Assessment of peri-urban coastal protection options in Paramaribo-Wanica, Suriname

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1. Background and Summary

The goal of this report is to inform the Surinamese Government and Public on peri-urban coastal protection options that include mangrove systems, and the necessity for mangrove conservation, these systems being a fundamental element of the coast of Suriname. The expertise proposed for the Suriname coast notably covers the following themes: (1) the Suriname coastal system and the role of mangroves in this system; (2) the importance of mangroves as 'soft' ecosystem engineers in coastal protection; and (3) the impacts of mangrove removal and the short- to long-term costs of coastal protection options (a: mangrove conservation; b: mangrove replanting; c: dykes; d: mangroves and dykes).

The work has been based on comprehensive facts, evaluations, and presentations drawn from: (1) personal expertise; (2) gathering of additional information, through consultation and exchanges with relevant agencies, interest groups and individuals; (3) field visits to the Paramaribo-Wanica coast site (Weg Naar Zee and neighbouring sites updrift and downdrift), and the Coronie coast. Convincing arguments for protecting mangroves are presented via the following:

(1) A simple but thorough explanation on how the Suriname coast functions and the role of mangroves in the short- to long-term functioning of this coast. This knowledge is based on nearly 2 decades of research on the dynamics of the Amazon-Orinoco coast with several publications on the subject (see Annex: expert's publications on the Guianas coast and on mangroves).

(2) A presentation of the importance of mangroves in ecosystem services, including, notably, coastal protection and the promotion of sedimentation, and the economic value of mangroves, using existing information in the literature, and from Suriname and the rest of the Guianas coast. This point demonstrates how mangroves actually play an important role in coastal protection on the Suriname coast within a framework of abundant but pulsed mud supply alongshore.

(3) Since dykes are being considered as a coastal protection, their short- and long-term costs (construction and maintenance) and impacts are demonstrated. Emphasis has been placed on showing how dykes replacing mangroves can actually generate greater liquefaction of mud, precluding sedimentation, and thus accelerating coastal erosion, in contrast to mangroves as efficient agents in the dissipation of wave energy. The sea-level scenario for the coast of Suriname is also highlighted, as it is important when considering the long-term sustainability of a dyke-versus mangrove scenario in coastal protection. The pitfalls and costs of mangrove replanting, following their eradication, are shown. The joint use of mangroves and dykes is now becoming an option commonly used in certain countries, including neighbouring Guyana. The implications, advantages (relative to a dyke-alone solution) and pitfalls of this mixed soft-hard approach are discussed.

The deliverables have been in the form of: (a) 2 draft fact sheets of 2 pages each on items 2 and 3 above; (b) PPT presentations on items 1, 2, 3; (c) this comprehensive final report with recommendations based on expertise, field visits and meetings with various actors and stake-holders on the coastal system and mangroves in Suriname. It is hoped that the generation of these comprehensive communication tools will not only help clarify aspects of the functioning of the unique coastal system of Suriname (common to the Guianas coast) but also the importance of a having a short- to resolutely long-term perspective of the future evolution of this coast by building up scenarii that critically examine mangrove conservation and the environmental impacts of dykes.

Summary

The 350 km long coast of Suriname is part of a unique system in the world characterized by large-scale muddy sedimentation in spite of the exposure of the coast to waves from the Atlantic. The coastal deposits form the Young (5-6000 years old) and Old Coastal Plains. The growth of this plain has been assured by mud supplied by the Amazon River in Brazil and transported westwards towards the Orinoco. The mud is organized into a series of banks that migrate along the coast under the influence of waves and currents. In 2012, there were nine mud banks identified on the Suriname coast. The mud banks are separated by 'inter-bank' zones, which also change in position as the banks migrate. In this unique system, mangroves play an important role by stabilizing the inner part of each mud bank and ensuring plant 'continuity' with the older muddy shoreline, from which subsequent mangrove regeneration is best assured by propagule dispersal. This role of mangroves means, in essence, that the inner part of mud banks becomes welded to the coast, thus creating new land (a process called progradation) that is added to the growing Young Coastal Plain. Much of the urban development of Paramaribo and other coastal towns is on the Young Coastal Plain. The relationship between mud banks, mangroves and the growth of the coastal plain is, thus, important in understanding the past, present and future state-of-health of the coast, as in the Paramaribo-Wanica area.

Mangroves in Suriname cover an estimated 100.000 ha, which is about 1.6-2% of the world's mangroves. They form large, variably wide (up to several km) stands of 'fringe' mangroves of *Avicennia germinans* throughout the coast of Suriname and are associated, in places, where erosion prevails, with sandy beach deposits called cheniers or 'rits'. In addition to their role in building the Young Coastal Plain in Suriname, mangroves provide several major ecological functions and services in Suriname. These include, notably, protection of the shoreline from erosion, provision of spawning zones and nurseries for coastal fisheries, and a habitat for millions of migratory shorebirds, breeding water birds and other wildlife. Mangrove efficiency in coastal protection has been demonstrated in numerous scientific studies, especially following the 2004 Indian Ocean tsunami. The protection role is assured not only by living mangroves, but also by dead and dying mangroves through their foliage, trunks and roots. Efficiency has been demonstrated to increase with wider, thicker (healthy) mangroves. Recent observations of inter-bank erosion in an area of shoreline formerly occupied by rice fields in French Guiana (Mana rice fields) following large-scale mangrove and backswamp clearing, has shown that shoreline retreat rates are extremely high (up to 180 m a year) in the absence of mangroves. Such retreat rates exceed usually observed retreat rates in the presence of mangroves (up to 40 m a year).

Removal of mangroves has been carried out in a number of areas along the Suriname coast, notably north of Paramaribo, where this practice is now going on at a very large scale under the impetus of building societies, thus leading to increasing urbanization at the expense of mangroves. This removal also goes with an increasing call for the building of dykes for coastal protection, echoing a move that has, unfortunately, not been a viable solution in coastal protection in neighbouring Guyana where dykes have largely replaced mangroves on the coast, and where mangroves are now being replanted. In Suriname, before choosing the dyke option, there is a need to have a very serious prior reflection on:

(1) the causes of shoreline erosion, which depend on the overarching influence of bank and inter-bank dynamics that are complex in time and space. A lack of understanding of this system could lead to poor judgment of options of protection;
(2) a cost-benefit analysis that also should consider the viability of the dyke option (including long-erm maintenance and sea-level rise scenarios). Dykes are costly and necessitate regular maintenance over time. They are static engineering structures in a highly dynamic environment and this is reflected in constraints that need to be carefully calculated such as bearing capacity,

hydraulic failure, sliding, breakage, and sinking. The view that a dyke, once constructed, is not necessarily an absolute protection barrier against marine flooding, and eventual damage and casualties, must be kept in mind and inculcated in people living behind the protection of dykes;

(3) dykes have an impact on the shoreline environment, especially on mangroves, as shown by experience from the Guyana coast. They may contribute to the formation of an erosive, concave foreshore profile because of wave energy reflection (case of many dykes in Georgetown, Guyana). Dykes may act as barriers that impede mangrove propagule exchange between mature forests behind the dyke and a new mud bank that is waiting to be colonized. They may also impede freshwater supply from inland to pioneer and young mangroves.

A mixed coastal protection option involving more or less wide swathes of mangroves fronting dykes is implemented in several countries, notably in Asia, the Mekong River delta in Vietnam providing fine examples. This mixed approach, wherein such dykes are built behind mangroves, is, in itself, demonstrative of the usefulness of mangroves in dissipating wave energy and protecting the coast. From modelling efforts and field observations, this solution requires that all the constraints related to dyke construction and maintenance are not overlooked, and the mangrove fringe fronting the dyke is sufficiently wide and healthy. In reality, dyke building commonly leads to the narrowing of this fringe. Where mangroves have been removed, their rehabilitation through replanting is a complex and delicate issue. The success rate in Guyana in 2012 ranged from 0 to 60% success.

Summary of recommendations

- Mangroves have played an active geological role in the building of the Young Coastal Plain in Suriname over the last 5-6000 years. This role needs to be understood and highlighted as an important part of any future coastal zone management initiative in Suriname. Greater citizen awareness, and participatory involvement of all parties and local communities on the way the Suriname coast functions, and the importance of mangroves in the development of the coast, need to be fostered.
- Mangrove conservation will necessitate the implementation and enforcement of setback lines beyond which urban development should be prohibited.
- A dyke solution as coastal protection, nor even a mixed dyke-mangrove solution, are not recommended, as it makes no sense destroying mangroves to replace them with dykes that are very costly in the long run, while mangrove replanting in areas where dykes are emplaced and the foreshore eroded is only feasible at great coast.
- An observatory of the coast of Suriname, alongside other initiatives such as the Mangrove Forum of Suriname, needs to be set up, as a there is an acute need for data on which to base coastal zone management decisions on this highly dynamic coast.

2. Introduction: the environmental context of Paramaribo-Wanica

The districts of Paramaribo and Wanica, which are part of the urban areas of the city of Paramaribo, capital of Suriname (population in 2012: 240,000) lie on the ***Young Coastal Plain of Surinam***. This coastal plain is part of the mud-dominated Atlantic coast of northern South America between Amapá, in Brazil, and the Paria Peninsula in Venezuela (Fig. 1). This coast is the terminus of rivers draining the Andes, the Andean foreland, the Llanos, and the Brazil and Guiana Shields. By far the most important of these rivers is the Amazon, which dominates the muddy fine-grained sediment dispersal and the geological development of this coast. The resulting sediment accumulation pattern has been significant coastal progradation (seaward growth of the coast) along much of the 1500 km of coast from Amapà to the Orinoco delta, including Suriname over the last 5-6000 years, since sea level reached about its present position. Much of this progradation, which presently forms the Young Coastal Plain on which Paramaribo is built, has occurred through onshore welding of mud derived from massive mud banks that migrate from the Amazon (Fig. 2).

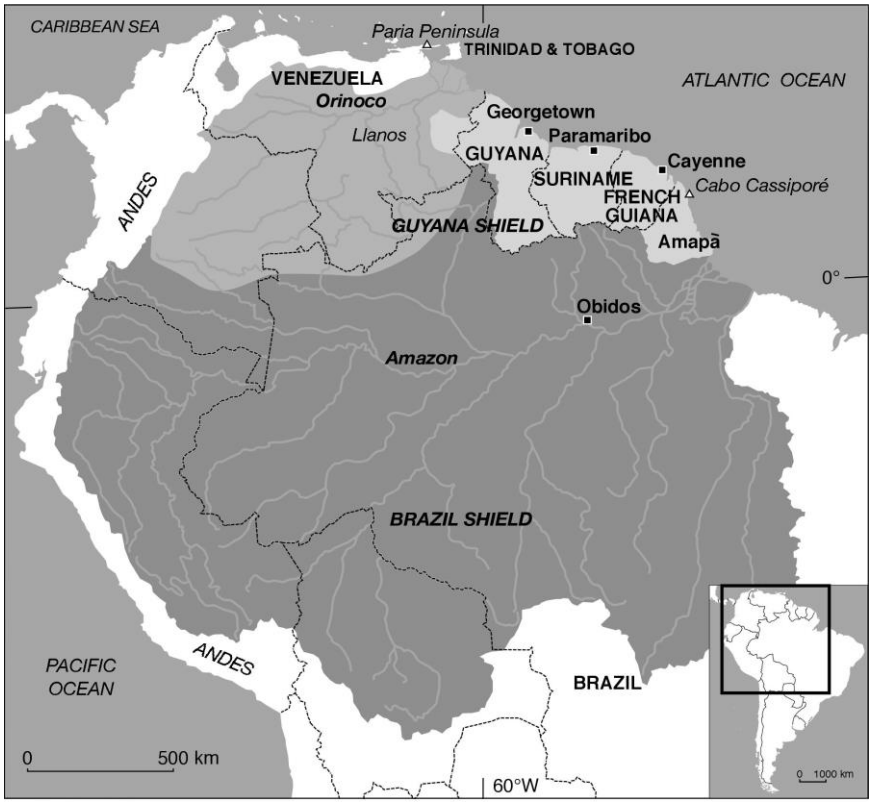

Fig. 1. Map showing Suriname and the Amazon-Orinoco coast, and, in three shades of grey, the drainage basins of the Amazon, the Orinoco rivers and, collectively, the smaller Guiana Shield rivers between Amapá, in Brazil, and Guyana.

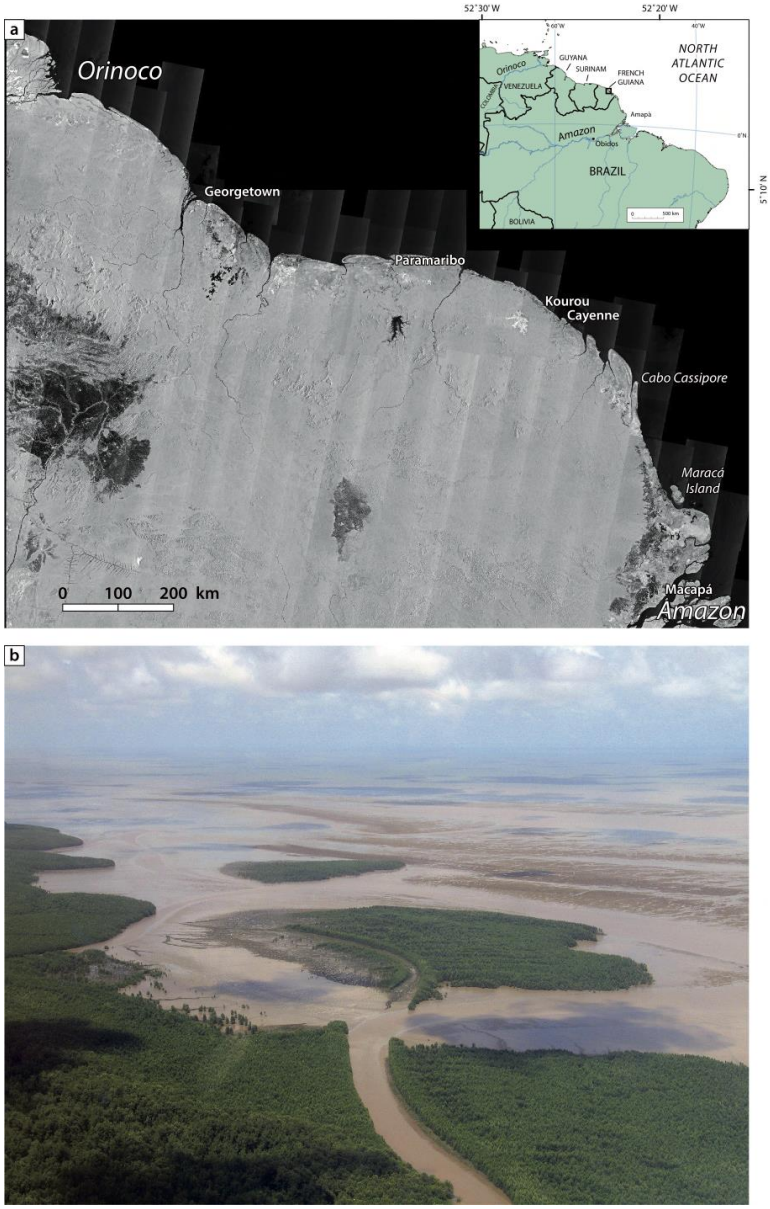

Fig. 2. A JERS-1 satellite image of the muddy Amazon-Orinoco coast, the world's longest muddy coast. Mud banks start forming in the Cabo Cassipore area in Brazil. The oblique aerial photograph shows a typical mud bank in French Guiana partly colonized by mangroves and cut by drainage channels. The bare part of the mud bank in the background shows a series of linear mud bars. This mud bank is one of several banks migrating at any time from the mouth of the Amazon River in Brazil to that of the Orinoco River in Venezuela. From Anthony et al. (2010).

