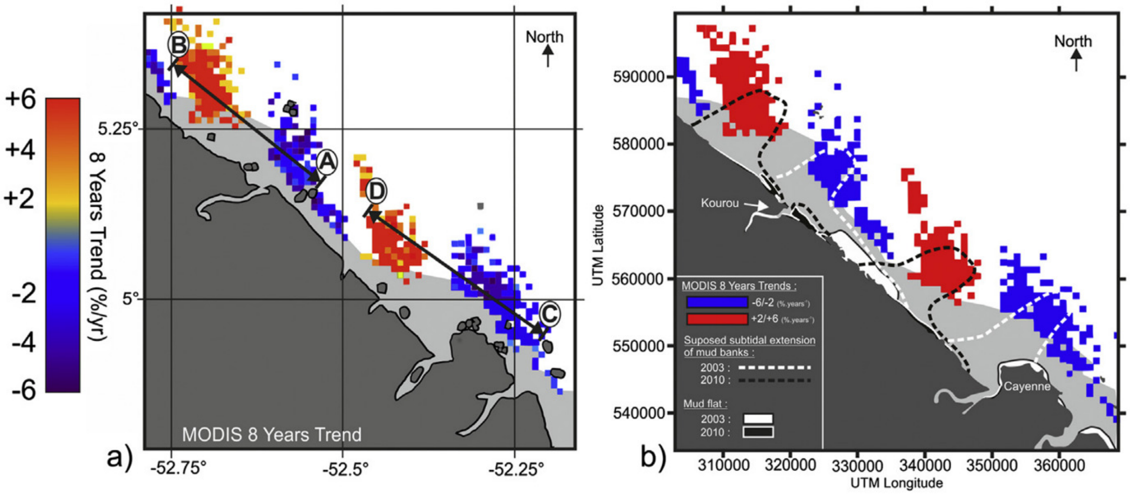

Figure 20.40 Significant trends in SPM detected over the French Guiana coast from the 8 year MODIS time series (a) (in % year^{-1}) and comparison with the mud banks estimated position and morphology (b). SPOT estimates of the location of the mud flat and subtidal extension of the mud bank at the beginning and end of the MODIS time series considered are represented by white and dark grey surfaces and dashed lines, respectively. The subtidal mud bank extension has been determined from swell damping characteristics (SPOT images). (Vantrepotte et al. 2013)

20.5.2.1.2 Decadal-scale mud bank dynamics and mangroves

The dynamics of mangroves on the Guianas coast are extremely variable as their spatial and temporal extension and stages of development are determined essentially by the waxing and waning of mud banks. In this system, mangroves play an important role by stabilizing the muddy substrate and ensuring plant 'continuity' with the older muddy shoreline, from which mangrove regeneration is best assured by propagule dispersal. Each erosive inter-bank phase can result in the partial, or rarely, total erosion of a previously welded bank. Such total erosion can occur during a subsequent inter-bank phase characterised by particularly high wave-energy seasons such as El Niño years or phasing of the NAO. Gardel and Gratiot (2006) showed, however, that such waves do not necessarily always have a destructive impact on mangroves. Their analysis of shoreline changes in French Guiana over the period 1995–2000, characterized by high wave energy, showed that mangroves in inter-bank areas underwent very active retreat (150 to 200 m/year), but at the same time the mud bank areas experienced mangrove colonization. Gratiot et al. (2007) also showed that notable phases of increased wave energy tended to be accompanied by higher annual rates of alongshore mud bank migration. Fromard et al. (2004) proposed a global scenario of mangrove forest dynamics, including a model of forest development, forest gap processes and sedimentological dynamics.

Gratiot et al. (2008) calculated a mass mud bank budget along the French Guiana coast from 1988-2004 based on satellite images, and suggested a link between budget fluctuations and the 18.6-year nodal tidal cycle, which they considered as an important factor in modulating coastal erosion and accretion in the Guianas. A detailed 64-year inventory (1950-2014) of mangroves and their multi-decadal area variations as a function of the spatial extent of mud bank and inter-bank zones on the French Guiana was conducted by Walcker et al. (2015). This inventory showed that the area covered by mangroves fluctuates significantly at this multi-decadal timescale depending on the global domination of bank or inter-bank phases at any time. The mangrove cover in French Guiana in 2014, for instance, has been estimated at 45,000 ha by Walcker et al. (2015). The authors showed that fluctuations in mangrove area were not due to current sea-level rise nor to the 18.6-year nodal tidal cycle identified by Gratiot et al. (2008) but to the pervasive role of NAO-driven multi-decadal fluctuations in wave energy (**Figure 20.41**). Proisy et al. (2016) proposed a model of the French Guiana coastal system where interaction functions between ecological and physical processes are written to specify how ocean/mangrove shoreline/mud bank change when they interact. This approach has been applied to study mangrove shoreline variations from 1986 to 2009. A time series of remote sensing images was used during the initialization and validation phases.

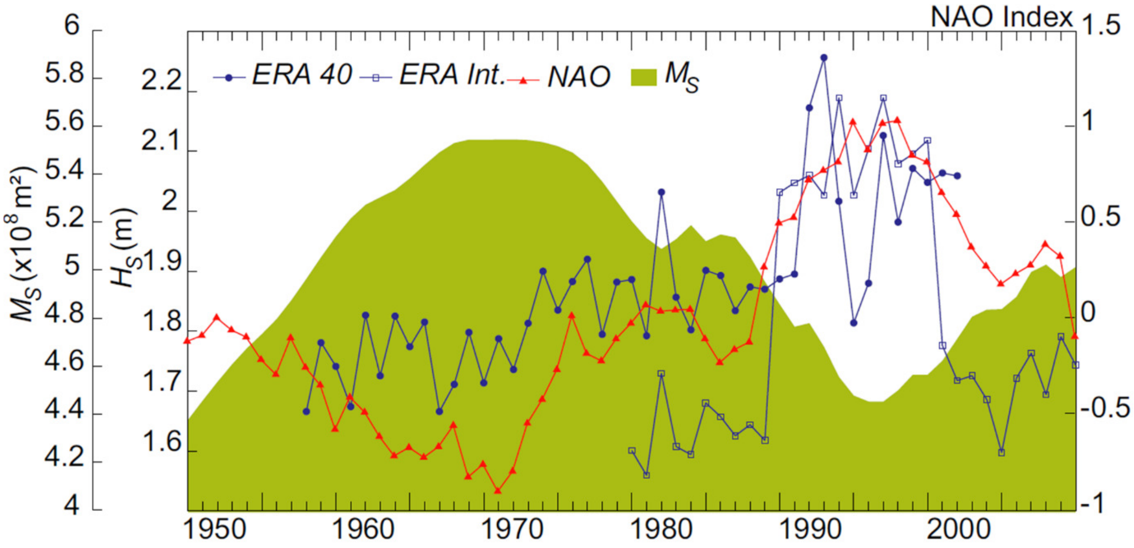

Figure 20.41 Relationship between the mangrove surface area (MS) and significant wave heights (HS), and their link with the North Atlantic Oscillation (NAO). The ERA-40 product was used to assess the winter HS from 1958 to 2002, whereas the ERA-Interim product was used for the period of 1980–2010. The 10–year moving average of the NAO winter index is also plotted on the graph; it exhibits a significant temporal correlation with MS and HS. (Walcker et al. 2015)

All of the foregoing studies have been significant in understanding the development, morphology and sediment dynamics of the coast and their relationship with mangrove ecology. Much still remains to be done, however, regarding these aspects. Areas for forthcoming research concern changing rates of mud bank migration, how these rates will be affected by climate change, and the corresponding impacts on mangroves.

20.5.2 Coastal engineering research in Suriname

The first important engineering study for the Suriname coast was performed by the Dutch engineering consultants group Nedeco (1968) in the framework of improving the navigation access to the ports. In-depth geomorphological research in Suriname has then been pioneered by Prof. Augustinus from the University of Utrecht (the Netherlands). Despite efforts, Suriname remained dependent for a long time on external expertise with regard to coastal engineering. This changed early 21st century when the Anton de Kom University of Suriname (AdeKUS) in Paramaribo appointed Surinamese scientists with the proper background, who studied abroad, as academic staff.

Within the framework of interuniversity development cooperation, funded by the Flemish Interuniversity Council (VLIR-UOS), the Hydraulics Division of the University of Leuven (KU Leuven, Belgium) has first established laboratory facilities for hydraulic engineering research. Subsequently, they ran a so-called “own initiative” project (2005-2010) to establish the necessary research capacity at the AdeKUS to study the coastal processes in more detail by carrying out field campaigns (www.kuleuven.be/hydr/SurinamCoast/SurinamCoast.htm).

The Hydraulics Laboratory, Department of Infrastructure, of AdeKUS now disposes of a small sea-borne motorboat equipped with a (by software) coupled system of GPS, dual-frequency echo-sounder and acoustic Doppler current profiler (ADCP) for transect monitoring of bathymetry, fluid mud layer thickness, velocity profiles and turbulence. Furthermore equipment is available for frame deployment to collect time series data on sediment concentrations with optical backscatter (OBS) probes, flow velocity, turbulence and water depth with acoustic Doppler velocity meters (ADV) and the same ADCP can also be used bottom-mounted, upside down to measure velocity profiles and directional waves. This allows7 local data collection and research to support the proposed sustainable management of the coastal zone.

A major goal of the research is the set-up of a complete morphodynamic model for the Guianas coast where all the physical processes, described above, are incorporated and local data used. This model is discussed in more detail in the following section.

20.5.3 Research in Guyana

Coastal research in Guyana is scarce and generally little known. Nevertheless, the continuous threats to the western part of the Guianas coast invited several geological studies (Nota 1958; Hawkes 1962; Morelock 1972; Daniel 1989; Lakhan et al. 1997, 2002, 2006). Important engineering studies related to the design of the coastal defence system have been carried out by Delft Hydraulics (1962) and Nedeco (1972). The “Institutional Capacity Building Activities on Guyana Sea Defences” project (2004-2005), carried out by the Dutch consortium of Delft

Hydraulics and Royal Haskoning, constitutes the most prominent research for the Guyana coast, reviewing existing knowledge and including the gathering of much new field data (Les and Westra 2004; Westra 2004) and the development of a powerful modelling tool (de Graaff and Bijlsma 2005; de Graaff et al. 2005; Winterwerp et al. 2005), briefly discussed in the next section.

20.5.4 Morphodynamic modelling of the Guianas Coast

Even though different studies have been looking at the actual time scales for the recent evolution of the Guianas coastline, there is no consensus. The main reason is that dedicated observations have only started around the ‘40s of the twentieth century, which constitutes a period of about 80 years of information which is too short relative to the estimated cycle of roughly 30 years for the passing of a mud bank. Looking at the sequence of all the mud banks over the entire 1000 km stretch of the Guianas coastline may give an impression of how the mud banks evolve during their migration from east to west, which takes them about 500 years. However, the effects of climate change and sea level rise may make the interpretation back in time uncertain. Moreover, the coast has been under increasing anthropogenic pressure during the last decades, and it becomes increasingly difficult to distinguish natural from anthropogenic effects.

Furthermore, it is dangerous to extrapolate the future based on the past, certainly in view of the large uncertainty on sea level rise (certainly for South America, where little SLR data are available). There have been various studies on how a mangrove coast responds to sea level rise (Alongi 2008; McIvor et al. 2013). Based on the study of the evolution of the Guianas coast over the Holocene period (Rine 1980; Rine and Ginsburg 1985), there is some evidence that a healthy and wide enough mangrove belt along may be resilient enough and may follow sea level rise, provided there is enough sediment supply. This may explain why the Guianas mangrove coast is not considered vulnerable by IPCC (Alongi 2008; Wong et al. 2014). Much depends on how the sediment supply from the Amazon basin will evolve and respond to climate change. Nevertheless, the local authorities have worries because of the reality of increasing flood events in vulnerable spots. Numerical models can be used to assess the impact for different scenarios. Such a model would then serve as a decision support tool to study potential threats to the coastline. This model should allow to answer (a.o.) the question if the coastline will be able to follow sea level rise by sediment accumulation, depending on the expected evolution of sediment supply from the Amazon. The latest data analysis indeed indicates that the sediment supply is increasing (see section 20.2).

These are some reasons why numerical models for the study of morphodynamic processes are believed to be a very useful tool. These models simulate the movement of water and sediments over periods of months to decades, depending on the specific research question, by solving the conservation equations of mass and momentum for water and the sediments. Several modelling initiatives have been undertaken over the past decade and will briefly be presented in the following sections.

20.5.4.1 French Guiana coast model

A 3D numerical model of the French Guiana coast was built by Chevalier et al. (2004) and further developed by Bourret et al. (2005 2008). The model covers most of the French Guiana coastline until the 100 m isobath line (**Figure 20.42 left**). This finite difference model was built to analyse the influences of river discharges and wind on the offshore current, salinity and temperature distribution. Special attention was paid to the treatment of the offshore boundary condition (passive or active boundary).

Numerical results (Bourret et al. 2008) point out the tidal currents are about 0.15-0.45 m/s on the inner shelf along the neap-spring cycle. They reach 0.55 m/s near Sinnamary and near the mouth of Oyapock river. Offshore tidal currents are weaker, 0.05-0.1 m/s, and the currents are then dominated by the oceanic circulation. The Guiana current can reach 1.1 m/s offshore and 0.3 m/s at 30 m depth. The surface salinity field (Bourret et al. 2008) describes a weak salinity tongue linked to two influences. The first one in the area between 10 and 20 psu (**Figure 20.42 right**) may be attributed to the Amazon influence. The second one in the area lower than 10 psu near the coast is due to the local river discharges.

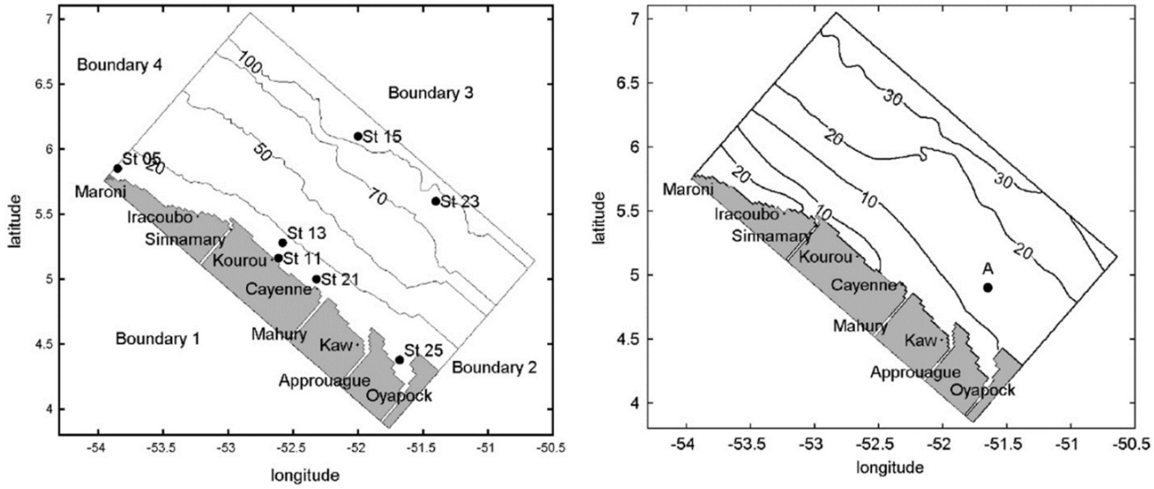

Figure 20.42 Numerical model of the French Guiana coast. Left: model domain and bathymetry (depth in meters); right: modelled field of sea surface salinity (in psu). (Bourret et al. 2008)

A smaller 3D model (**Figure 20.43**) was also built by Chevalier et al. (2008) to analyse the combined effect of the current and wave on the mud transport around mud bank. This model extends 60 km length alongshore and up to 25 m depth. Between 20 m depth and the coastline, the bathymetry is continuously changing due to banks mobility. As no regular survey of the bathymetry is performed, Chevalier et al. (2008) rather propose to work with an idealized bathymetry (**Figure 20.44**).

For this study, only hydrodynamics and suspended sediment concentrations were calculated. The influence of salinity and temperature have been neglected. Waves are modelled using Fudaa-Vag (CEREMA 2011) and the wave damping is integrated through the model of Rodriguez and Mehta (2001).

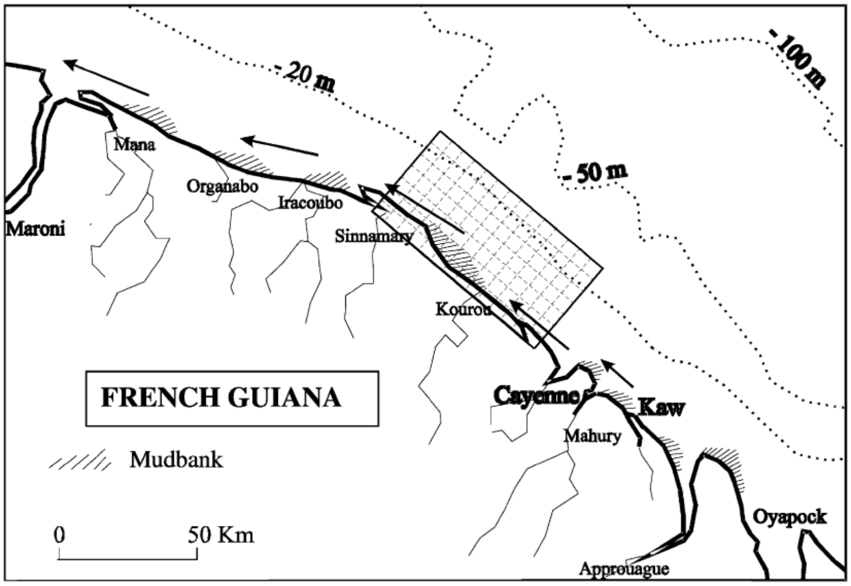

Figure 20.43 Situation of the mud bank model of Chevalier et al. (2008)

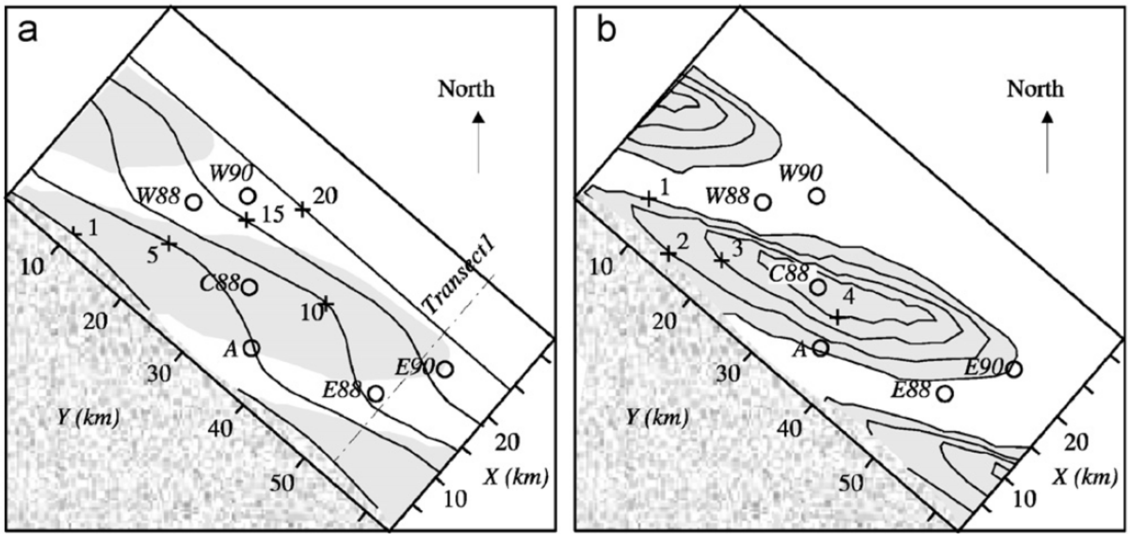

Figure 20.44 Mud bank model: a) idealized bathymetry; b) mud layer thickness contours (Chevalier et al. 2008)

The models (Chevalier et al. 2004 and 2008, Bourret et al. 2005 and 2008) allow to give general insight on the influence of the different forcing. However, full validation of these models were not feasible because of the lack of physical in situ data.