The mud-bank system is unique in the world in terms of both the magnitude of mud migration alongshore and the mud dynamics, as a result of the extremely large and pervasive supply of mud by the Amazon. The rivers in Suriname essentially drain the Guiana Shield, and thus supply sand-sized sediments that, together with the mud supplied alongshore from the Amazon, have contributed in building up the Suriname coastal plain. Among these rivers is the Suriname River, on the west bank of which Paramaribo has developed.

The Amazon is the world's largest river system and has a drainage basin of 6.1 x 10^6 km^2 (Organization of American States, 2005). A recent estimate of the mean annual water discharge of the river at Óbidos, 900 km upstream of the mouth, has been set at 173,000 $m^3.s^{-1}$ (Martinez et al., 2009). Recent estimates of sediment discharge range from 754 to 1000 x 10^6 $t.a^{-1}$ (Martinez et al., 2009; Wittmann et al., 2011). The Amazon also discharges the highest total sediment load to the global oceans because of both this large drainage basin and a high total runoff of 6300 $km^3.a^{-1}$, although the specific sediment yield of 190 t $km^{-2}.a^{-1}$ corresponds to the world's average (Milliman and Farnsworth, 2011). Martinez et al. (2009) have shown that the liquid discharge is relatively regular whereas sediment discharge shows more significant inter-annual variability.

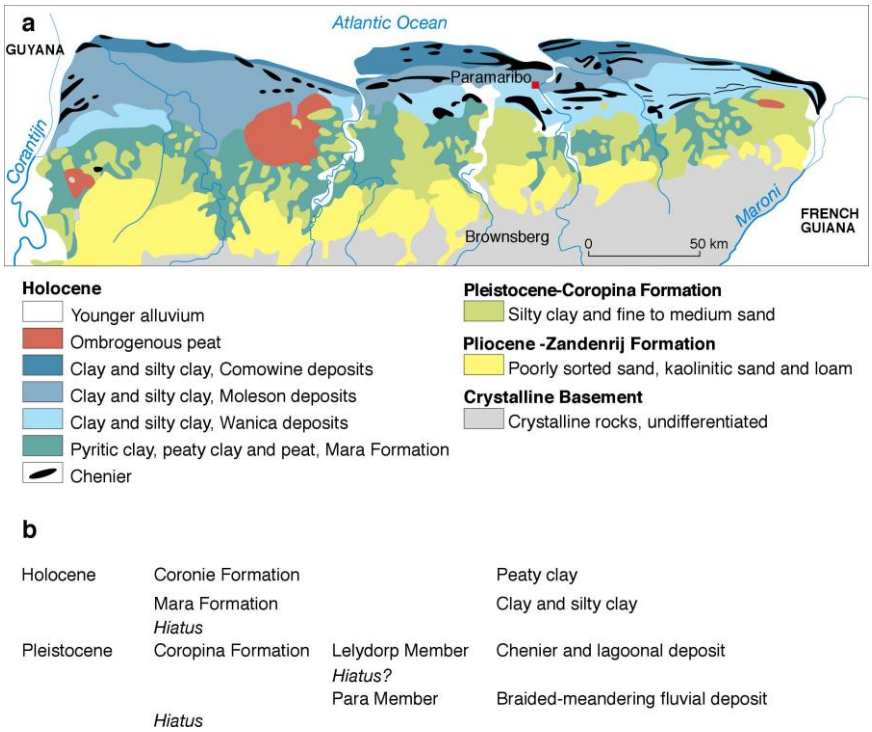

Fig. 3. Coastal geology of Suriname. (a) Holocene deposits of the present (Young) coastal plain, and Old Coastal Plain deposits of Pleistocene (Coropina) and older age. (b) Stratigraphy of the Pleistocene and Holocene deposits. (Modified from Wong et al. 2009).

Within the muddy coastal plain of the Guianas, sandy beach deposits, called "cheniers" in the international literature, and "RITS" in Suriname, are common in the vicinity of the larger river mouths, especially in Suriname and Guyana, reflecting an important contribution of the Guiana Shield rivers such as the Suriname River to the coastal depositional system of the Guianas coast (Anthony et al., 2014). The muddy Holocene-to-modern (5-6000 years) progradational system and its incorporated rits have been shown to have operated also during earlier periods, according to work in Suriname (Wong et al., 2009), where the Coropina Formation largely constitutes the Old Coastal Plain, which is of Pleistocene age (> 70-100,000 years old), formed during a previous sea-level phase similar to the present. The Young and Old Coastal Plains (Fig. 3) are chronologically separated by a long phase of several

tens of thousands of years during which sea level was lower than today by at least 100 m and the rivers drained across the present continental shelf to the Atlantic Ocean.

3. Waves and mud-bank migration in Suriname

Beyond their overarching importance in the recent geological history of the Suriname coast, the mud banks from the mouths of the Amazon have, by virtue of their sheer volume and alongshore migration, an overwhelming impact on the Suriname coast. Their interaction with waves induces rapid shoreline accretion and/or erosion, as well as important ecological changes involving the development and destruction of mangrove forests (see section 3). This cyclic instability also strongly impacts on the coastal economy of Suriname, as of all the countries between the mouths of the Amazon and the Orinoco: Brazil, French Guiana, Guyana and Venezuela.

The mud banks affecting the Suriname coast start forming in the Cabo Cassipore area in Brazil (Allison et al., 1995), a muddy cape 350 km northwest of Maracá Island at the mouth of the Amazon, and where up to 150 x 10^6 tons of mud (ca. 15-20% of the annual mud discharge) may be stored in a year. The northwest flow of the sediment-charged water occurs in a narrow coastal band from January to April (Molleri et al., 2010), in response to both the strong mud discharge during these months of the year (51% on average according to Martinez et al., 2009) and the annual peak in trade winds and wave activity. The Suriname coast is affected by trade winds from the northeast that are mainly active from January to May (Fig. 4). These winds generate rains on the coast from December to July, with an intervening relatively dry month in March. The annual rainfall in the coastal zone varies from 2 to 3 m. Ocean wind stress by these trade winds generates strong flow of the North Brazil Current along the coast (Geyer et al., 1996). Trade winds are also the main generators of waves from the North and Central Atlantic Ocean affecting the Suriname the coast. These waves come from an east to northeast direction (Gratiot et al., 2007). Waves have significant periods (T_s) of 6 to 10 s, and significant offshore heights (H_s) of 1 to 2 m, the longer periods (> 8 s) being associated with short spates of large swell waves generated by North Atlantic storms in autumn and winter and by Central Atlantic cyclones in summer and autumn. These longer waves have a directional range from north to north-northwest. The most energetic trade-wind waves occur from December to April whereas swell waves appear to be most frequent in autumn and winter, reinforcing the relatively energetic winter to early spring wave regime induced by the trade winds. Tides are semi-diurnal and the spring tidal range in Suriname is microtidal to low-mesotidal (about 1.5 to 3 m). The Suriname coast is, thus, essentially a “wave-dominated coast” (Fig. 4).

An unanswered question concerns how discrete mud banks are formed from the mud stored in the Cabo Cassipore area. Anthony et al. (2010) concluded that seasonality in mud discharge from the Amazon is not responsible for bank successions. This conclusion was based on the estimated volume of a typical mud bank and on the fact that up to 15+ mud

banks, spaced at intervals of 15 to 25 km, migrate at any time along the Guianas coast at rates of 1 to 5 km.a^{-1} (Gardel and Gratiot, 2004, 2005). Between 2006 and 2010, for instance, the 350 km-long coast of Suriname had up to 9 mud banks migrating alongshore (Fig. 5). The bank migration time from the Cabo Cassipore area to the mouths of the Orinoco varies thus from 250 to 900 years, i.e., about 50-250 years along the coast of Suriname. ***This is an important point when subsequently trying to understand the problems of coastal protection faced by the Paramaribo-Wanica districts in Suriname***.

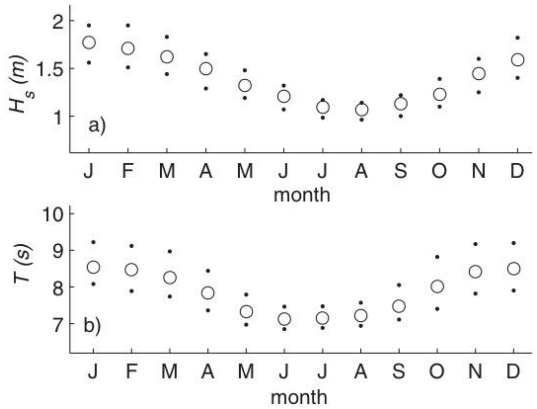

Fig. 4. The wave climate off the coast of Suriname (modified after Gratiot et al., 2007). Daily averages of wave-climate parameters, significant wave height H_s and significant wave period T_s, derived from a 44-year record of the ERA-40 (European ReAnalysis) wave dataset generated by the European Centre for Medium-Range Weather Forecasts (ECMWF) for the location 5° N, 52° W. Dots correspond to the first and third inter-quartiles, and circles to the median values. The climate is dominated by moderately long waves generated by northeast trade winds, and comprises longer swell waves generated in the Central and North Atlantic. The Suriname coast is, thus, a "wave-dominated" coast.

Each mud bank can be up to 5 m thick, 10 to 60 km long and 20 to 30 km wide. A bank migrating alongshore is separated from its neighbours along the coast by inter-bank areas where erosion prevails (Fig. 6). ***Since the banks migrate alongshore, the shoreline at any point will swing over time between bank (accretion) and inter-bank phases (erosion)***. The duration of each of these phases at any point on the coast depends on the size of a bank and its migration rate, such that accretion (bank) or erosion (inter-bank) can prevail at any location along the coast for decades. The timing between banks ranges from 10-40 years. The volume of each bank contains from the equivalent of the annual mud supply of the Amazon to several times this annual supply. The time period of formation between two banks is therefore not determined by fluctuations in the mud supply of the Amazon, which is pervasively high, as seen previously, but in meso-scale (decadal-to-multidecadal) coupled atmospheric-oceanographic interactions involving changes in trade-wind intensity and their effect on the waves generated by these winds, as hypothesised by Eisma et al. (1991), and subsequently by Allison et al. (2000) and Augustinus (2004). According to recent work by Walcker (2015) and Walcker et al. (2015), such multidecadal changes in wind intensity are very likely related to the North Atlantic Oscillation, commonly referred to as the NAO. By

inducing variations in wind speed, the NAO oscillations thus influence the rate at which mud banks migrate, and this has consequences on the dynamics of the coast and of mangroves, as shown in a subsequent section.

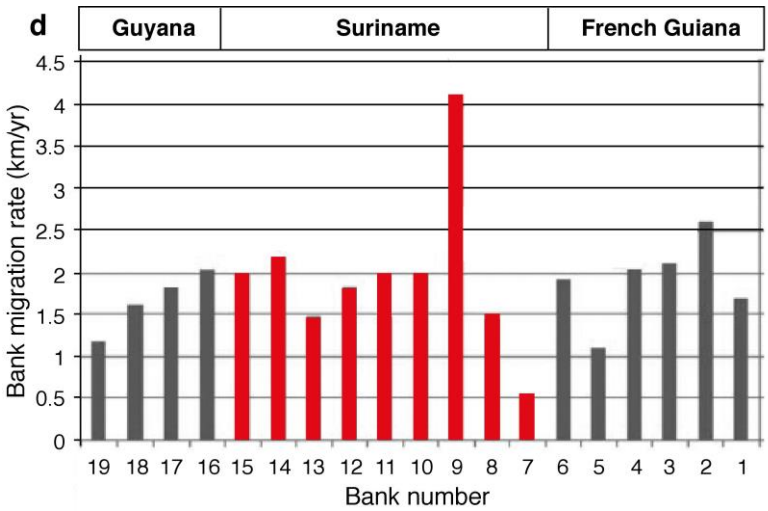

Fig. 5. Rates of migration of 19 enumerated mud banks from French Guiana to Guyana, averaged between 2006 and 2010. Nine of these were migrating along the Suriname coast. Modified from Gensac 2012.

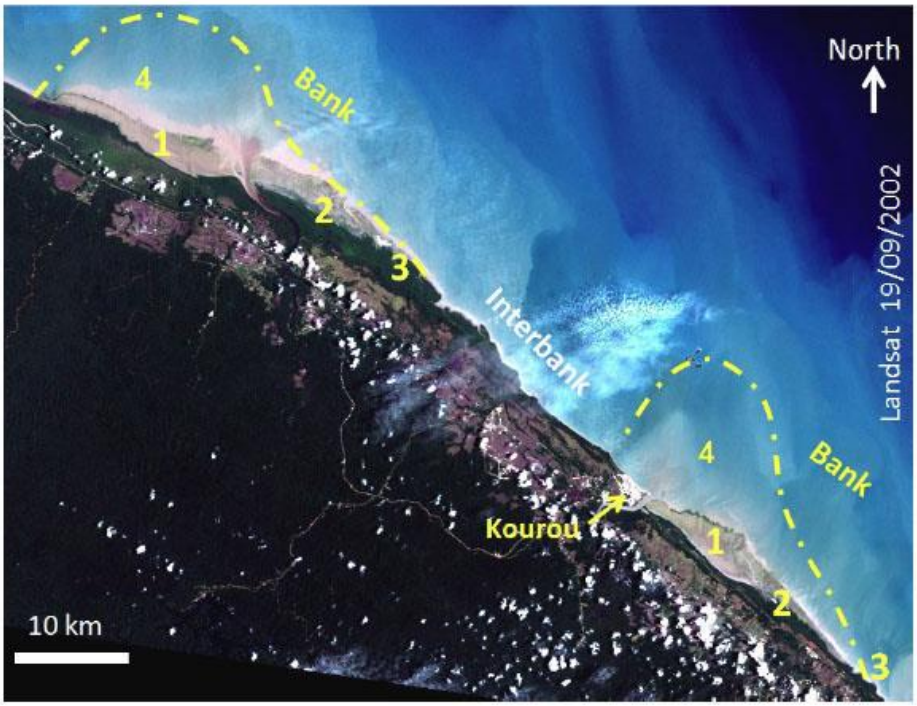

Fig. 6. A satellite image of two successive mud banks in central French Guiana separated by an inter-bank zone. (1) bare intertidal mudflat, (2) mudflat being colonised by mangroves, (3) mud-bank trailing edge undergoing erosion, and (4) a subtidal leading edge sector. From Anthony et al. (2014).