20.5.4.2 Mahury Estuary (French Guiana) model

A 3D numerical model of the Mahury Estuary (**Figure 20.45**) has been built in the framework of research on the accessibility of the port of Cayenne during a period of passage of a mud bank over the approach channel (Orseau 2016). The model is built with the TELEMAC software (www.opentelemac.org). The work here focusses more on the estuarine dynamic. In situ data sets collected by Orseau (2016) are exploited to perform calibration and validation of the model. The model extends 20 km alongshore20 km offshore and 40 km inland. The extension has been chosen according to the annual bathymetric surveys occurring around the navigation channel. The horizontal mesh (**Figure 20.45b**) comprises about 21 000 nodes. Simulations are run for 6 months with 8 vertical layers. For the turbulence, a mixing length model is selected with damping function to account for stratification.

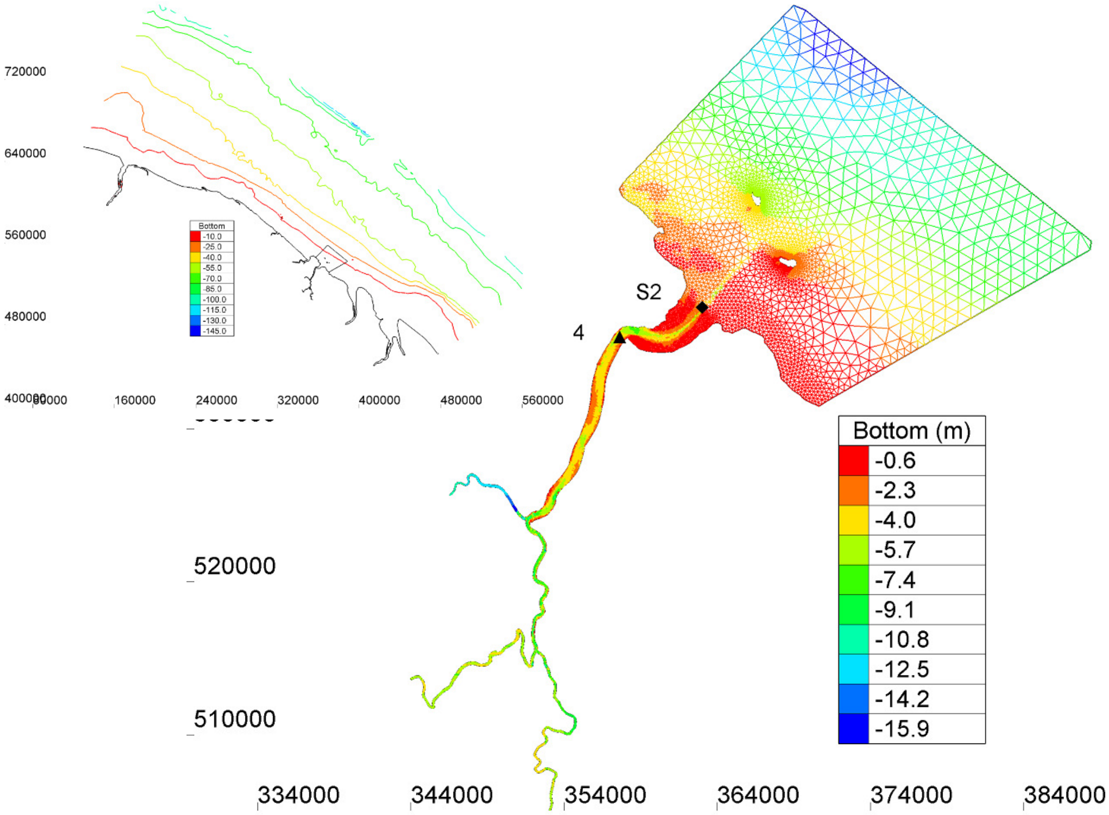

Figure 20.45 Numerical model of the Mahury Estuary: (left) situation and model extend, (right) the horizontal mesh. (Credit: S. Orseau, ULCO/CNRS/CEREMA)

Up to now, only the 3D hydrodynamic model has been validated in regards of salinity and current. **Figure 20.46** illustrates comparison of the modelled salinity with measurement (Orseau 2016) at the bottom on station S2 and S4 during a neap-spring cycle in the wet season. The 3D sediment transport model is still under development. In addition, it is also foreseen to build a larger scale model covering the whole French Guiana coastline which includes the Maroni and Oyapock estuaries. This model would serve to study the Maroni dynamics and to provide offshore boundary conditions to local estuarine model in term of salinity and SPM plume or wave forcing.

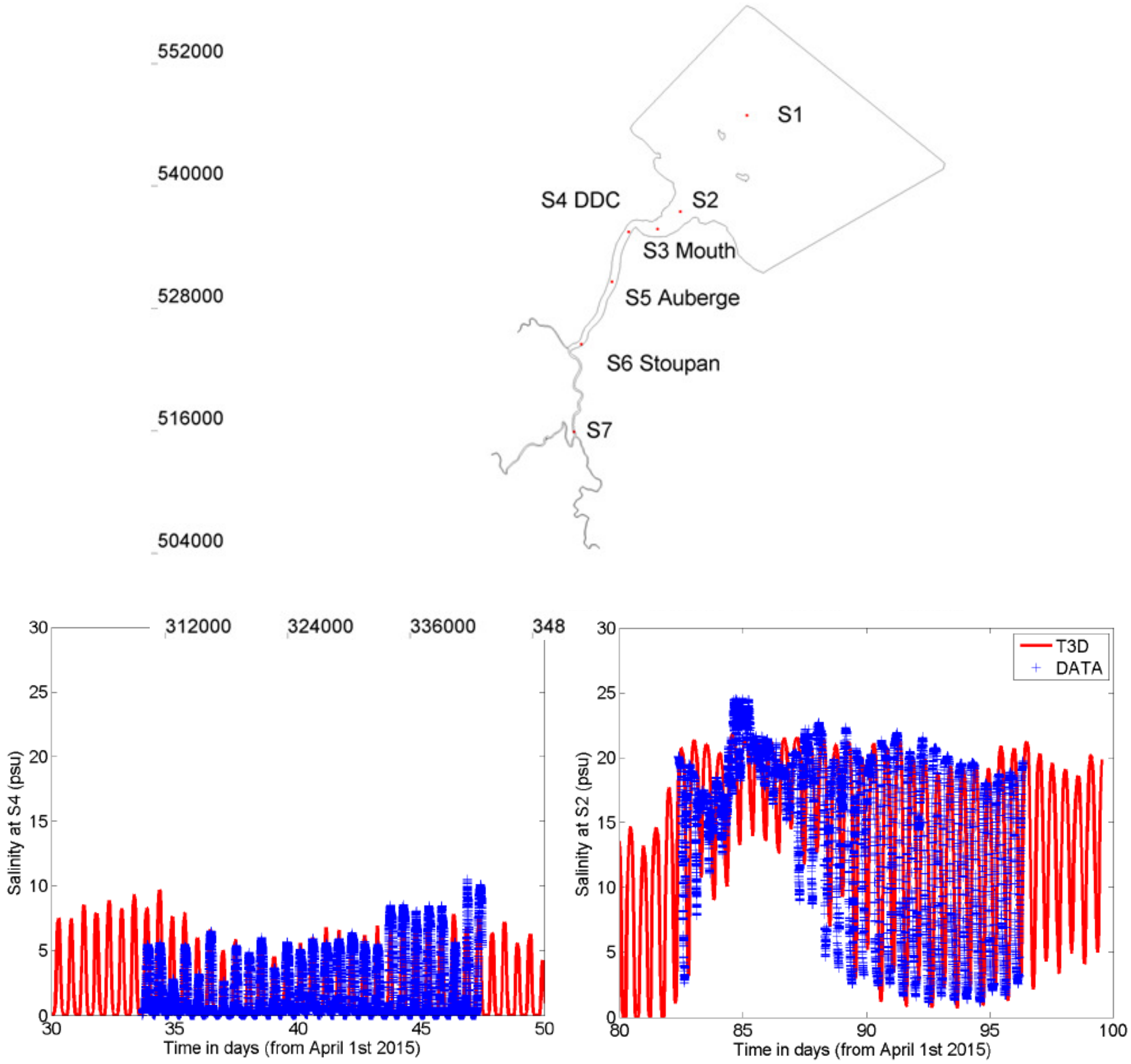

Figure 20.46 Location of the measuring stations (top). Time evolution of the salinity at the bottom: (left) at station S4 near the only harbour of French Guiana (left) and at the mouth (right). (Credit: S. Orseau, ULCO/CNRS/CEREMA)

20.5.4.3 Suriname coast model

The KU Leuven morphodynamic model for the Suriname coast has been under development since 2005 with the help of several MSc thesis projects (Gyssels and Van der Zype 2006; Dewaelheyns and Etneo 2007; Dirkx and Fockedey 2008; Hermans and Kroeders 2012; Pelckmans 2014) and an internship (Wongsoredjo 2017). The model is based on the open source TELEMAC software (www.opentelemac.org), using the hydrodynamic module TELEMAC (Hervouet 2007), the spectral wave module TOMAWAC (Benoit et al. 1996) and the sediment transport module SISYPHE. Several modifications to the code are developed and tested.