Once formed, the mud banks translate alongshore under a continuous process of recycling by waves (Fig. 7). This migration is assured by wave dissipation, and by wave- and wind-induced currents. Gratiot et al. (2007) showed that notable phases of increased wave energy were accompanied by higher annual rates of alongshore mud-bank migration, but these authors found a poor correlation between the wave forcing parameter, a combination of wave height (*H*) and period (*T*), H_0^3/T^2, and migration rates, because of the contribution of other mechanisms to bank migration, including wave incidence angle and wind stress. Other potential sources of migration-rate variability are rock outcrops in French Guiana, and river mouths (Gardel and Gratiot 2005; Anthony et al., 2013). The migrating mud banks tend to imprint a northwest deflection of the river mouths on the coast (Fig. 2). This is the case, for instance, of the Suriname River (Fig. 3), the deflection commonly forming a more or less pro-eminent muddy cape colonized by mangroves, and which generally provides shelter for parts of the coast to the west from direct attack by trade-wind waves coming from the northeast. Paramaribo is niched on the west bank of such a cape deflection of the Suriname River.

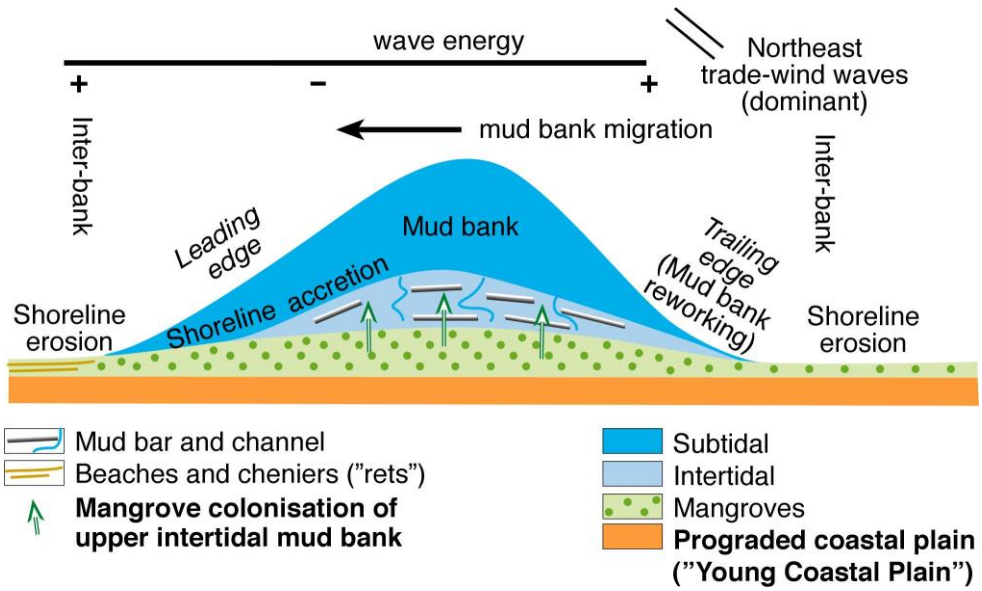

Fig. 7. Schematic of a typical mud bank showing its dynamics combining wave reworking of the bank surface, shoreline accretion and erosion, and mangrove colonisation and removal, all of which are embedded in the bank migration process. Wave breaking and dissipation lead to the mobilisation of mud patches and mud bars near the terrestrial shoreline where accretion in the upper intertidal zones paves the way for rapid and large-scale mangrove colonization that ultimately leads to 'welding' of part of the vegetated bank onto the terrestrial shoreline, resulting in the creation of new land (land-building role of mangroves) that contributes to the growth of the Young Coastal Plain. Inter-bank erosion is an integral part of the mud-bank migration process. The extent to which the shore-welded part of a mud bank is preserved from erosion in the inter-bank area in the course of the bank migration process determines the degree of coastal progradation generated by each bank. By dissipating wave energy, mangroves slow down this erosion process until the next bank phase (coastal protection role of mangroves). Modified after Anthony et al. (2014).

The large liquid discharge of the bigger rivers (1700 m^3 per second, for instance, for the Maroni (Marowijne) River on the French Guiana-Suriname border) appears, however, to generate what can be called a “hydraulic-groyne effect” (Anthony et al., 2013), wherein the strong river-mouth outflow acts just like a groyne. A groyne is an engineering structure built more or less perpendicular to the shore, and is generally aimed at blocking the alongshore drift of sediment and/or protecting parts of the coast situated on the down side (called the ‘downdrift’ side) of a coast relative to the angle of wave incidence. Such a “hydraulic-groyne” effect leads to specific forms of river-mouth sedimentation, including the formation of sand banks (Fig. 8) that act as a fluvial sand supply reservoir for the construction of beaches adjacent to the river mouths and cheniers (rits) further downdrift (towards the west) along the coast in inter-bank zones and, therefore, during inter-bank phases. This effect may also be responsible for:

(1) persistent muddy accretion on coastal sectors updrift of the large river mouths by slowing down the migration of mud, encouraging updrift mud concentration and hindered muddy sedimentation downdrift as a result of significant offshore deflection of the mud banks in transit alongshore, as schematised in Fig. 8; this phenomenon thus goes with the formation of mild river-mouth mud capes for some of the moderately sized rivers such as the Suriname;

(2) temporary and partial liquefaction (disintegration) of mud banks.

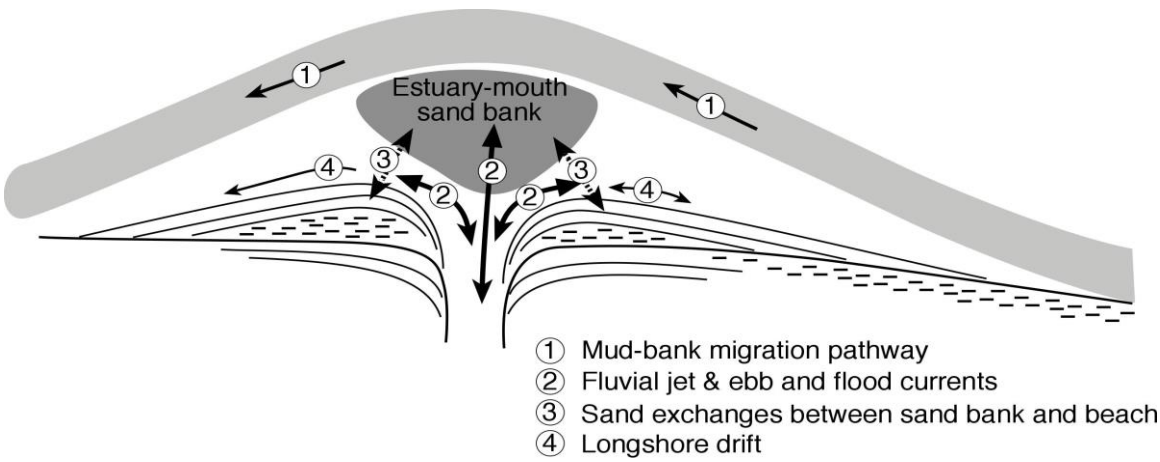

Fig. 8. Schematic illustration of the “hydraulic-groyne effect” in river mouths on the Guianas coast. The strong river-mouth outflow (1) acts just like a groyne, liquefying and diverting offshore the migrating mud bank (2), leading to specific forms of river-mouth sedimentation, including the formation of sand banks that act as a fluvial sand supply reservoir for the construction of beaches adjacent to the river mouths and cheniers (rets) further downdrift (towards the west) along the coast in inter-bank zones (3,4).

The "hydraulic-groyne effect" is potentially an important aspect to consider in attempting to understand, in a section below, the specific local context of the Paramaribo-Wanica sector of the coast and its long-term (multidecadal) behaviour.

Mud banks have been shown to respond in a non-linear way to wave stress. Beyond a threshold forcing, the mud viscosity decreases considerably, and this could, in turn, strongly affect mud-bank migration rates (Fiot and Gratiot, 2006). A decrease in mud viscosity could also be induced by large local river discharge through the "hydraulic-groyne effect" (eg. Suriname River). The ensuing differences in migration rates may account in part for variations in the spacing between the banks, and possibly variations in bank morphology, notably where mud banks are 'stretched' alongshore. The role of variations in trade-wind activity and wave incidence, notably on the Suriname coast, in fluctuations in bank migration rates has been suggested by Eisma et al. (1991) and Augustinus (2004). Another 'bank-stretching effect' may be related to greater liquefaction of the banks favoured by large-scale anthropogenic modifications of the shoreline that notably involve mangrove removal. This aspect may be expected on the Guyana coast where much of the shoreline is lined with dykes. It is discussed further in section 4.5.

Given the volume of mud contained in each mud bank, the alongshore migration process does not involve an 'en masse' movement, but rather recycling and transport of mud by incident waves (Fig. 7) that reach the coast at an angle (obliquely-incident waves). The dynamic interactions between waves and the mud bank substrate depend on both the wave energy regime and mud concentration, which generally ranges from very high-suspended sediment concentrations (1-10 g per litre), through fluid mud, to settled mud, which, in turn, ranges from under-consolidated (≤650 g per litre) to over-consolidated beds (≥750 g per litre). These levels of concentration and consolidation depend on various conditions such as proximity to the shore, elevation above the low-tide level, rainfall, the degree of mangrove colonization, and processes of liquefaction by waves (Gratiot et al., 2007). Regarding wave energy, observations carried out in French Guiana show that the mobilization of mud can be particularly significant following long periods of low waves, essentially during the dry season from July to October, and during small (neap) tides. On such occasions, even moderate-energy waves, generally in autumn, can generate significant mobilization of mud. Periodic longer swell waves from the North Atlantic, such as those reported by van Ledden et al. (2009), are also expected to cause sometimes massive and sudden reworking of mud-bank sediments and of muddy inter-bank shores. The commonly sudden onshore arrival of fluid mud, or sudden phases of coastal erosion are, thus, generally caused by such higher-energy pulses.

The relationship between mud banks, mangroves and the growth of the coastal plain is important in understanding the past, present and future state-of-health of the coast, as in the Paramaribo-Wanica area. An early conception of this relationship was that a mud bank was a feature welded to the shoreline. A later conception is that the mud bank is disconnected from the shoreline, and sediment reaches the upper intertidal zone to generate accretion (sediment accumulation) of the shoreline by fluid mud being driven

onshore during periods of stronger waves and large (flood) tides. In reality, the relationship between a mud bank and the shoreline is more a mix of these two conceptions, rather than either. Although fluid mud is recycled onshore such that the terrestrial part of the bank over which this mud is recycled may be disconnected (notably, but not exclusively) in the low-lying subtidal to low intertidal seaward and leading (front) edges of a bank, widespread mangrove colonization constitutes a mechanism of onshore welding of the higher accreted landward edge of a bank (Fig. 7).

Over large parts of the bank surface, fluid mud pushed shoreward by breaking and dissipating waves during the neap-to-spring tide cycle results in overall accretion and increase in elevation of the bank. Near Cayenne in French Guiana, we identified a sequence wherein a 1-3 m-thick mud layer liquefied by the cyclic wave pressure drifted shoreward *en masse* over a period of 80 days (Gratiot et al., 2007). The mobilized mud layer formed a mud bar feature that was translated shoreward as gel-like fluid mud, especially when high waves prevailed. Subsequent observations, analysis of water levels on SPOT images, Lidar data, and high-resolution topographic monitoring surveys of bank surfaces (Fig. 9) have shown that mud bars constitute a fundamental feature of wave-mud interactions, while also playing a significant role in mangrove colonization (Anthony et al., 2008; Proisy et al., 2009; Gardel et al., 2011). The gel-like mud forming these bars becomes progressively consolidated in areas where the wave energy has been completed dissipated. Although these linear features generally occur as shore-parallel bodies in the inner mud bank areas near the terrestrial shoreline (Fig. 10), bar-like features with an angular offset relative to the terrestrial shoreline are observed at the eroding trailing (back) edges of mud banks, where they are reworked by the obliquely incident trade-wind waves from the northeast. Successive bands of linear shore-parallel bars may reflect successive phases of wave-induced shoreward transport of mud under variations in wave energy and in the neap-spring tidal cycle. Topographic variability in these bars is further enhanced by dissection by drainage channels. Field measurements and remote sensing observations suggest that the bars have a feedback influence on subsequent patterns of accumulation of fluid mud that leads to accretion of the bank surface, as well as on the development of the intricate network of channels that drain the mud bank, and finally, on the way mangroves colonise the mud banks (Fig. 9).

An inter-bank area occurs in the wake of the trailing edge of each bank, which is an eroding part of the bank (Figs. 6, 7). The shoreline corresponding to this eroding trailing edge of the bank will be encroached on by the leading edge of the following mud bank years later. These relatively 'mud-deficient' inter-bank areas are characterized by a deeper foreshore of old bank mud, and the shoreline is composed of either stiff consolidated mud bearing mangroves that may be rapidly eroded, or, more rarely, sandy cheniers (rits) commonly overwashed by waves (Fig. 11). The muddy shorelines in inter-bank areas undergo progressive retreat and mangrove destruction, especially at high tide, but they can also undergo significant event-scale retreat during short spates of high-energy waves. Erosion of the over-consolidated shoreline mud releases fluid mud that is kept in suspension by waves and transported alongshore by wave- and wind-generated currents. The erosion process may result in the breakage and transport of large mud clasts that form mud 'pebbles' away

from the wave breaker zone. Figure 12 summarises bank and inter-bank aspects drawn from a recently compiled mangrove cover of the French Guiana coast by Walcker (2015).

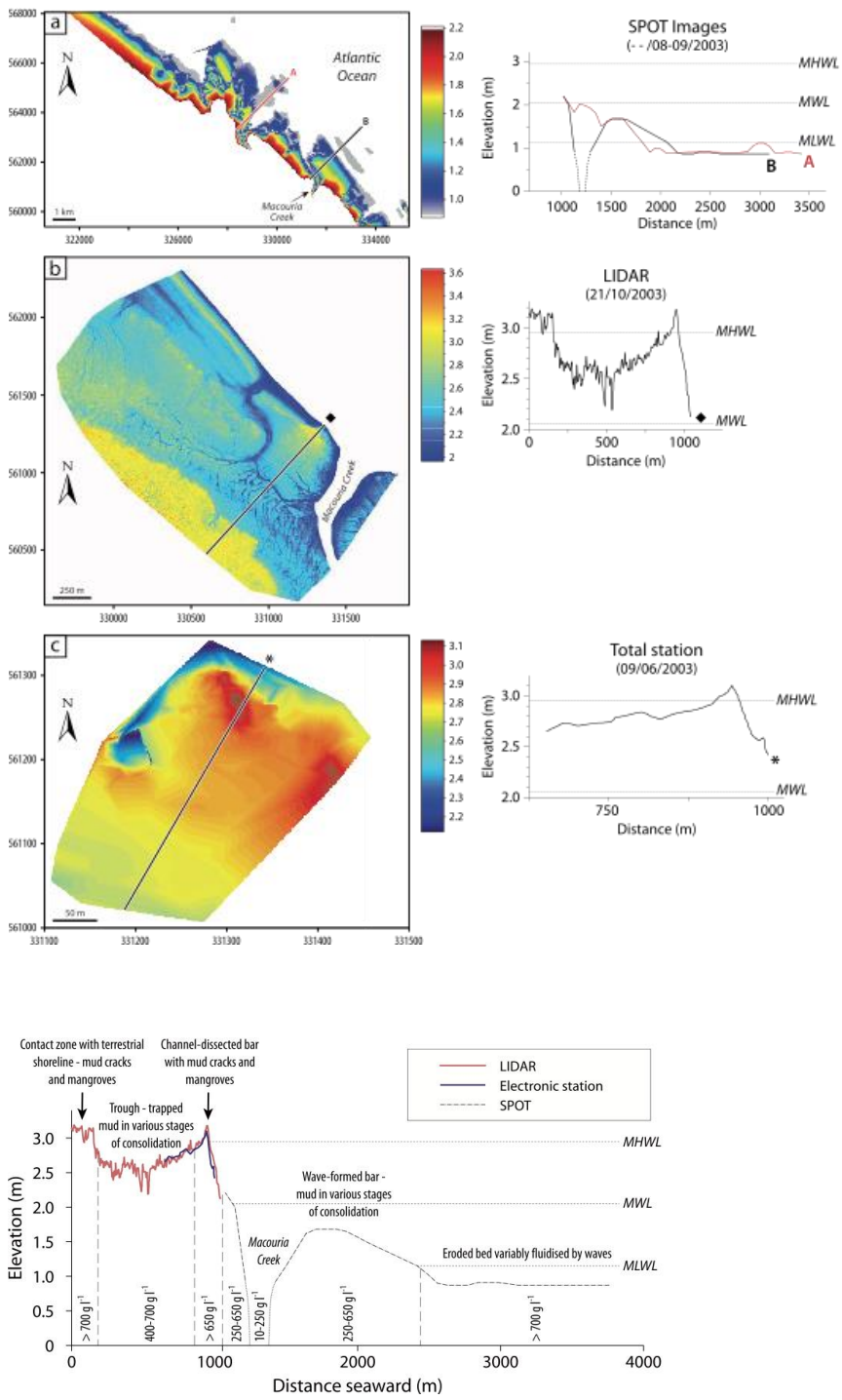

Fig. 9. Digital elevation models, representative topographic profiles, and combined profile (bottom) of a typical mud bank near Macouria, French Guiana, constructed from the meshing of data from: (a) SPOT images, (b) a LIDAR image, (c) a field survey. MHWL = Mean high water level; MWL = Mean water level; MLWL = Mean low water level. From Anthony et al. (2008). Large-scale mangrove colonization occurs generally at an elevation of 2.45 m above MLW.

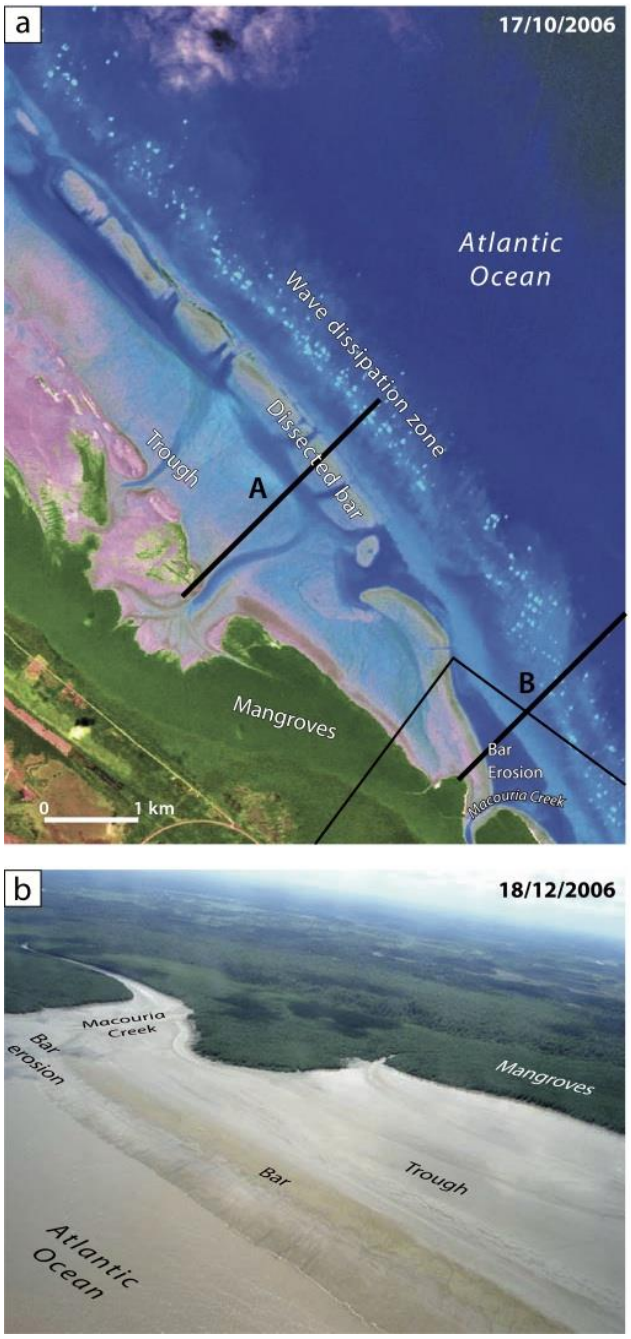

Fig. 10. SPOT image (a, 17 October 2006) and oblique aerial photograph (b, 18 December 2006) showing linear bar features characterizing mud-bank topography (trailing edge of a mud bank near Macouria in French Guiana). The bars are drained by tidal channels. Lines A and B show locations of profiles generated from SPOT images in Fig. 9. Lower left corner of (a) shows erosion of the trailing edge of the bank, resulting in a flat consolidated bed and an offset between the distal edge of the bar and the eroding proximal edge and the terrestrial shoreline. From Anthony et al. (2008). Mud bars can be rapidly colonized by mangroves.

Mud banks are also subject to diagenetic processes (Aller et al., 2004; Aller et al., 2010a). Aller et al. (2004) showed that mud banks are characterized by extraordinarily intense biogeochemical recycling that considerably exceeds that of stable coastal systems,

such as salt marshes, in material exchange with the sea. It has been suggested that such intense recycling is favourable to the generation of biosphere diversity over geological time (Aller et al., 2010b).

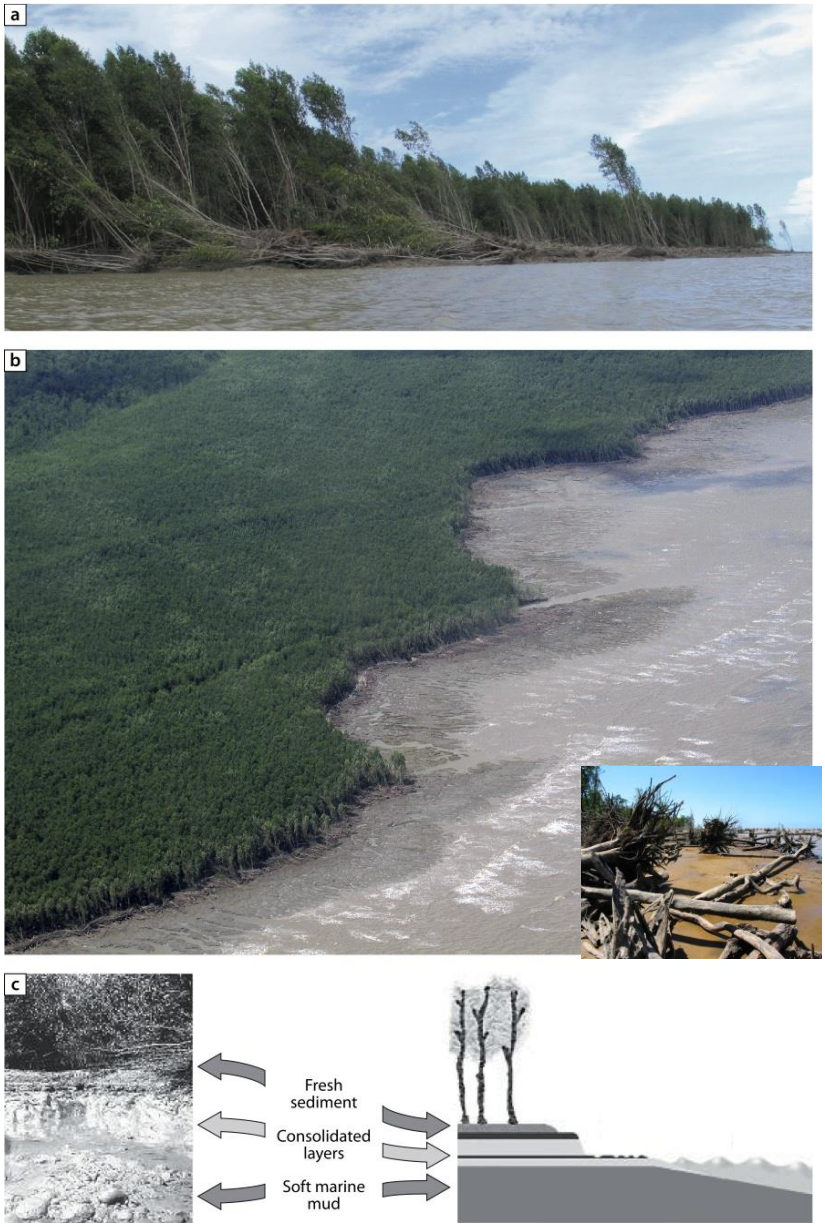

Fig. 11. (a) Shoreline retreat in the course of an inter-bank phase in French Guiana, and (b) alternations of megacusps and embayments associated with inter-bank erosion (from Anthony et al. (2010); (c) substrate layering pattern in an inter-bank zone following the erosion and retreat of a consolidated mangrove substrate. Fresh mud may be deposited over the marsh surface but net retreat leads to scarping and the formation of mud pebbles that are visible above the freshly deposited mud (from Lefebvre et al., 2004). During such inter-bank phases, mangroves play an important role by absorbing the pounding from the waves, thus slowing down the retreat process until the next bank comes along.

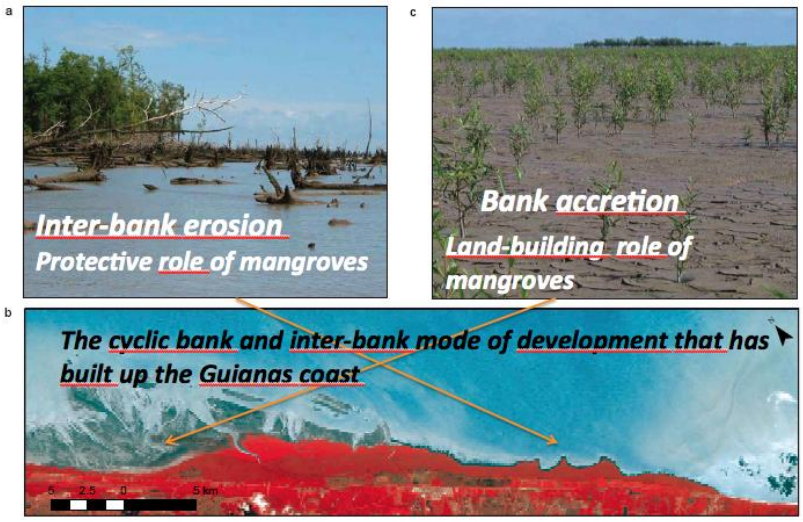

Fig. 12. Summary of bank and inter-bank aspects and the roles of mangroves in the geological development of the Guianas coast, based on a recently compiled mangrove cover of the French Guiana coast by Walcker (2015).

4. Mangroves in Suriname

Mangroves are the most productive forests on Earth and among the ecosystems most threatened by deforestation (Duke et al., 2007; Donato et al., 2011). Their decline rate is alarming, since ~20% of the world's mangroves were lost between 1980 and 2005 (FAO, 2007; Giri et al., 2011). Mangroves are important in coastal ecosystems because they act as filters of pollutants reaching estuarine and coastal waters. ***Their protective role on coasts exposed to high-energy events such as cyclones and tsunami (Fig. 13) has been demonstrated in numerous scientific publications***. The ecosystem services provided by mangroves are finely summarised in a recent paper by Lee et al. (2015). Mangroves serve as nurseries for subsistence fishing and commercial fisheries, provide opportunities for recreation, are important in assuring marine biodiversity, and act as carbon sinks that reduce greenhouse gas emissions, an important consideration in a time of climate change. Mangroves are, undisputedly, ecological engineering actors in coastal protection in the sense described by Borsje et al. (2011). Large-scale mangrove degradation on the world's coasts inevitably reduces the nursery role of these systems as well as their roles in wave dissipation, coastal protection and promotion of coastal sedimentation.