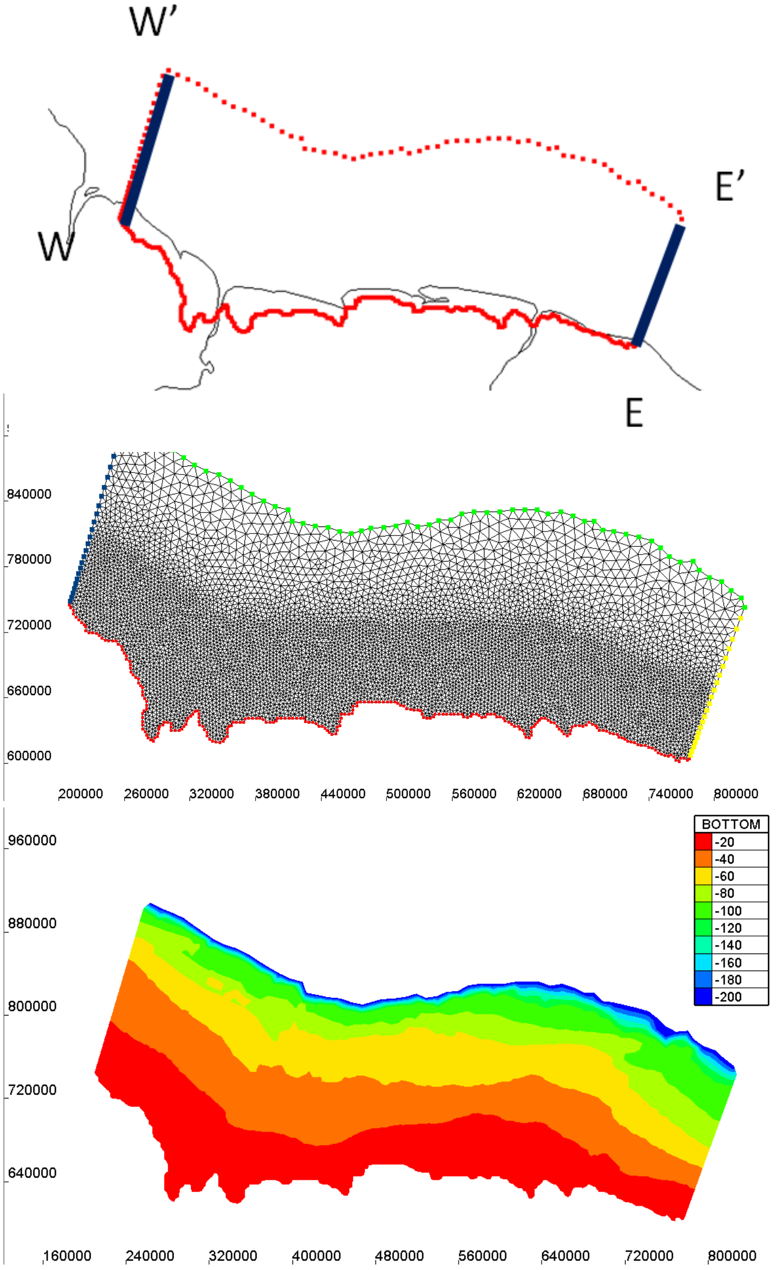

Figure 20.47 Suriname coast model: domain boundaries, relative to the actual coastline (top); numerical model mesh (middle) and bathymetry (bottom). (Credit: Hydraulics Division, KU Leuven)

The model domain (**Figure 20.47**) comprises the entire Suriname coast, from the Maroni river in the east, which is the border with French Guiana, to the Corentyne river in the west, which is the border with Guyana, and a part of each neighbour's coastline. The land boundary has been taken more inland, allowing to simulate inundation of the mangrove forests. The northern boundary is taken along the edge of the continental shelf.

Mud banks have been given different erosion properties than the interbank areas, since the former consist of soft mud, which is much more erodible than the overconsolidated mud layer exposed in the interbank areas. For this purpose, the mud banks had to be identified, which was done based on comparison of bathymetric data with satellite images (**Figure 20.48**).

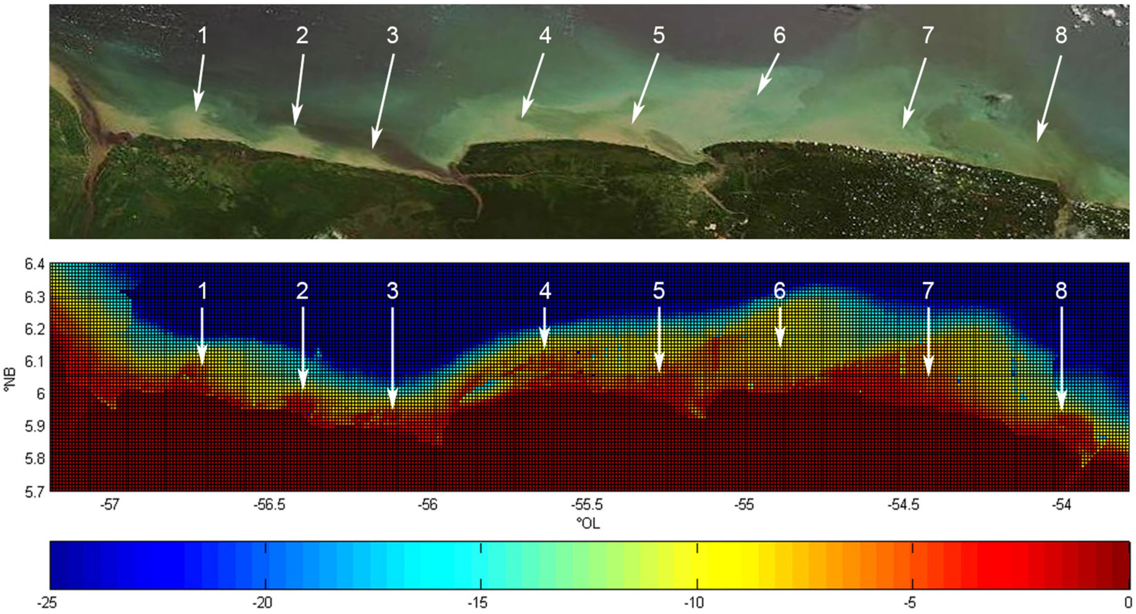

Figure 20.48 Upper image: MERIS satellite image of 1 August 2006 in visible spectrum (ESA Earth Online), lower image: bathymetry along the coast of Suriname in 2005 (the shift in location of the individual mud banks corresponds with the shift in time between both images) (Dewaelheyns and Etneo 2007).

Like for the other models, by lack of sufficient in-situ data for calibration and validation, only qualitative results have been obtained thus far. Future efforts will be dedicated to including wave damping by the mud banks. Subsequently, the model can be used for scenario studies to include sea level rise and subsequent inundation of the mangroves (cf. Lovelock et al. 2015). The mangrove field can be given a higher resistance by modification of the friction coefficients for currents and waves (Escobar Ramos 2017). The latter can be developed more accurately based on the recent work of Maza et al. (2015) where wave damping by regularly and arbitrarily distributed stems has been simulated in detail at the scale of laboratory flume studies.

20.5.4.4 Guyana coast model

In the framework of the *Institutional Capacity Building Activities on Guyana Sea Defences* project, carried out by the Dutch engineering consultants WL Delft Hydraulics (now Deltares) and Royal Haskoning, a modelling framework was developed to study 3D currents, waves and morphodynamics along the Guyana coast (de Graaff and Bijlsma, 2005; de Graaff 2005; Winterwerp et al. 2005) with the software Delft3D and SWAN (Booij et al. 1999). For this purpose the SWAN model was extended to allow simulation of wave damping by fluid mud (Kranenburg et al. 2011). Necessary data have been collected during various campaigns (Les and Westra 2004; Westra 2004). The model was aimed as research tool and as assessment tool for defining operational and extreme hydraulic conditions for the design of sea defence structures. Application of the model (**Figure 20.49**) has demonstrated that wave damping has to be accounted for in order to simulate observed conditions (Winterwerp et al. 2006). The model has subsequently been used to study the coastal evolution of the Guyana coast since 1950 (Welage 2005).