The Suriname mangrove system is part of the West Coast of America sub-zone in the Atlantic Zone of mangroves which is characterised by a much more limited number of species than the Indo-Pacific Zone. The Suriname coast is undoubtedly part of the longest (1500 km) and most important continuous mangrove system in the world, although large-scale mangrove removal in parts of Suriname, and especially Guyana, and possibly Brazil in the future (Anthony and Gratiot, 2012a), is resulting in increasing fragmentation of this system, with consequences that are discussed in a later section. The mangroves on the

Suriname coast belong to the category of 'fringe mangroves' found along the coastal belt and in a seafront position, but also along the lower river courses. This fringe is variably wide, depending on the waxing and waning of mud bank activity described in the previous section, but commonly attains several km on the mangrove-rich Guianas coast. This seafront fringe is dominated by monospecific stands of *Avicennia germinans* (parwa) that may be backed by *Rhizophora* spp, more common along the banks of river estuaries, and to a lesser extent *Laguncularia*. Behind the mangrove band occur marsh forests composed of *Symphonia globulifera, Virola surinamensis, Ficus sp., Euterpe oleracea* intermixed with old mature stands of *A. germinans*. Behind rets are found *Hymenea courbaril, Acrostichum aureum, Rhabdadenia biflora, Astrocaryum sp., Hibiscus tiliaceus*. Mangrove forests in the Guianas comprise one or more of the following stands, ranging from pioneer mangroves that start colonizing the mud banks to cemetery stands comprising dead and dying mangoves (Table 1).

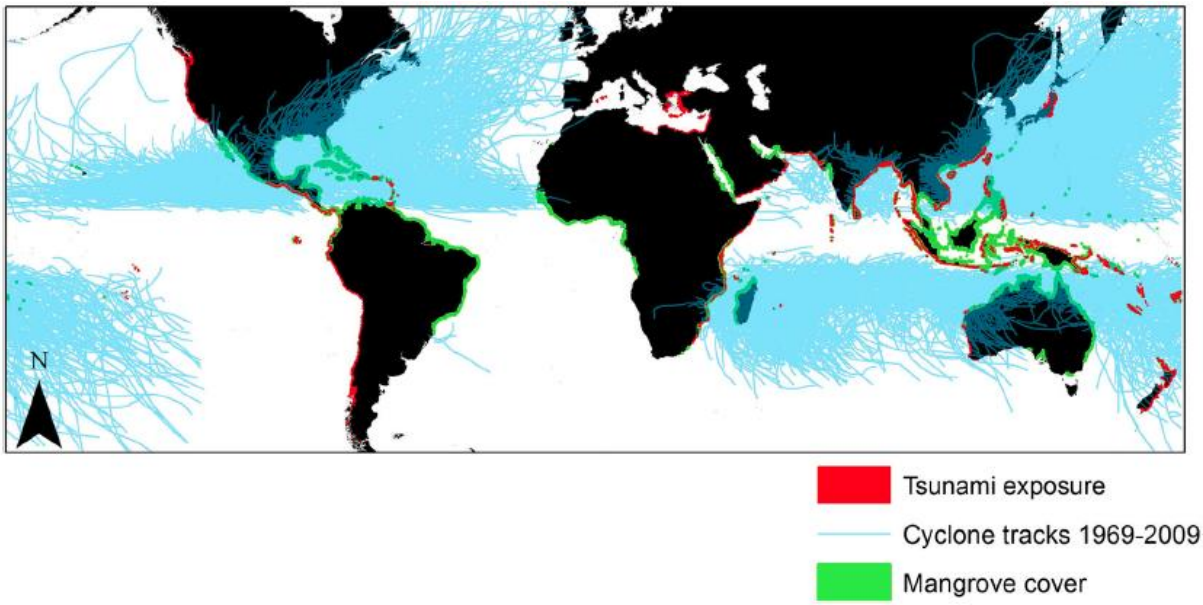

Fig. 13. Map of global mangrove distribution (UNEP-WCMC) and physical exposure to tsunamis and cyclones (UNEP-GRID). From Balke et al., 2015. Mangroves are considered as important in providing protection against such high-energy events, especially in the tsunami- and cyclone-prone areas of Asia.

The dynamics of mangroves on the Guianas coast are extremely variable as their spatial and temporal extension and stages of development hinge essentially on the waxing and waning of mud banks (Figs. 7, 8, 12). A detailed 64-year inventory 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 has been conducted by Walcker (2015) and Walcker et al. (2015). This inventory shows 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. Such inventories are non-existent in Suriname and Guyana, although the

gravity of shoreline destabilization in Guyana has now led to a programme of monitoring of mangrove area. The 'average' mangrove cover in Suriname has been estimated at 50,000 ha, which is about 0.8-1% of the world's mangroves. Respective covers in French Guiana (2014) and Guyana are 45,000 ha and about 20,000, the latter figure reflecting large-scale removal along the highly empoldered and dyked coast of Guyana.

Table 1. Mangrove stages in the Guianas (from Fromard et al., 1998).

Stage	***Density***	***Mean height***	***Surface area***	***Mean diameter***	***Aerial biomass***
	trees.ha^{-1}	*metres*	*m².ha^{-1}*	*cm*	*t.ha^{-1}*
Pioneer	8 400 - 31 100	2.5 - 5	4 - 21	2.3 – 2.7	11.4 – 56.6
Young	2 400 - 9 200	5 – 6.1	4 – 21.4	4.3 – 4.8	14.6 – 73.1
Adult	450 - 917	18.2 - 22	22.5 – 26.8	23.6 – 44.9	180 – 228.8
Mature	162	24.8	51.4	67.1	431.9
Mixed	3047	19	17.8	21.7	122.2
Cemetary	267 - 825	15 -17	13.8 – 18.5	28.5 – 31.1	77.6 - 110

Mangroves provide several major ecological functions and services in Suriname, notably protection of the shoreline from erosion, and are very important for coastal fisheries and as a habitat for millions of migratory shorebirds, breeding water birds and other wildlife (DELTARES, 2009). In addition to coastal protection by mangroves, the extensive mangrove development on the Suriname coast implies important carbon storage. The importance of such carbon storage (indicated by mangrove biomass in Table 1) can be further considered in terms of the long-term coastal progradation involving the significant development of coastal marshes and organic matter locked up in the Young Coastal Plain deposits (Fig. 3).

5. Mangroves and coastal protection in Suriname: facts that need to be considered

A debate on mangroves and the extent to which they protect the coast and coastal populations in Suriname, and especially the districts of Paramaribo and Wanica, needs to take into account the following question: what exactly is the relationship between waves, mud banks, and mangroves?

This is an overarching question, since recognition of the fundamental role of mangroves in protecting the coast of Suriname must hinge on a good understanding of the roles mangroves play at various timescales on this coast. It is possible that these roles are not sufficiently, nor even really, recognized by the local populations in Suriname. An Environmental and Social Impact Assessment report published in June 2015 (ESIA, ESMP, 2015) regarding the construction of a dyke with a length of 9 km and a width of approximate

40 m, aimed at protecting people and property in the Weg Naar Zee area of Wanica district from flooding and saline intrusions, claimed that 82% of individuals interviewed did not consider mangroves as a useful source of coastal protection. The basis on which this survey was carried out was not specified nor the representativeness of the interviewed sample. If true, this reflection on whether mangroves are pertinent or not in coastal protection is probably explained by the important fluctuations of the coast at the historical timescale and by the fact that mangroves appear as 'passive' background elements in this highly dynamic system, under the overarching influence of the mud banks. They appear and disappear as a function of mud-bank waxing and waning under the influence of waves and currents that generate bank migration. Nijbroek (2014), in his recent evocation of the relationship between mud banks, dykes and mangroves, mentions the 'secondary' role of mangroves in coastal protection in Suriname, as opposed to what may appear elsewhere as a 'primary' role where a large muddy foreshore provided by mud banks is absent, which is commonly the case on other coasts of the world where mangrove protection against storms, tsunami and large waves has been amply demonstrated. Barbier et al. (2008) showed that whereas the role of mangroves in protecting coastal areas in Thailand and Vietnam is best approached by considering non-linear wave attenuation, this attenuation function is enhanced where extensive shoals, such as mud banks, front mangroves. The distinction by Nijbroek (2014) between primary and secondary protection is probably irrelevant when the mangrove dynamics are considered on the Suriname coast, and is, somewhat, an oversimplification of the roles of mangroves in the geological development and protection of the coast of Suriname. These roles need to be considered in terms of embedded timescales and in understanding how mangroves actually operate, rather than in simply considering whether or not mangroves play a primary or secondary role in coastal protection in Suriname.

The Suriname coast is fundamentally a wave-dominated coast as stated earlier, exposed to ocean waves throughout the year (Fig. 4). Potentially, therefore, the Suriname coast would have been either an erosive coast without the input of Amazon mud, or, much more likely, a sandy coast bounded by barriers and beaches built of sand supplied by the rivers debouching on its coast. It is highly unusual having muddy progradational shores on wave-dominated coasts (Anthony et al., 2014). This relatively rare association between muddy progradation and waves is due to the large capacity of mud in dissipating waves. ***In inter-bank situations, where the coast can be effectively exposed to high waves once the residual (migrating part of the mud reservoir) mud bank has moved past a given area (Fig. 7), this wave dampening capacity is vested essentially in mangroves and their muddy substrate (Fig. 12). The large-scale pounding by waves taken by the mangroves effectively dissipates wave energy. This dissipation is assured by both live and dead mangroves, and it also induces organic recycling. The wider the mangrove fringe, the longer the time over which this role is assured until the next mud bank comes along. In essence, the foliage, trunks and roots of the living and dead mangroves slow down erosion of the shoreline.***

Efficiency of mangroves in dissipating wave energy has been found to vary with species (Barbier et al., 2008), and with mangrove forest characteristics (Bao, 2011). In

Vietnam, low, sparse, shrubby mangroves may offer low protection even with a wide (240 m) mangrove fringe, whereas high, dense mangroves can generate high protection even with a narrow (40 m) mangrove fringe (Bao, 2011). No comparative studies have been carried out regarding the mangroves of the Guianas, but the monospecfic seafront *Avicennia g.* forests generally are dense, mature stands that are efficient in dissipating wave energy. A recent study on inter-bank erosion in an area of shoreline formerly occupied by rice fields in French Guiana (Mana rice fields), following large-scale mangrove and backswamp clearing (Fig. 14), has shown that shoreline retreat rates are extremely high (up to 180 m a year) in the absence of mangroves (Brunier, 2015). Such retreat rates exceed usually observed retreat rates in the presence of mangroves (up to 40 m a year).

Fig. 14. Accelerated inter-bank erosion near Mana, French Guiana, where mangroves and freshwater backshore swamps were removed in the 1980s to create rice fields. Field observations and analysis of aerial photographs show that inter-bank retreat rates in such empoldered areas without mangroves are much higher than in mangrove-colonized sectors on the French Guiana coast. Retreat has led to the formation of a sandy chenier ('rits') subject to wave overwash at high tide and undergoing landward migration.

Here, we will critically demonstrate the importance of mangroves to the state-of-health of the Suriname coast. In showing how mangroves interact with mud banks that are the overarching environmental feature of the coast, we will demonstrate the contribution of mangroves to coastal stability at timescales ranging from instantaneous turbulent dissipation of wave energy that favours sedimentation, to that of the geological development of the Suriname coast.

5.1. Mangroves and mud banks: a 'symbiotic' relationship

Mud-bank mobility is an extremely dynamic process that affects the entire mud bank, leading to recycling of mud and mangroves in the framework of coastal accretion and coastal erosion.

i. Micro-scale: turbulence and flocculation

Biological mediation of mangroves in wave energy dissipation and subsequent coastal protection mainly occurs through turbulence created by the plants that emerge well into the water column from the bottom boundary layer. While dissipating wave energy, mangrove ecosystems also generate a positive feedback loop as the mechanical energy dissipation and the generated micro-turbulence can contribute actively to flocculation processes and fine-grained sedimentation (Fig. 15), which, in turn, offer optimum conditions for mangrove regeneration (Furukawa et al., 1997).

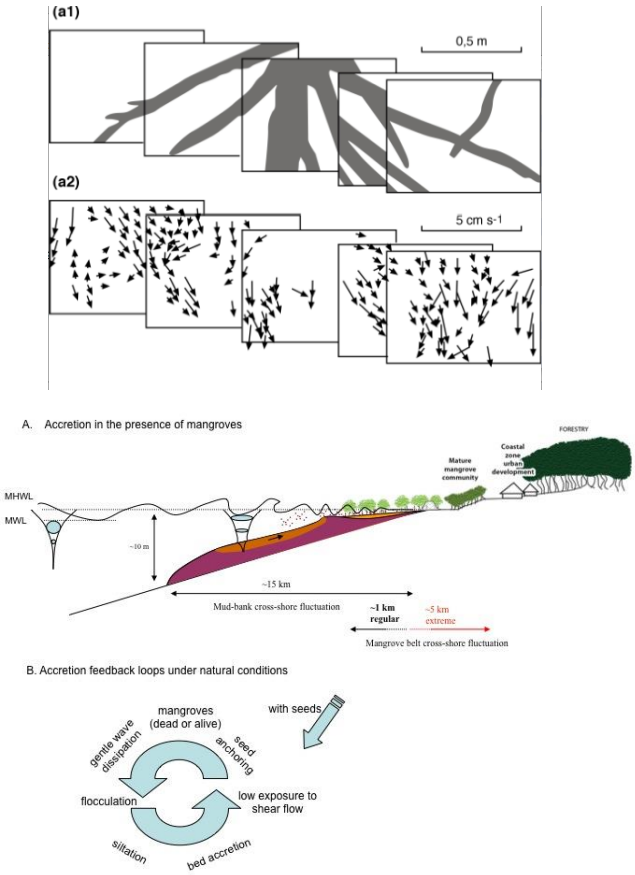

Fig. 15. Rhizophora-*type mangrove root system (a1) and panels (a2) showing patterns of disorganization (dissipation) of energy. From Furukawa et al. (1997). Bottom illustration shows the attendant accretion feedback loops in the case of mangroves on the Guianas coast. The fluctuation fringe of a typical mud bank can attain 15 km. Within this dissipative fringe, mud recycling by waves results in landward and alongshore mud translation. Energy dissipation is further assured by the mangroves. The mud bank and mangrove belt are connected over a cross-shore width that regularly attains 1 km. From Anthony and Gratiot (2012b).*

Flocculation is a process of aggregation or binding together of small organic and inorganic particles by bacteria, other organisms, and organic detritus into porous aggregates or *flocs*. The dynamically active process of flocculation alters the velocity at which clay particles (which comprise about 90% of Amazon mud) and associated organic matter particles (which in the coastal zone are strongly supplied by mangroves as they are organically recycled) settle from the water column to the bed, and consequently, the rates and patterns of deposition and accumulation. An important fraction of fine sediment in turbid discharge plumes forms large flocs. The net result of flocculation is an overall increase in the size and settling velocity of the fine-grained material that favours deposition of silt- and clay-sized sediment. Individual floc settling velocities on the wave-dominated Suriname coast are too small to counterbalance the turbulent mixing induced by breaking waves. Hindered settling, favoured by sediment liquefaction by waves and by the high background suspended sediment concentrations, is thus an overarching process in wave-driven mud bank migration. This pervasive hindered settling regime is characteristic of the wave-exposed outer and leading edges of mud banks where active mobilisation of mud assures mud bank migration. As a result, consolidation of the mud bank is theoretically precluded.