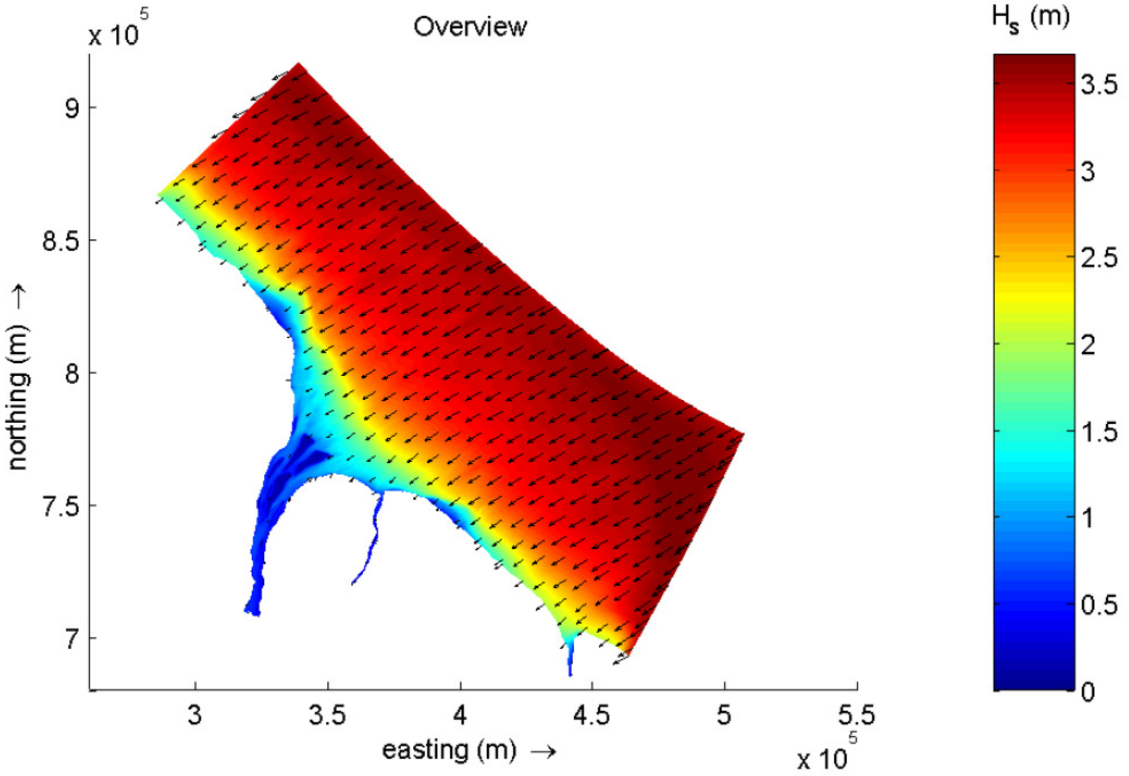

Figure 20.49 Modelled significant wave heights (m) in the detailed Delft3D Guyana model for a return period of 1 year and the dominant north-eastern wind and wave direction of 60°, including wave damping by fluid mud (de Graaff et al. 2005b).

20.6 Conclusions and Perspectives

The potential of mangroves to protect coastal areas is very site specific. In many studies only the interaction between vegetation and hydrodynamics is considered, forgetting that the local sediment dynamics should be taken into account in order to understand how the natural system works.

In the case of the Guianas coast, the interaction between these three key players: mangroves, hydrodynamics and sediment dynamics, is now quite well understood. The mangroves require (relatively) quiet hydrodynamic conditions in order to capture and stabilize sediments. This shelter is provided when a mud bank shields the mangroves from direct wave action. During interbank periods (when there is no protecting mud bank in front of the mangroves), the mangroves are slowly destabilized by wave action and washed away, and the coast erodes; i.e. on their own mangroves do not provide sustainable protection. In the Guianas there is an alternation of mud bank and interbank periods, a cycle of the order of 30 years. For an undisturbed mangrove belt, this results into a net accretion of the order of one meter per cycle, which is supported by geological evidence. Furthermore, there are indications that the sediment supply form the Amazon basin has been increasing significantly over the past decades, which raises hope that flood risks by potential sea level rise can be mitigated by nature itself.

The knowledge and understanding of these processes provide the necessary arguments to protect the mangrove belt as the most efficient, cost-effective and sustainable shore protection. Action needs to be taken to prevent further deterioration of the mangrove belt. Vulnerable places where the mangrove fringe has become too narrow or has been removed, are now considered for mangrove rehabilitation projects. Several pilot restoration projects are currently ongoing in Guyana and Suriname. Both mangrove rehabilitation projects do many efforts to realize community based mangrove management. They are working in the areas of administrative capacity development, monitoring and research, community development and capacity building, awareness and education.

The presented overview of recent research initiatives shows that much work still remains. Collection of field data and long-term monitoring remain too limited because of insufficient resources. Moreover, many places are difficult to access either from land or from the sea. Remote sensing plays an important role for filling up data gaps. They have already been used to analyse coastal erosion, mud bank migration and mangrove dynamics. They allow also the generation of instantaneous surface suspended sediment concentration maps for the entire coastal area (even though the conversion algorithms are still subject of research since they need improvement).

Development of numerical morphodynamic models for each of the Guianas is ongoing. Several interacting complex processes (i.e. interaction of waves with non-homogeneous fluid mud and of currents and waves with mangroves) are still difficult to be modelled correctly and require more fundamental research. Eventually, it is intended that operational models will become available to local authorities as decision support tools for coastal zone management.

Furthermore, scientific capacity building is locally realized through the international MSc program in "Sustainable Management of Natural Resources", taught in English at the Anton de Kom University of Suriname (http://vlir-iuc.uvs.edu/smnr/), established in 2007 with support of the University Development Cooperation division of the Flemish Inter-University Council (www.vliruos.be). In this program, a specialized training course on "Coastal erosion and protection" is taught in collaboration with hydrodynamic and morphodynamic experts from the Hydraulics Division of the Department of Civil Engineering from the KU Leuven (Belgium). This course provides the general theory on the interaction between hydrodynamics, morphodynamics and mangroves and is then applied specifically to the Guianas coast. Furthermore, it provides an introduction to field monitoring techniques, numerical modelling and field excursions.

The Guianas mangrove coast in many aspects is unique. Nevertheless, the ongoing research efforts and mangrove rehabilitation projects may provide important insights and lessons for other mangrove coastlines around the world.

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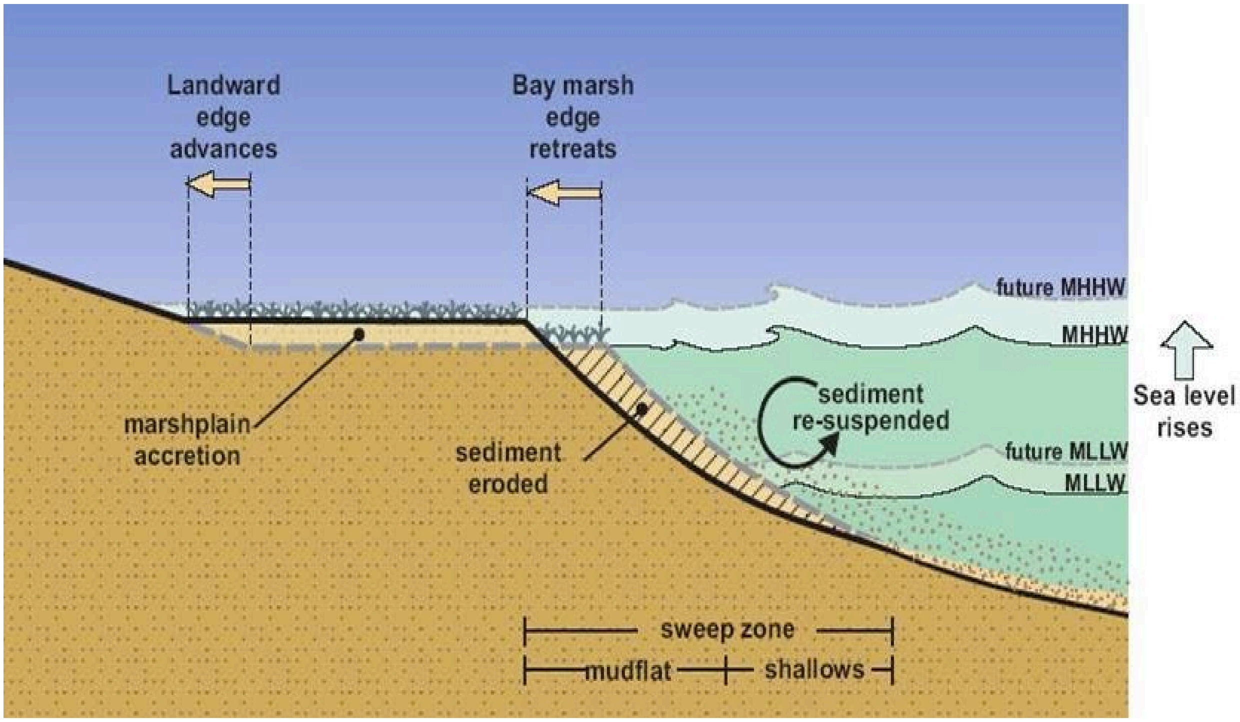
Appendix 2. Model Description: Coastal Wetland Soil Carbon Stock Accounting Tool

To:	North Brazil Shelf Mangrove Project Team
From:	Stephen Crooks Ph.D
Subject:	Model Description: Coastal Wetland Soil Carbon Stock Accounting Tool
Date:	May 11th 2019

Coastal Wetland Soil Carbon Stock Accounting Tool

Rationale

The purpose of this simple geometric model is to explore change in tidal wetland (marsh or mangrove) soil volume and carbon stock in response to sea level rise under a range of geomorphic parameters that influence wetland resilience (Figure 1).



Source: Environmental Science Associates

Figure 1. Conceptualization of tidal wetland landward transgression with sea level rise.

Model Construct

Figure 2 illustrates the model construct. The model describes a 1 m strip through a tidal wetland surface (B2-B3) width, set at model initiation. This wetland is bounded by an upland (A1-A2) and a mudflat (A4-A5), each with a definable slope. Tidal range and initial soil depth are definable parameters. Wetland surface is assumed to be at Mean High Water Spring Elevation (e.g., half the tidal range). The seaward edge of the wetland can be ascribed a cliff edge of zero or greater (B3 to B4). Soil depth (B3-A3) can be defined based on reference site conditions or set to a common reference depth of 1 m.

The model calculates annual time steps for a 100-year period change in soil volume, responding to wetland accretion capacity (set by a non-dynamic variable[1]), landward transgression (calculated from wetland surface elevation gain and upland slope), and wetland edge retreat.

Changes in soil carbon stock are based upon changes in soil volume and a carbon density variable. The fate of eroded carbon can also be set. For instance, an assumption could be made that 80% of eroded soil carbon is remineralized in well-oxygenated and energetic nearshore settings, or lower percentage for depositional sinks.

Wetland resilience to sea level rise and sensitivity to 'elevation capital'[2] can be explored by varying tidal range (which sets wetland elevation above mean tides [and assumes drowning elevation]), as well as definable wetland accretion and sea level rise parameters.

Outputs

The model provides visual and tabular outputs in annual timesteps (Figure 3) of:

1. Tidal wetland profile evolution – calculating location relative to initial condition back of the wetland, wetland edge as well as wetland width.
2. Tidal wetland volume – calculating net change based on surface accretion and edge erosion and landwards migration.
3. Tidal wetland soil carbon stock (per meter segment of wetland for a given width) based on changes in soil volume and a soil carbon density input.

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[1] The current version of the model does not represent suspended sediment delivery specifically but through a prescribed wetland accretion rate of 10 mm yr^{-1}. This is a simplification of a process known to be non-linear. The accretion rate value would be considered high in other locations but for the highly muddy coastline of the Guianas, this value is likely conservatively low. Future versions of the model may include variable accretion based upon wetland surface elevation relative to tidal frame and sediment concentration.

[2] Elevation capital reflects the height of a tidal wetland surface above the drowning elevation of the vegetation, and as such reflects the amount of sea level rise a wetland can accommodate before vegetation drowns.

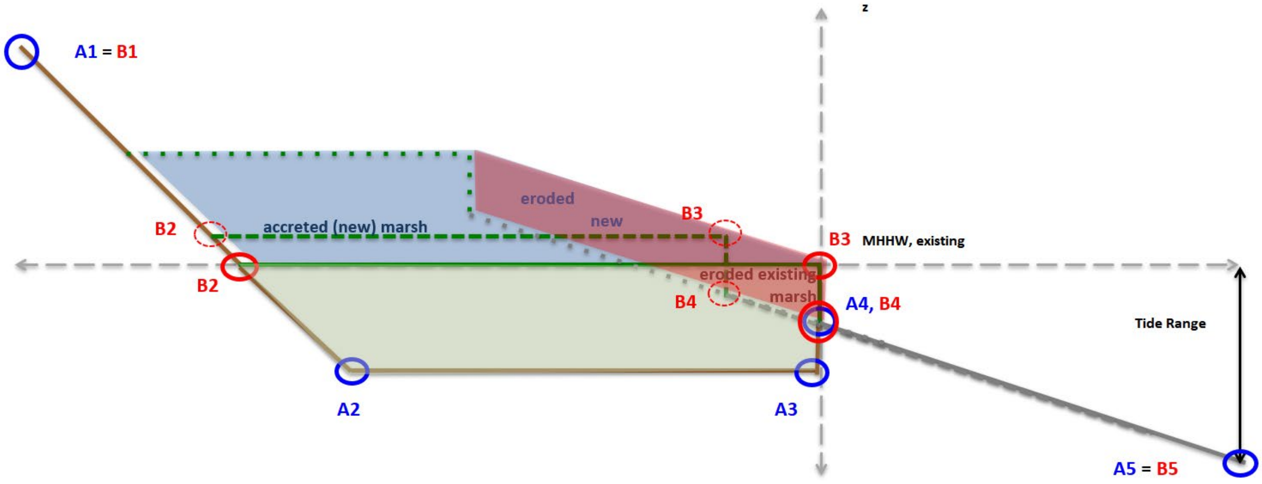


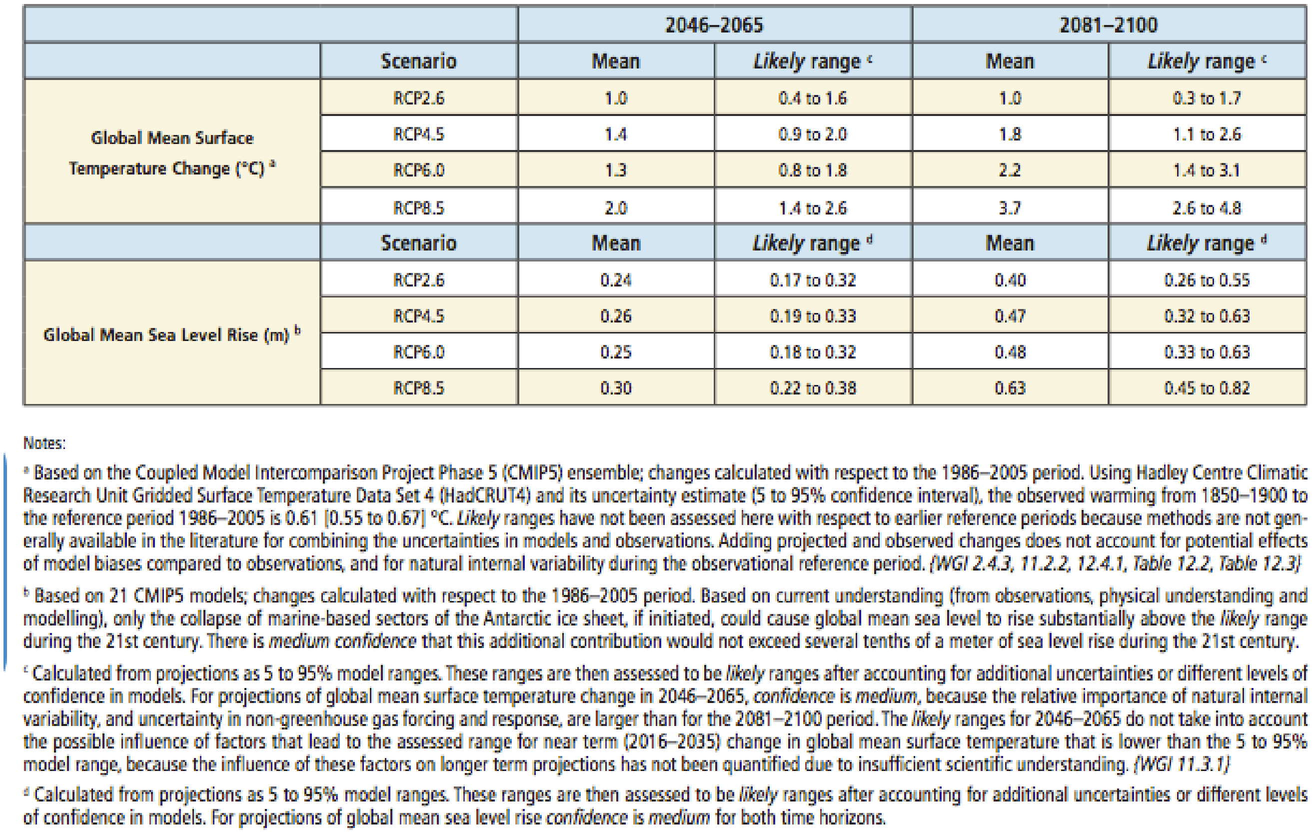
Figure 2. Model schematic.

Wetland edge erosion rate and distance may be set based upon:

1. The rate of sea level rise and the slope of a mudflat (e.g. to analyze geomorphic settings where mudflat elevation is in dynamic equilibrium with sediment supply and wave energy, and sediment supply is sufficient to maintain mudflat building with sea level rise).
2. A defined rate of lateral retreat (e.g. to analyze settings where either the slope is not defining the rate of wetland loss such as sheltered locations or a constructed intervention has been placed to protect the edge from erosion).
3. A combination of sea level rise and a defined lateral retreat (addition of one and two).

Three IPCC (AR5) eustatic sea level rise projections have been selected to bracket a range of low (RCP2.6 mean), medium (RCP8.5 mean) and high (RCP8.5 max) scenarios (Table 1, IPCC 2014).

Table 1 Projected change in global mean surface temperature and global mean sea level rise for the mid- and late 21st century, relative to 1995-2005 period (IPCC, 2014).



		2046–2065		2081–2100	
	Scenario	Mean	*Likely* range [c]	Mean	*Likely* range [c]
Global Mean Surface Temperature Change (°C) [a]	RCP2.6	1.0	0.4 to 1.6	1.0	0.3 to 1.7
	RCP4.5	1.4	0.9 to 2.0	1.8	1.1 to 2.6
	RCP6.0	1.3	0.8 to 1.8	2.2	1.4 to 3.1
	RCP8.5	2.0	1.4 to 2.6	3.7	2.6 to 4.8
	Scenario	Mean	*Likely* range [d]	Mean	*Likely* range [d]
Global Mean Sea Level Rise (m) [b]	RCP2.6	0.24	0.17 to 0.32	0.40	0.26 to 0.55
	RCP4.5	0.26	0.19 to 0.33	0.47	0.32 to 0.63
	RCP6.0	0.25	0.18 to 0.32	0.48	0.33 to 0.63
	RCP8.5	0.30	0.22 to 0.38	0.63	0.45 to 0.82

Notes:

[a] Based on the Coupled Model Intercomparison Project Phase 5 (CMIP5) ensemble; changes calculated with respect to the 1986–2005 period. Using Hadley Centre Climatic Research Unit Gridded Surface Temperature Data Set 4 (HadCRUT4) and its uncertainty estimate (5 to 95% confidence interval), the observed warming from 1850–1900 to the reference period 1986–2005 is 0.61 [0.55 to 0.67] °C. *Likely* ranges have not been assessed here with respect to earlier reference periods because methods are not generally available in the literature for combining the uncertainties in models and observations. Adding projected and observed changes does not account for potential effects of model biases compared to observations, and for natural internal variability during the observational reference period. *{WGI 2.4.3, 11.2.2, 12.4.1, Table 12.2, Table 12.3}*

[b] Based on 21 CMIP5 models; changes calculated with respect to the 1986–2005 period. Based on current understanding (from observations, physical understanding and modelling), only the collapse of marine-based sectors of the Antarctic ice sheet, if initiated, could cause global mean sea level to rise substantially above the *likely* range during the 21st century. There is *medium confidence* that this additional contribution would not exceed several tenths of a meter of sea level rise during the 21st century.