We have recently shown, however, from experimental work conducted in French Guiana (Gratiot and Anthony, accepted) that additional flocculation and differential settling should 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 described earlier. These characteristic features of the low-energy inner leading part of banks form the precursor substrate conditions for mangrove colonisation. 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.

ii. Mesoscale processes: mangrove colonization strategies and mud-bank stabilization

Mangrove establishment in the inner part of a mud bank plays an important role in temporarily stabilizing part of the muddy substrate (Figs. 7, 8). This is tantamount to a degree of welding of part of the bank onto the terrestrial shoreline, which may be an eroded mangrove-colonized shoreline (Fig. 11), or, locally, a chenier (Fig. 14) composed of sand or shelly sand. The trailing edge and the seaward part of the bank are zones of active mud recycling by waves to feed the afore-mentioned accretion (Figs. 7, 8). These zones being hitherto part of the inner sector and of the leading edge of the bank, they are generally areas of dense mangrove development that assures stabilization of the muddy substrate.

In the leading edge of a mud bank, accreted bars (Figs. 9, 10) form a dynamic 'suture' zone with the muddy (or locally sandy) intertidal terrestrial shoreline (Anthony et al., 2009). 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). Rapid drying and compaction are associated with the development of mud cracks and diatom biofilms, typically during neap tides. These cracks facilitate mangrove colonization (Fig. 16) by trapping floating propagules of *Avicennia germinans* (Proisy et al., 2009). 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 (Fig. 16). These processes have created one of the most extensive and most dynamic mangrove coasts in the world. Under favourable elevation conditions, mangrove colonization can be extremely rapid, with plant densities exceeding 30 per m^2. We have also shown (Proisy et al., 2009) that very subtle elevation changes in the upper intertidal zone (order of a few centimetres) can have a strong influence on successful mangrove colonization, and, from high-resolution field topographic measurements and analysis of satellite images, we have succeeded in predicting rates of mangrove colonization based on the definition of the geographic limits of a carefully determined elevation threshold of 2.45 m above the local datum (Gensac et al., 2011). Rates of mangrove colonization vary considerably, however, as a function of available intertidal area. In reality, several other parameters can intervene even when the available area is there. Following colonization, extremely rapid mangrove growth (these rates are up to 2 m a year) leads to the establishment of a fringe of young mangroves and mud stabilization. Mangroves at all stages of establishment, from young pioneers to mature forests (Table 1), 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). The ensuing pattern may, therefore, be one of coexistence of young opportunistic rapid-growth juveniles adapted to the new substrate topography and dying and dead mangroves that are asphyxiated as mud accretion occurs, as described in section 2. This rapid growth of *Avicennia germinans* mangroves on the Guianas coast appears to reflect a form of ***neoteny*** unique to the mangroves of this region. ***The coexistence of dead, dying, and thriving young mangroves thus reflects active mangrove renewal that is also unique feature of the mangroves of the Guianas coast.***

iii. Macro-scale relationship between mud banks, mangroves and the geological development of the Suriname coast

As mud banks migrate alongshore, they lose volume to the benefit of muddy coastal accretion, although erosion, during inter-bank phases, of mud shed by previous banks must be expected to compensate in part for this. Such erosion can be variable alongshore and as a function of wave energy, which can fluctuate in response to ocean oscillations such as those associated with El Niño évents (Gratiot et al., 2007) and the North Atlantic Oscillation (Walcker et al., 2015). The net integration of mud from the mud-bank system into the coastal plain has assured marshy progradation, with incorporated cheniers where sand has been locally available.

Fig. 16. *Rapid preferential colonization of mud cracks by* Avicennia germinans *on the accreted inner portion of a mud bank in French Guiana, the surface of which shows a diatom film that commonly develops above a threshold of 2.45 m above MLW (top). Rapid colonization by opportunistic mangroves of fresh mud translated across-shore during the onset of a bank phase in French Guiana (bottom). This freshly translated mud will progressively stifle the older mangroves in the background.*

The important Holocene progradation of the muddy Suriname coast (Young Coastal Plain, Fig. 3) reflects, thus, the interaction between Amazon mud, waves and mangroves (Figs. 7, 8), an extremely dynamic system that can fluctuate at significant short-term (order of weeks to a few years) rates of several tens of metres to several kilometres in the cross-shore direction. ***In this progradational 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.*** The

extent to which this welded part of the bank is removed during the interbank phase, as waves rework the trailing and seaward edges of the bank, determines the degree of shoreline progradation. Each erosive inter-bank phase thus results in the partial, or rarely, total removal, of the coastal accumulation package built during bank phases. Total removal of the accumulation package deposited during a bank phase 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. A thorough analysis of the extent of mangroves in French Guiana from aerial photographs and satellite images spanning the period 1950-2014 showed, for instance, that mangrove regeneration was notably absent over periods during which inter-bank zones were more extensive along the coast than bank zones (Walcker, 2015). More commonly, however, removal is partial, signifying that there is a net coastal plain growth with each cycle (Allison and Lee, 2004). It is this net growth (Fig. 17) that has generated the Young Coastal Plain of Suriname on which Paramaribo has thrived.

5.2. Urban development and mangrove destruction in Paramaribo-Wanica

The city of Paramaribo has a population of about 240,000 people, according to the 2012 census. This is about 50% of the population of Suriname. The two districts Paramaribo and Wanica form the greater urban area around Paramaribo. A situation of virtually continuous erosion since 1914 appears to have prevailed along parts of this coast, according to Nijbroek (2014). Figure 18 shows an eroding section of the Weg Naar Zee shore near the Indian Temple. A synthesis of shoreline fluctuations by Augustinus (2004, in Winterwerp et al., 2013) does indeed show that erosion in the Paramaribo area has been persistent (Fig. 19). The reasons for this almost continuous erosion still need to be elucidated. It is known that phases of coastal accretion and erosion can be embedded in cycles that are up to 64 years long (Walcker, 2015). However, local variability is also a marked characteristic of the dynamics of accretion and erosion, and local context factors can lengthen or shorten inter-bank phases, the former especially occurring where successive banks do not 'weld' onshore, a common trait near river mouths.

Beyond the mechanisms of cyclic shoreline accretion during bank phases and erosion during inter-bank phases, and medium timescale changes, shoreline behaviour at longer (multi-decadal) timescales appears, thus, to be variable, with sectors of coast being subject to long periods of stability, accretion and erosion that incorporate at any given site several successive bank and inter-bank phases. Plaziat and Augustinus (2004) identified multi-decadal scale shoreline changes in French Guiana from historical data and old maps. A fine example is provided by the mouth of the Mana, a small river (catchment: 12,090 km^2) in French Guiana just east of the Maroni river and which has been characterised by successive phases of mud cape growth and erosion between the 18th and 20th centuries (Plaziat and Augustinus 2004), culminating in an erosive phase that has been active since 1950. In this situation, successive bank phases do not generate shoreward mud translation and welding on a scale liable to promote progradation of the terrestrial shoreline, whereas successive

inter-bank phases generate sustained erosion. Multi-decadal shoreline fluctuations in French Guiana have also been identified by Fromard et al. (2004) from remote sensing data and analysis of mangrove ecosystems. The reasons for such longer-term patterns of shoreline change are not clear but they may involve local changes in wave-bank interactions as well as coastal mud budget adjustments alongshore. Experience from French Guiana shows that such zones are more likely to be associated with river mouths where "hydraulic-groyne" effects (Fig. 8) may durably impact on mud bank dynamics.

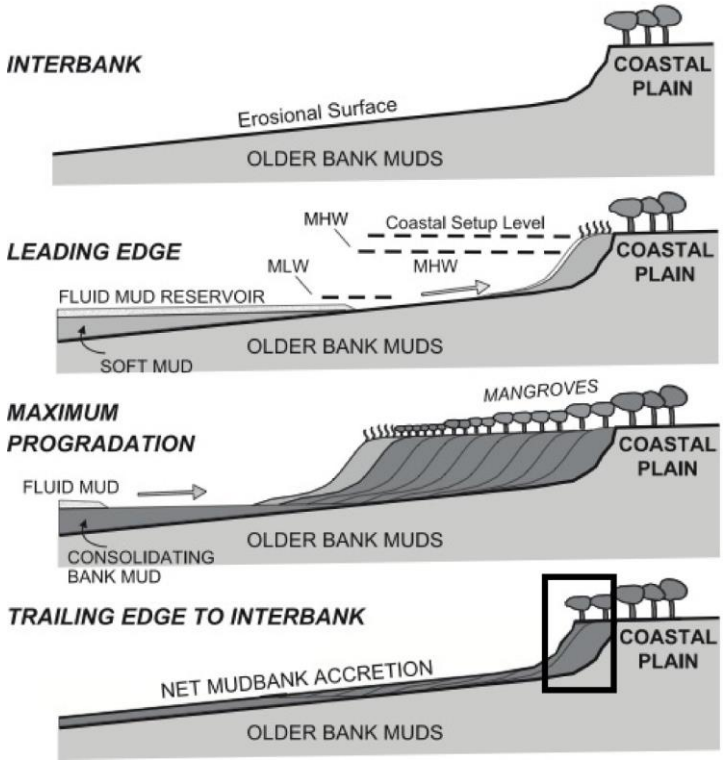

Fig. 17. A model (with high vertical exaggeration of the offshore slopes) for shoreline evolution in the Guianas based on remote sensing and field observations. From Allison and Lee (2004). The diagram shows a succession of nearshore cross-sections of stratigraphy (top to bottom) with the passage of an offshore mud bank. The eroded, relatively low-porosity inter-bank surface (top panel) is succeeded (second panel) by leading-edge mud-bank deposition in the subtidal zone and the upper intertidal zone driven by fluid mud delivered onshore during phases of coastal setup. Accretion continues (third panel) in the upper intertidal zone as it translates seaward with mangrove stabilization, but ceases offshore with passage of the leading edge of the mud bank. With continued consolidation offshore (bottom panel), wave attack resumes and the coastal stratigraphic package is partially removed. This partial removal indicates that there is a net coastal plain growth (schematised by the black rectangle in bottom panel) with each mud bank–inter-bank cycle, with mangroves contributing significantly to this land-building of the Young Coastal Plain.

Fig. 18. Part of the eroding shoreline of Weg Naar Zee (Indian Temple in the background), October 2015.

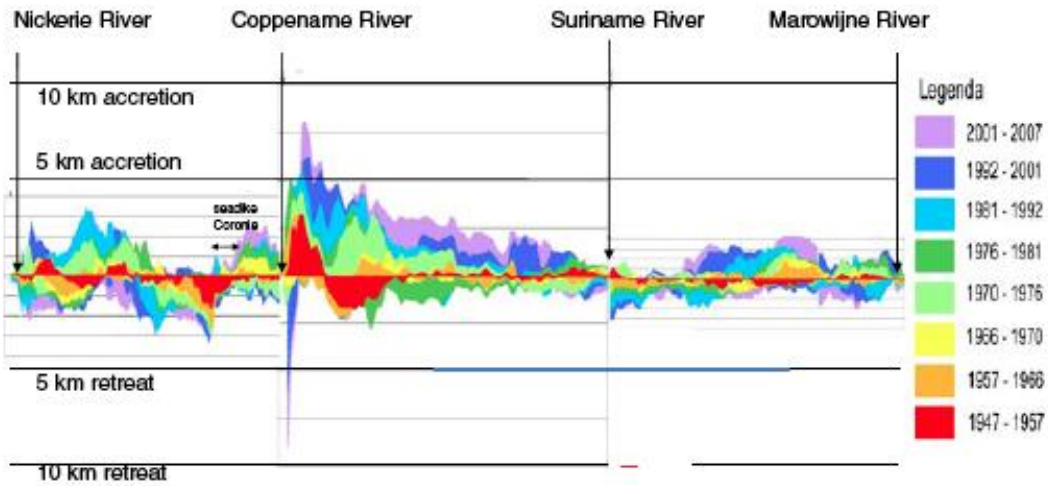

Fig. 19. Alternating retreat and accretion of Suriname's coastline since 1947, over eight periods of time (from Winterwerp et al., 2013, redrawn from Augustinus 2004). Variations are cyclic both in space and time. Most of the coast has accreted over longer periods of time, except near Paramaribo (located along the Suriname River, and Coronie coast where more than 5 km erosion has been observed since 1900. Apparently, the trend in Coronie is now reverting back to accretion.

The most plausible explanation for any sustained erosion of parts of the Paramaribo-Wanica coast may therefore be hinged on: (1) the relationship between freshwater outflow and behaviour of the freshwater jet (reinforced by urban runoff?) from the Suriname River, and mud bank dynamics, and (2) mediation by increasing modification of these dynamics by human occupation of the coast, its urbanization and the attendant interventions on the coastal mangrove and hydrological system. The "hydraulic-groyne"

effect of water outflow from the river may have implied more important mud liquefaction, and, consequently, fluid mud streaming westwards across the mouth of the Suriname River that precludes active bank sedimentation on the on the west bank shore of the river.

Regarding point 1, there is no doubt that multi-decadal erosion, will, in time, be superseded by a phase of accretion, as attested by the geological development of the Young Coastal Plain, which shows overall massive progradation in the course of the last 5-6000 years throughout the 350 km-long coast of Suriname. Regarding point 2 above, changes in land use driven by economic development and the northward spread of urbanization of Paramaribo (Fig. 20) threaten the positive feedback loops between mangroves and mud banks (Fig. 15) that play a fundamental role in coastal stability.

This has involved two conjugate processes: large-scale mangrove removal over time, and the construction of coastal defences and water and waste control systems along the coast. Large tracts of mangrove stands have been removed to make way for peri-urban housing (Fig. 20). But, even where erosion durably prevails, as on the Weg Naar Zee (Fig. 18), the wider the mangrove fringe, the longer the time over which this eroding fringe will act as a protective barrier until a shift to bank sedimentation. This 'symbiotic' and highly dynamic system between mud banks and mangroves has functioned over the last 5-6000 years, progressively resulting in net coastal progradation. At present, pressures on the Paramaribo-Wanica coast are strongly increasing, echoing a similar but more serious situation in Guyana, where major agricultural and aquaculture activities and large-scale coastal empoldering have significantly and durably reduced the mangrove cover, which is also being impacted by hard-rock coastal defences aimed at protecting communities and socio-economic installations. It is highly unlikely that dykes, static forms in such a highly dynamic environment, will represent a sustainable means of coastal defence in lieu of mangroves.