[c] Calculated from projections as 5 to 95% model ranges. These ranges are then assessed to be *likely* ranges after accounting for additional uncertainties or different levels of confidence in models. For projections of global mean surface temperature change in 2046–2065, *confidence* is *medium*, because the relative importance of natural internal variability, and uncertainty in non-greenhouse gas forcing and response, are larger than for the 2081–2100 period. The *likely* ranges for 2046–2065 do not take into account the possible influence of factors that lead to the assessed range for near term (2016–2035) change in global mean surface temperature that is lower than the 5 to 95% model range, because the influence of these factors on longer term projections has not been quantified due to insufficient scientific understanding. *{WGI 11.3.1}*

[d] Calculated from projections as 5 to 95% model ranges. These ranges are then assessed to be *likely* ranges after accounting for additional uncertainties or different levels of confidence in models. For projections of global mean sea level rise *confidence* is *medium* for both time horizons.

Source: IPCC 2014

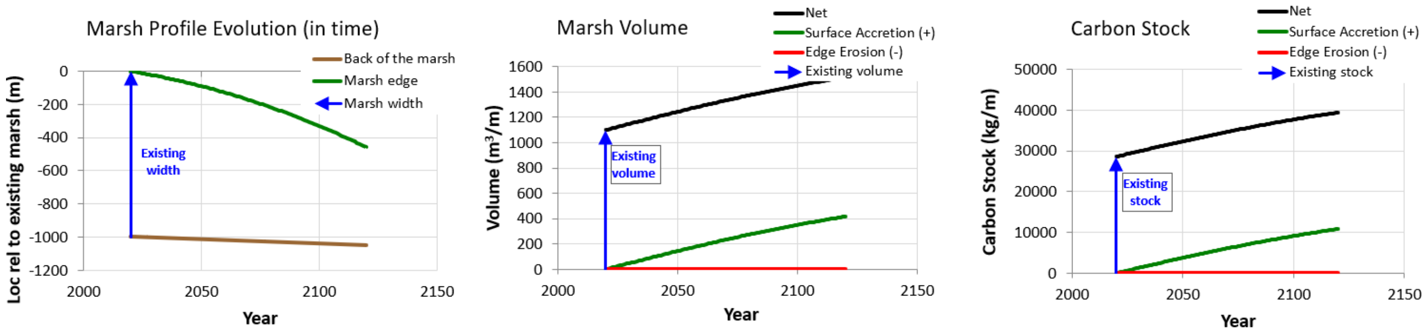


Figure 3. Model outputs.

Closing

The model inputs are uncalibrated but based upon best judgement to represent the coastal conditions and to test sensitive to a high rate of sea level rise scenario. Calibration of the model can be improved with data on shoreline topography and bathymetry, time averaged surface water suspended sediment concentrations and regional sea level rise rates.

For additional information on geomorphic modeling for coastal systems see:

Deng, Junjie & Woodroffe, Colin & Rogers, Kerrylee & Harff, Jan. (2017). Morphogenetic modelling of coastal and estuarine evolution. Earth-Science Reviews. 171. 254-271. 10.1016/j.earscirev.2017.05.011.

Whitehouse, R.J.S, Cooper, N., Pethick, J., Spearman, J., Townend, I.H. and Fox, D. Dealing with geomorphological concepts and broad scale approaches for estuaries. In: 40th Defra Flood and Coastal Management Conference, 5 - 7 July 2005, York, UK. http://eprints.hrwallingford.co.uk/75/

Literature Cited

IPCC. 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 [Core Writing Team, R.K. Pachauri and L.A. Meyer (eds.)]. IPCC, Geneva, Switzerland, 151 pp.

Appendix 3. NBS-LME Coastal Wetland Soil Carbon Stock Accounting Tool Application

To:	North Brazil Shelf Mangrove Project Team
From:	Stephen Crooks Ph.D
Subject:	NBS: Coastal Wetland Soil Carbon Stock Accounting Tool Application
Date:	May 11th 2019

This memo describes an application of the Coastal Wetland Soil Carbon Stock Accounting Tool (CWSCSAT) to a hypothetical shore profile on the North Brazil Shelf. Though the model is uncalibrated, it is possible through explicated assumptions and available information to investigate the sensitivity of the shoreline and mangroves to sea level rise. Key parameters that drive sensitivity to sea level rise are explored.

Model setup

Fixed variables: C density (0.026 g cm^{-3}); oxidized fraction of remobilized C (80%); erosion mechanism (scenario 1 based upon mudflat slope and rate of sea level rise); rate of sea level rise – high (AR5 RPC8.5 max).

Additional information: Mean Spring Tide Range set conservative at 2 m[3].

Tested Scenarios

A base model setup is provided in Figure 1. For the basis of comparison, an assumed mangrove width of 3,000 m is applied, incorporating a transition to coastal swamp forest. The mangrove is assumed to transition to open mudflat at a 1 m cliff. The slope of adjacent upland is 1:100 and mudflat 1:200. Sea level rise is assumed to rise at a high rate and attain 1.22 m above present levels by the year 2120 to test sensitivity to greatest extent of sea level change over a century. Initial elevation of the mangrove surface is set at 1 m above mean sea level.

Observations from model

1) With a tidal range of 2 m, the mangrove likely has meaningful elevation capital to maintain the forest against sea level rise over the coming decades. The average elevation of the mangrove soil surface is not known. Applying an assumption that much of this surface is at least 1 m above mean sea level, and that the mangrove has a minimal capacity to build soil at 10 mm

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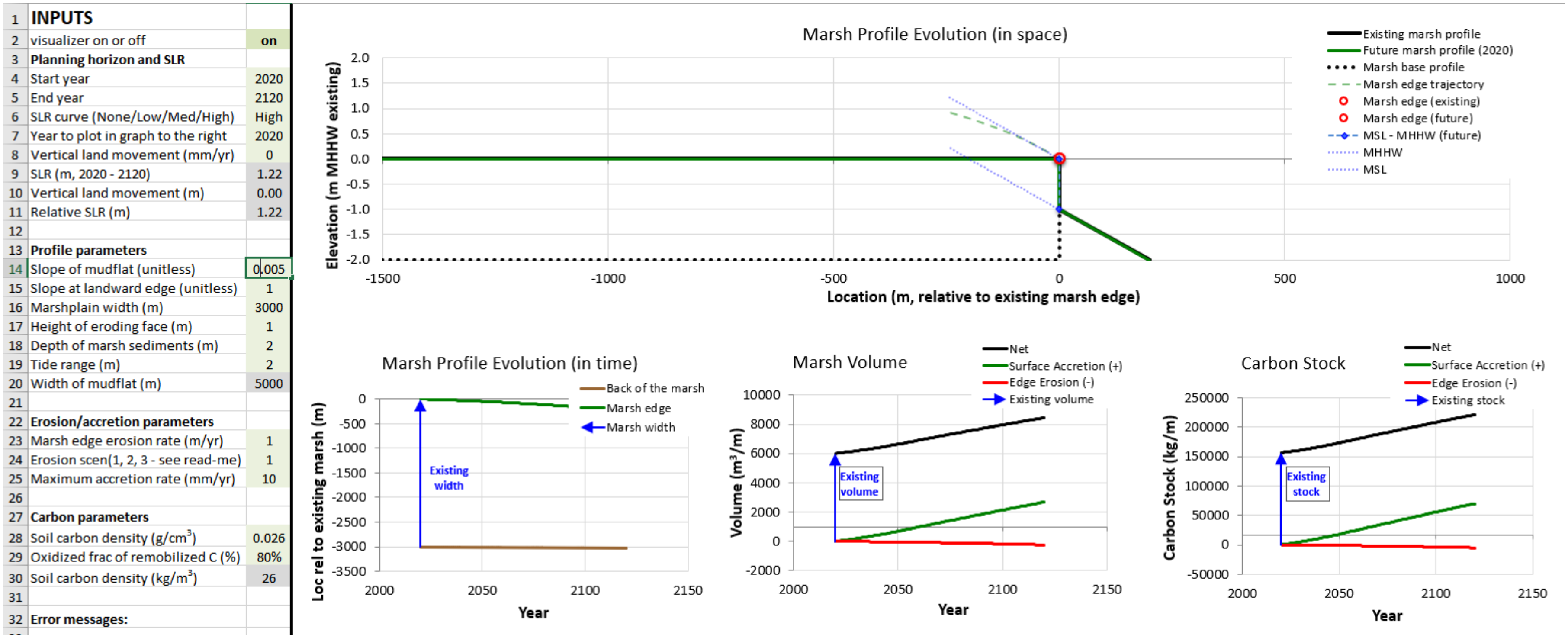
[3] 10 mm yr^{-1} soil building through mineral sediment deposition is an atypical value for many parts of the World but here we consider this assumption to be reasonable if not conservative.

yr-^{1} would keep the mangrove above drowning elevation through 2120. Even with retreat of the mangrove edge (243 m over 100 years), the mangrove – coastal forest will be a net sink of carbon both over a crediting period of 20-50 years and over the 100-year timeframe.

2) Figure 2 illustrates the implications of sea level rise if the mangrove has 50 cm of elevation capital rather than 100 cm. Under both conditions, the mangrove would not drown within the 100 year time frame. Gain of soil carbon across the mangrove surface would exceed losses at the eroding edge.
3) The scale of existing intact coastal forest along much of the NBS-LME coastline is a benefit to potential carbon management. Reducing mangrove width to 500 m from 3,000 m, a gradual carbon accumulation is calculated that declines towards zero at the end of the century and carbon loss with erosion from the mangrove edge exceeds carbon accumulation on the surface (Figure 3). Nevertheless, under modeled conditions, a 500 m width of mangrove would not be a net source of soil carbon over the 100-year timeframe.
4) Figure 4 explores the sensitivity of the carbon stock losses to assumptions about the morphology of the mangrove edge and mudflat slope. The base model assumes a 100 cm high slope break at the edge of the mangrove. The morphology of the slope break can vary considerably depending upon tidal range, wave exposure, capacity of the mangrove to build and maintain an edge in an erosional environment and the mudflat dynamics in response to increased wave energy. In this case, difference in carbon stock change trajectories are insignificant.
5) Figure 5 illustrates the sensitivity of carbon stock calculations associated with assumptions about dominant slope of intertidal mudflat. Shallowing the intertidal slope from to 0.002 (1:500) from 0.005 (1:200) and maintaining sea level using the high RCP 8.5 max scenario trajectory results in a retreat of the mangrove edge by 609 m compared with 243 m for a wide carbon stock. There is minimal difference in net soil carbon stock over the long term driven (220,968 versus 209,486 tC per unit width of mangrove) driven by assumptions of mangrove capacity to build with sea level rise even as the edge retreats.



1	**INPUTS**	
2	visualizer on or off	on
3	**Planning horizon and SLR**	
4	Start year	2020
5	End year	2120
6	SLR curve (None/Low/Med/High)	High
7	Year to plot in graph to the right	2020
8	Vertical land movement (mm/yr)	0
9	SLR (m, 2020 - 2120)	1.22
10	Vertical land movement (m)	0.00
11	Relative SLR (m)	1.22
12		
13	**Profile parameters**	
14	Slope of mudflat (unitless)	0.005
15	Slope at landward edge (unitless)	1
16	Marshplain width (m)	3000
17	Height of eroding face (m)	1
18	Depth of marsh sediments (m)	2
19	Tide range (m)	2
20	Width of mudflat (m)	5000
21		
22	**Erosion/accretion parameters**	
23	Marsh edge erosion rate (m/yr)	1
24	Erosion scen(1, 2, 3 - see read-me)	1
25	Maximum accretion rate (mm/yr)	10
26		
27	**Carbon parameters**	
28	Soil carbon density (g/cm^3)	0.026
29	Oxidized frac of remobilized C (%)	80%
30	Soil carbon density (kg/m^3)	26
31		
32	**Error messages:**	

Figure 1: Illustration of the model setup. Within the model, initial mangrove surface elevation (and hence elevation capital) is set by adjusting tidal range. Here the mangrove surface is 1 mMSL (m above mean sea level) and an accretion rate of 10 mm yr^{-1} maintains vegetation at or just above the mangrove drowning elevation by year 2020. Retreat of a 0.5 m high cliff mangrove edge by 609 m with sea level rise over a century leads to release of soil carbon, 80% of which is assumed to be mineralized.

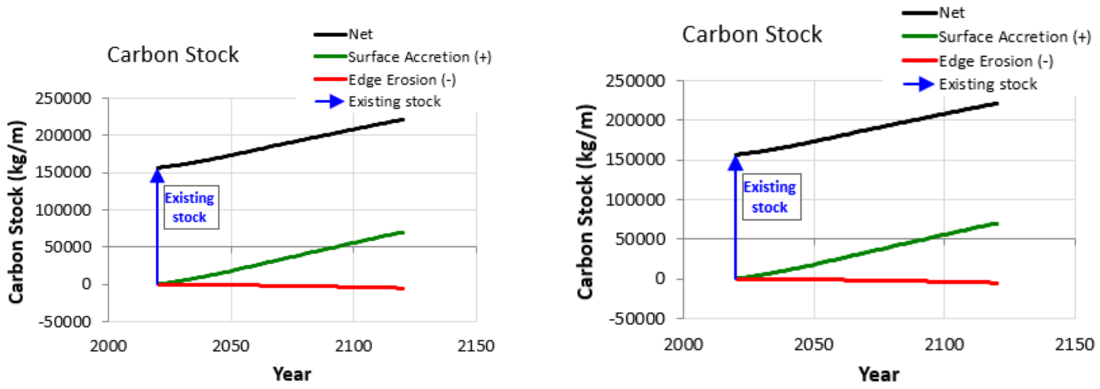


Figure 2. Model estimates of mangrove soil C stock change over 100 years: mangrove width = 3,000 m, with (left) elevation capital = 1 m and (right) elevation capital = 0.5 m.

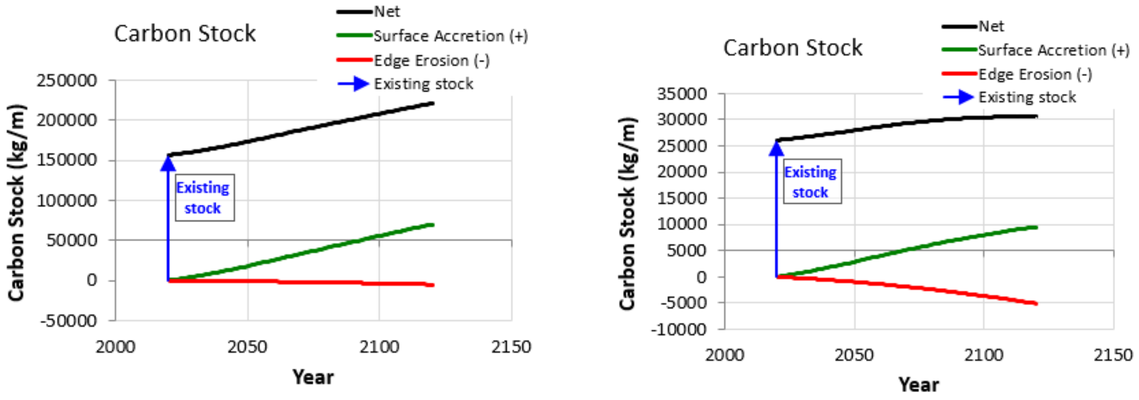


Figure 3. Model estimates of mangrove soil C stock change over 100 years: elevation capital 1 m, with (left) mangrove width = 3,000 m and (right) mangrove width = 500 m.

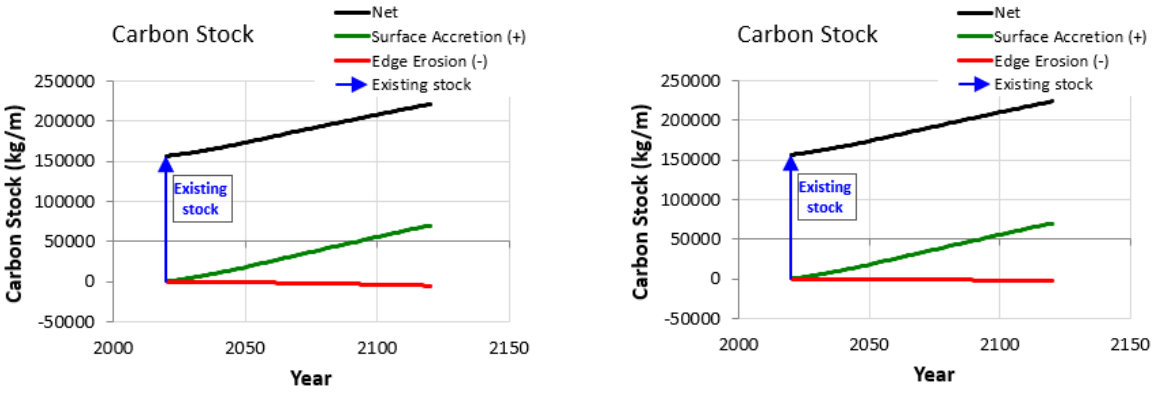


Figure 4. Model estimates of mangrove soil C stock change over 100 years: elevation capital = 1 m and mangrove width = 3,000 m, with an edge cliff reduced in height from (left) 0.5 m to (right) 0 m.

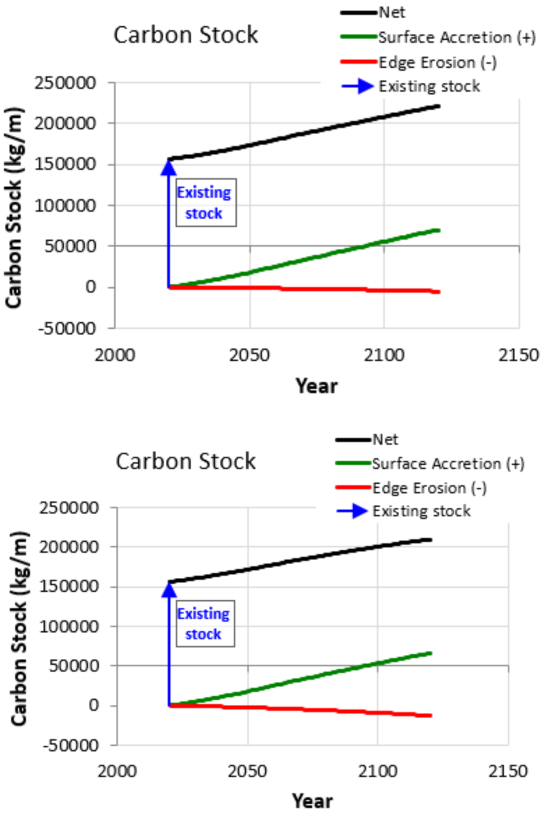


Figure 5. Model estimates of mangrove soil C stock change over 100 years: elevation capital = 1 m and mangrove width = 3,000 m; the mudflat slope decreases from (left) 1:200 to (right) 1:500 with a cliff edge height increased to 1 m.