Fig. 20. Large-scale conversion of inland adult Avicennia g. *mangrove stands on dewatered coastal plain mud north of Paramaribo. Mangrove removal is accelerated by burning in the background (left). Photograph on the right depicts a billboard advertising sale of cleared plots for future urbanization (sale prices in October 2015 started at €25 per m^2).*

According to a recent report by Deltares (2009, p.57): ''*While two-thirds of Suriname's mangroves and other coastal wetlands are protected or managed for wise use, and various environmental laws and regulations are in place, the management of mangrove resources in Suriname is facing a number of major problems, such as habitat destruction and conversion, coastal erosion and sea level rise, hydrological disturbances and various other threats and challenges. Currently the mangrove area north of Paramaribo is not protected or specifically managed from an ecological point of view as it is not designated as nature reserve, MUMA or Ramsar site. There are several laws and regulations (EIA regulations, forestry and mining acts) in place, however these do not seem to be adequate enough or enforcement is too limited*''.

What clearly comes out in fact is that mangroves are probably not considered as important in a system under strong pressures from urbanization. This is clearly brought out in the EIAS report (2015) on dyke construction which hardly takes into account the impact on mangroves. As mangroves are progressively destroyed, the breakdown in the positive feedback loops they create relative to coastal stability will have some long-term consequences that are either ignored or have been seriously underestimated in Suriname, as they were in Guyana (see Section 4.5).

5.3. Dykes versus mangroves in coastal protection

Whereas the valuation of engineering structures aimed at coastal protection, such as dykes, is feasible but needs to be based on realistic long-term scenarii, the same does not hold true for mangroves, the monetary valuation of the ecosystem services of which is fraught with difficulties and is still in its relative infancy. ***The ecosystem services provided by mangroves in the world have been collectively and conservatively estimated to be worth US$194,000 per hectare per year (Costanza et al., 2014; Brander et al., 2012).*** Rao et al. (2015) showed that valuation of the coastal protection role of mangroves is determined by site characteristics, which include the valuation method, and context variables including measures of development, anthropogenic pressures, biodiversity, and population density. The authors showed that variables significantly affecting this ecosystem service value included size, level of development, storm frequency, valuation method and gross domestic product per capita. A similar analysis could be conducted on valuation of mangrove protection in due course in Suriname.

Protection valuation needs to take into account the monetary value represented by the efficiency of the buffering effect of mangroves on wave energy and eventual flooding, i.e., the extent to which the marine flooding front penetrates inland. In the Guianas, the existence of large mature 'dry' mangrove zones, which, by themselves, reflect the coastal 'land-building' role of mangroves, shows the high capacity of mangroves in dissipating wave energy and reducing marine penetration. Valuation of this capacity has been analysed on the basis of comparative values of ecosystem-based management (a mix of economic ventures ≤

20% max, and mangrove conservation) for mangroves in Vietnam and Thailand (Barbier et al., 2008). These authors showed that the monetary value of mangrove protection largely exceeded that of the value of other products associated with economic ventures at the expense of mangroves such as shrimp farming (Fig. 20). The protection value on the Vietnam coast (Table 2) by a 10 km^2 swathe of *Candela Kandel* mangroves forming a 100 m-wide fringe along 1 km of shoreline and capable of dissipating up to nearly 90% of wave energy has thus been estimated by Barbier et al. (2008) at US$14,317,997 in 2008.

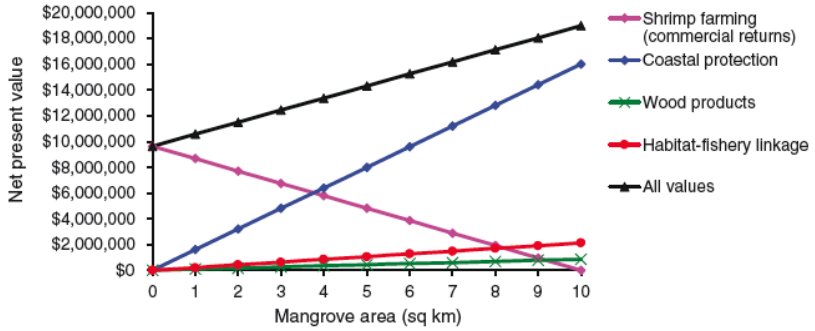

Fig. 21. Conventional comparison of shrimp farming to various mangrove services at coastal landscape level (10 km^2), in Thailand (net value in 2008, 10% discount rate, 1996 dollars) on the basis of total economic returns as a function of mangrove area (km^2) for the commercial returns from shrimp farming plus three mangrove ecosystem service values: coastal protection, wood product collection, and habitat support for offshore fisheries. From Barbier et al. (2008).

Table 2. Non-linear estimates of coastal protection service of mangroves (Kandelia candel) in Vietnam (from Barbier et al., 2008).

Mangrove area, km^2 (M_i)	100 m inshore mangrove distance (x_i)	Proportionate change in wave height $W(x_i)$	Value of coastal protection service, $ $V(M_i)$
0	0	0	$0
1	100	0.1726	$2,760,546
2	200	0.3208	$5,131,977
3	300	0.4469	$7,149,601
4	400	0.5532	$8,849,953
5	500	0.642	$10,269,517
6	600	0.7154	$11,443,689
7	700	0.7755	$12,405,983
8	800	0.8244	$13,187,464
9	900	0.8637	$13,816,385
10	1000	0.8951	$14,317,997

Dykes are employed in many countries in the world for coastal protection from waves, flooding and salinity intrusions. They may be suitable but their usefulness and efficiency, which generally go with higher construction costs, strongly depend on context. ***In***

Suriname, before choosing the dyke option, there is a need to have a very serious prior reflection on: (1) the causes of shoreline erosion; (2) the suitability of a dyke option; (3) a cost-benefit analysis, and (4) the environmental impacts of dykes (discussed in the next section).

(1) The causes of shoreline erosion

As shown earlier, in the Guianas, erosion-accretion phases, which have been documented for the Suriname coast (Fig. 19), depend on the overarching influence of bank and inter-bank dynamics, which have been shown to be complex in time and space, and on local influences, such as headlands, river jet outflow, and human modifications. The Suriname coast has grown through the positive mud-bank stabilising and land-building effects of mangroves and the natural protection both dead and living mangroves offer during inter-bank phases. A lack of understanding of this system could lead to poor judgment of options of protection.

(2) The suitability of a dyke option

Dykes are static engineering structures in a highly dynamic environment and this is reflected in constraints that need to be carefully calculated such as bearing capacity, hydraulic failure, sliding, breakage, and sinking. This is particularly the case on soft muddy coasts where traditional hard structures often fail because the subsoil of mangrove-mud coasts and foreshores is too soft and prone to consolidation and base failure (Albers and Schmitt, 2015). The required soil improvement or bed protection is either too expensive or insufficient depending on the thickness of the soft mud layer (Fowler 1989; Hartlén1996). Finally, the view that a dyke, once constructed, is not necessarily an absolute protection barrier against marine flooding and eventual damage and casualties needs to be inculcated in communities living behind the protection of dykes.

(3) A cost-benefit analysis

A cost-benefit analysis over the long term should always be implemented. ***Dykes are costly, even when built from Young Coastal Plain mud***, and they necessitate regular maintenance over time. The viability of the dyke option (including long-term maintenance and a sea-level rise scenario) therefore needs to be seriously considered. The dyke option is generally too expensive to protect large rural areas (Temmerman et al. 2013), especially in developing countries. The 14 km-long dyke constructed in Coronie, near Totness (Fig. 22), a relatively small community (population in 2012: 3391), cost US$70 million (Nijbroek, 2014), i.e., US$5 million per km. Apparently, the cost of maintenance of this dyke has not been budgeted by the government of Suriname even though maintenance cost of a similar, but much longer, dyke in neighboring Guyana is equivalent to 10% of the country's GDP (D. Singh, personal communication, February 21, 2012, in Nijbroek, 2014). This dyke was destined to halt erosion in Coronie. In fact this erosion was simply part of a prolonged inter-bank phase. The arrival of a bank and its rapid colonization by mangroves over the last two

years is resulting in the isolation of this dyke inland. According to Nijbroek (2014), the government also failed to study the impact of this dyke on coastal ecology elsewhere along the coastline. As noted by this author, if this dyke alters the behavior of mud banks further west, this will become disastrous for the economy of Nickerie where additional dykes may need to be constructed in the future.

A choice of a dyke as a solution to coastal erosion is also being projected for the Weg Naar Zee (Fig. 23) shoreline (ESIA, ESMP, 2015). The dyke has the following characteristics:

- Length: 9 km
- Height: 4.8 meters above NSP (Nieuw Surinaams Peil)
- Width: ~ 40 metres
- Cost: (? - US$45 million?, if extrapolated from the cost of the Coronie dyke?)
- Impacts on mangroves: totally underplayed.

A 300 m-long concrete dyke constructed as recently as 2013 west of the Indian Temple in Weg Naar Zee is now largely destroyed (Fig. 24).

Fig. 22. The recently constructed 14 km-long dyke in Coronie. The seaward face is reinforced with rock armouring. A growing mangrove fringe is now present in front of this dyke.

Long-term (decades) maintenance costs can largely exceed the initial cost of a dyke. Estimates of costs of dyke construction in 2012 in neighbouring Guyana without maintenance costs amount to US$16,000 for a 1 km-long compacted earth dike (cf, cost of dyke in Coronie above) and US$3,000,000 for a 1 km-long rock armour dike. On the Mekong delta shoreline, Vietnam, an earth dyke of 23,725 m^3 + 1600 m of toe protection (rock armouring) with maintenance costs (Table 3), ***and protected by mangroves in front***, is estimated at US$276,375 over 30 years (US$9212 a year). Of this, the earth dyke accounts for 26% of the total cost, the toe protection for 26%, and maintenance costs 48% (Albers and Scmitt, unpub. data).

Fig. 23. Projected location (in yellow) of the future 9 km-long dyke in Weg Naar Zee.

Fig. 24. Remnants of a poorly designed concrete dyke in Weg Naar Zee (west of Indian Temple) built in 2013, with no subsequent maintenance, October 2015.

Table 3. Construction costs of a dyke in Vietnam fronted by protective mangroves (from Albers and Schmitt, unpub. data).

Construction costs			**USD**
Earth works	23,725 m³	3 USD/m³	71,175
Toe protection	1,600 m	50 USD/m	72,000
Additional costs (5% of 1 and 2)			7,200
Maintenance costs			
Yearly (2% of 1, 2, 3)	3,000 USD/year	30 years	90,000
Every 5 years (4% of 1, 2, 3)	6,000 USD/5 years	30 years	36,000
Total (over 30 years)			**276,375**

5.4. A mixed mangrove-dyke option in coastal protection?

A mixed coastal protection option involving more or less wide swathes of mangroves fronting dykes is implemented in several countries, notably in Asia, the Mekong River delta in Vietnam providing fine examples (see Table 3). This mixed approach, wherein such dykes are built behind mangroves, is, in itself, demonstrative of the usefulness of mangroves in dissipating wave energy and protecting the coast. The experience gained from the Mekong delta examples is very recent the available studies have only started being published. However, in such an option, the dykes are built to prevent eventual saline intrusions in areas of shrimp farming or agriculture, and are commonly resorted to as a result of the large-scale degradation of the mangrove fringe, in a Mekong delta context of increasingly shoreline erosion as a result of falling sediment supplies (Anthony et al., 2015).

From modeling efforts and field observations, it has been shown that this solution, which can be advantageous in terms of cost, can be viable, provided: (1) all the constraints related to dyke construction and maintenance are not overlooked, and (2) the mangrove fringe fronting the dyke is sufficiently wide and healthy - a minimum of 140 m has been identified to attenuate waves (Phan et al., 2015). This study (Phan et al., 2015) also shows, however, that dyke construction is, together with conversion of mangrove lands into shrimp farms and for miscellaneous agricultural activities, largely responsible for 'mangrove squeeze', which reduces the width of the efficient mangrove fringe, thus impairing mangrove efficiency in coastal protection. The Coronie example in Suriname, which is now characterised by what has been dubbed in Suriname a 'sleeping dyke', suggests that dyke construction in this area was not necessary.

A dyke solution may be necessary to provide protection from flooding along the banks of the Suriname River (eastern flank of Paramaribo), but probably not along the Weg Naar Zee shoreline where the mangrove band is still sufficiently wide to buffer marine inundation inland. ***Obviously, the rapid reduction of the width of this band by rampant peri-urban growth towards the Weg Naar Zee shoreline (Fig. 23) will reduce the protective role of the mangroves in buffering marine inundation, thus generating the necessity for the construction of a costly dyke.***

5.5. Environmental impacts of dykes

The effect of mangrove removal and an increasing resort to 'hard' engineering structures such as dykes will have a threefold effect on the coastal system. This will generate negative feedback loops on the Suriname coast. Two of these are related to local-scale processes, while the third relates to the large-scale mud-bank migration process.

i. Whereas a wide (> 200 m) mangrove fringe serves as a dissipative swathe against wave energy (Anthony and Gratiot, 2012b) as shown in Fig. 15, dykes or seawalls constitute narrow linear ramparts that tend to concentrate and reflect wave energy at the shoreline (Winterwerp et al., 2013). A subsidiary effect of wave energy concentration at the shoreline is overtopping of dykes when strong wave activity coincides with spring tides and surge conditions associated with strong onshore winds. Overtopping occurred, for instance, over the dykes of parts of Georgetown, Guyana, in February 2013, during a spate of high-energy waves that coincided with spring tides, thus resulting in flooding of parts of city.

ii. Observations of the foreshore profile in front of dykes in Guyana suggest that mud is transported offshore by wave energy reflection (Fig. 25). The effect of dykes on the foreshore morphology is, thus, a shift towards a disequilibrium concave profile shape that is inscribed in a feedback loop of maintained non-deposition of mud (Fig. 26). This concave profile type differs from the accretionary convex inshore profile where mud supply is active, resulting in the formation of mud bars, nearshore accumulation and mangrove colonization once the tidal frame becomes appropriate. Depending on wave approach direction, another apparent effect of dykes is to reinforce alongshore currents as energy is concentrated in the narrow high-tide breaker zone fronting the dyke (Fig. 27).

iii. An increasing density of coastal socio-economic development and urbanization is likely to be accompanied by a multiplicity of engineering structures erected along the coast – coastal defences and water and waste regulation structures, in the absence of a coherent coastal zone management and regulatory framework on rampant coastal urbanization. Such development is necessarily costly, whether compared to mangrove conservation or halted by setback lines, and has been deemed as nefarious for the future of the coast of Suriname (Noordam, 2007; DELTARES, 2009). Continued development will lead to an extremely degraded and fragmented mangrove system, elements of which are already visible in Paramaribo-Wanica, and the functions of which, in terms of inter-bank wave energy dissipation, will be strongly reduced in consequence.

The first two processes can result in a strongly localized input of diffusive turbulence, which facilitates bed erosion, and ultimately leads to a net loss of sediment evacuated offshore, and alongshore, by currents (Anthony and Gratiot, 2012b; Winterwerp et al., 2013). These mechanisms are in stark contrast with the strongly dissipative effects of mangroves, which tend to break down currents and longshore drift (Fig. 27). This can even occur during strongly erosive interbank phases when a cell circulation can develop as the mangrove-colonized substrate is cut out into cuspate embayments (Fig. 11b). Figure 28, based on experience from Guyana (Anthony and Gratiot, 2012b), depicts a negative feedback loop related to the breakdown in coastal sedimentation induced by dykes.

Fig. 25. Photograph of a deepened, concave foreshore profile caused by wave reflection and offshore dispersal of mud in front of a dyke in Guyana (May, 2012).

Without mangrove contribution to sedimentation and wave energy dissipation, mud-bank liquefaction and migration rates are also likely to increase, as stated above. This could lead to a progressive shift in mud-bank migration mode from gel-like fluid mud and the reworking of fluid mud to form mud bars to larger-scale fluid-mud 'streaming' that is apparently presently characterizing the coasts of Suriname and Guyana, according to MERIS images analysed by E. Gensac (pers. com., April, 2015). Larger mud streaming could lead, in turn, to more persistent wave-exposed inter-bank shorelines that would need further uninterrupted hard sea defences in order to be stabilised in the face of impinging waves.

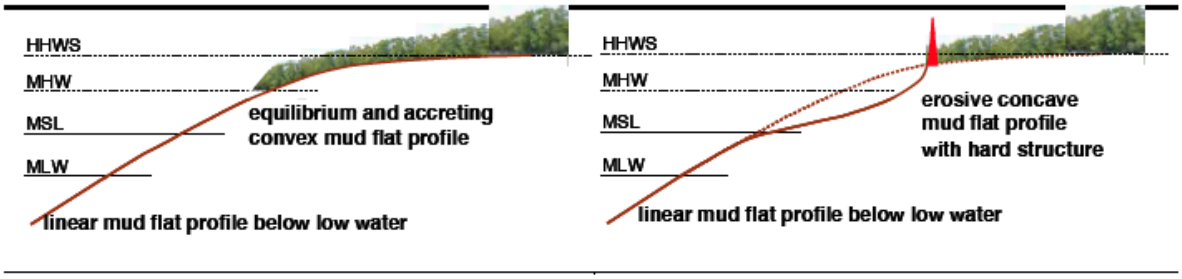

Fig. 26. Equilibrium/accreting convex-up mudflat profile (left panel) and eroding convex-up mudflat profile (right panel). The latter profile, generated by dyke reflection of wave energy, allows for larger waves near the mangrove fringe. From Winterwerp et al. (2013).

5.6. The potential for mangrove regeneration following removal

Once completely destabilised, the natural capacity of the coast to regenerate the mud-bank and inter-bank system is likely to be very poor, since it would require mud supply

from the Amazon, coupled with the re-establishment of mangroves (Anthony and Gratiot, 2012b). The potential for mangrove regeneration in bank areas or during bank phases that are favourable to mangrove development is dependent on two primary factors that would occur naturally in an intact system: (a) an elevation sufficient enough to enable drying out and the development of mud cracks that favour the trapping of propagules, and (b) the presence of an important propagule reservoir. As stated earlier, work from neighbouring French Guiana has shown that the optimal mud elevation for natural mangrove recruitment is around 2.45 m above the hydrographic zero (Proisy et al., 2009; Gardel et al., 2009; Gensac et al., 2011). At this stage, the mud begins to crack, thus facilitating the trapping and establishment of mangrove seedlings. In several areas, sea defences could potentially isolate the mature mangrove community from the sea and act as barriers to the dissemination of propagules necessary to mangrove regeneration seaward. This is a fine example of "propagule limitation" as defined by Lewis (2005).

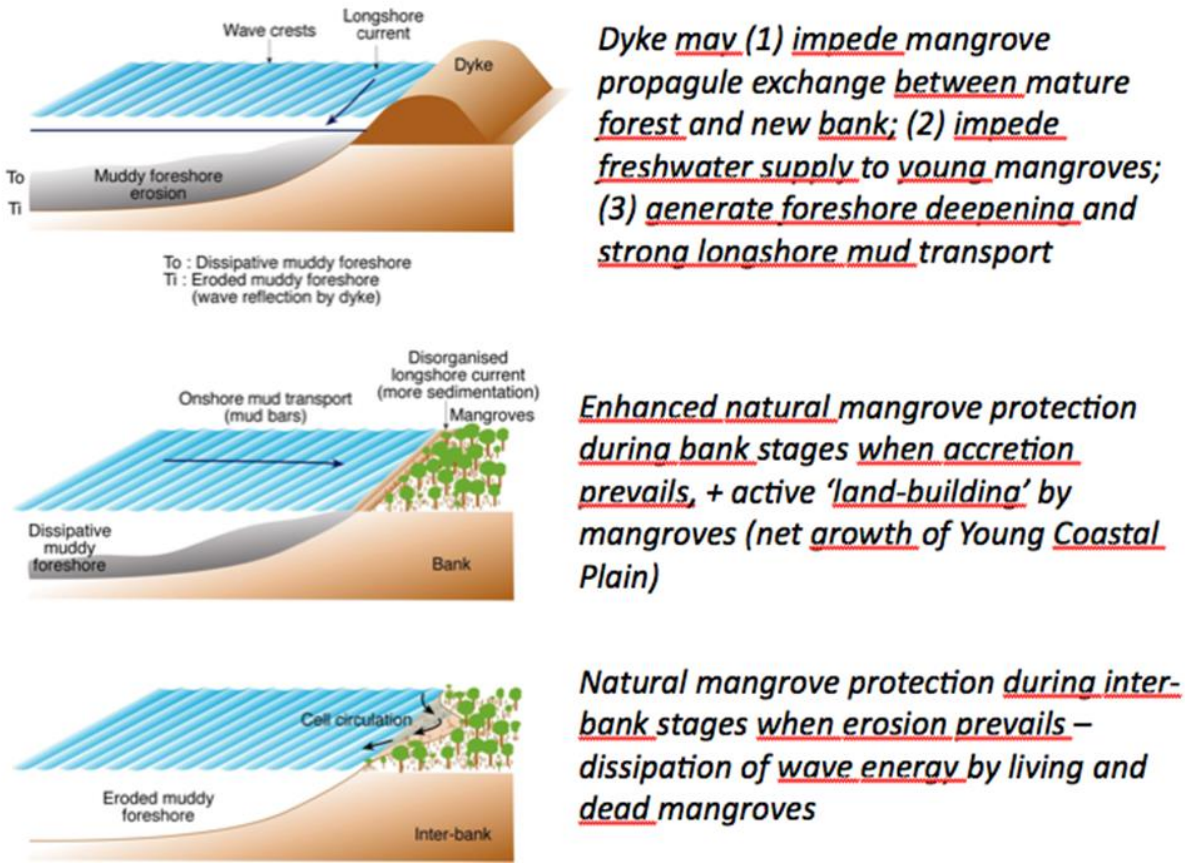

Fig. 27. Schematic comparative dynamics of dykes and mangroves, and their respective effects on the coastal hydrodynamics and sedimentation.

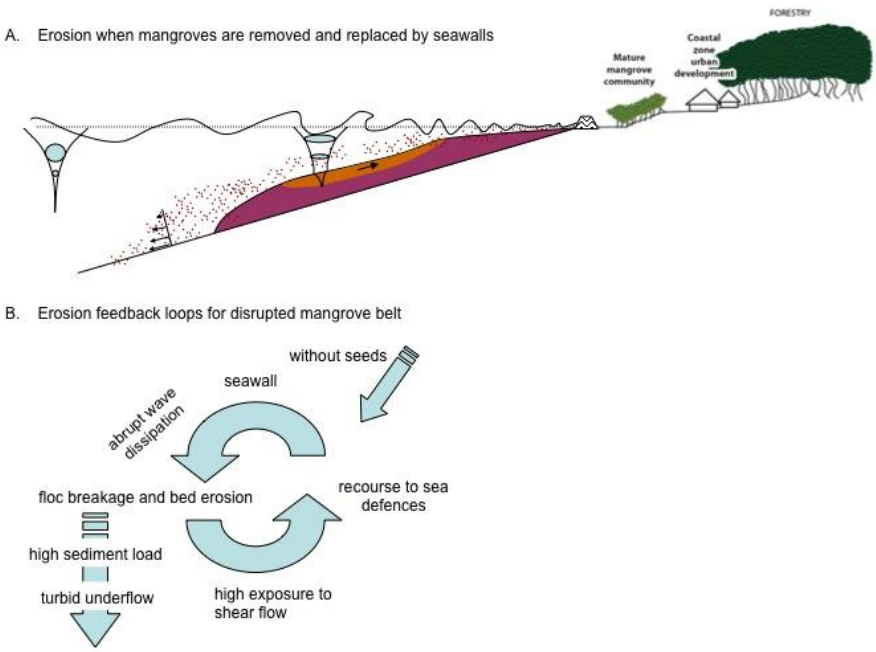

Fig. 28. The nexus between mangroves and mud banks is vital to a dynamic mud-bank and mangrove system. Disruption of this connection can result in a system switch from a positive feedback loop, under which mangroves are regenerated (Fig. 15), to a disruptive feedback loop, under which the system is no longer capable of fixing mud and favouring mangrove regeneration. Where dykes have been built, maintaining artificially this connection between the old mangrove belt and the mud-bank fringe is, thus, essential to the success of renewed mangrove colonisation. From Anthony and Gratiot (2012b).

Natural zones of mangrove colonization occur in the Paramaribo-Wanica districts. Considering the scale of the muddy coastal system, the soundest approach, both in terms of ecology and costs, is to simply maintain the subsisting natural zones of colonization, avoid further urbanization, impose setback lines, and especially avoid alongshore fragmentation, given the propensity for rapid mangrove spread, but also ensure that the connection between mangrove propagules and the muddy shoreline is not impeded. The time needed for regeneration of the mud bank-interbank system is hard to evaluate but is hypothesised to be of the order of decades, on the basis of the migration rates of mud banks and the phasing of successive banks separated by erosive inter-bank stages (Gratiot et al., 2008). Kamali and Hashim (2011) showed that successful mangrove restoration does not always require planting (see section below). The loss of mangrove forests can be reversed through the application of basic principles of ecological restoration (Lewis, 2005; Bosire et al., 2008). Where dykes are necessary for water control purposes, technical solutions, such as the provision of tidal channels across dykes to facilitate the transfer of floating *Avicennia* seeds from mature mangroves to the ocean, could be one fundamental way to restore the system. Field observations from neighbouring Guyana show that the process of mangrove recolonization even during bank phases can be hindered by the following conditions:

- a low foreshore level due to low levels of mud accretion;
- propagule limitation caused by discontinuity of the mangrove fringe; and
- where seedlings are available, their longshore transport can be further hampered by the multicplicity of shore-normal coastal structures (groynes, sluices, etc), and by sharp changes in dyke orientation, all of which result in adverse local trapping of an already limited stock of propagules.

5.7. Mangrove replanting: a costly option

Mangrove replanting is commonly resorted to in order to restore mangrove systems. Replanting operations can be both costly and very uncertain in terms of success. In neighbouring Guyana, a vigorous programme of replanting (***Guyana Mangrove Restoration Project***) is underway, following recognition of the urgency of mangrove conservation (Fig. 29). The costs in 2012 worked out at US$ 5000-20,000 (4000-16,000 €) for a 100 x 20 m swathe of replanted mangroves (source: Guyana Information Agency: 2012). 60,000 seedlings were planted in 2011 and 200,000 more in 2012 at a cost of US$ 25,000 for 100 ha^{-1} (Guyana Information Agency, 2012). This solution is ecologically sound but is also costly given the natural mangrove-rich context of Guyana (Anthony and Gratiot, 2012b). The range of reported costs for mangrove restoration ranges widely from US$ 225–216,000 ha^{-1} without the cost of the land. Lewis (2005) reported a cost range of mangrove restoration of US$ 225–216,000 ha^{-1} without the cost of the land. Whatever the option, the price to pay for coastal defence is hard for a developing country like Guyana with a population of 700,000, notwithstanding the virtually total concentration of the population in the coastal zone.

Fig. 29. Photograph of a billboard near Georgetown, Guyana, advertising the Guyana Mangrove Restoration Project. April 2012.

The lessons from the errors in Guyana need to be taken into account in Suriname where the population is less, mangroves are still largely preserved, and pressures on the coastal fringe less acute. Any future efforts at replanting will need careful monitoring of mud-bank topography in order to identify optimal zones for replanting, as shown by data on mangrove colonization and mudflat elevation in French Guiana. The success of mangrove propagule or seedling planting has been shown to depend strongly on topography, with the failure of restoration generally attributed to a poor evaluation of this parameter (Lewis, 2005). Any future efforts at replanting will need careful monitoring of mud-bank topography in order to identify optimal zones for replanting, as shown by data on mangrove colonization and mudflat elevation in French Guiana. The success of mangrove replanting is further dependent on three factors that can randomly affect the newly planted seedlings (Balke et al., 2013): dislodgement due to waves, erosion around roots, and burial by sediment input. Dislodgement occurs due to hydrodynamic drag forces and is especially relevant to recently anchored (viviparous) propagules (*Avicennia germinans*) with short roots. Erosion around the roots can increase the susceptibility to dislodgement. Bigger seedlings facing erosion will fail before they get dislodged, as remaining roots in the soil are not strong enough to support the seedling to stand upright, resulting in toppling-failure. Fluid motion exerts a force on the seedling decreasing the resistance to toppling. New layers of sediment can get deposited and smother established seedlings and anchored propagules or entirely bury them.

The first two conditions are very likely the main explanation for differences in the success of mangrove replanting carried out in Guyana since 2011 in various sites, where the success ranged from high to very low. Low success levels occur where replanting has been inadvertently carried out in interbank areas, resulting in waves washing away the young plants, or where levels of accretion, despite the presence of a bank, have been too low.

5.8. Mud-accretion enhancement options

Measures aimed at enhancing sedimentation rates along portions of the coast of Suriname that have suffered from erosion have been recommended by DELTARES (2009) who identified three options to increase sedimentation rates, preferably during phases of natural accretion, or just after, i.e. along coastline stretches protected by mud banks:

1. The erection of works in the form of permeable groynes (using bamboo or similar materials) to trap fines on the mudflats in front of the mangroves with the aim of enhancing accretion above the mean high water level. DELTARES (2009) recognised that such works will only be effective in very shallow areas, or areas characterized by natural accretion (behind mud banks).
2. The deployment of mud engine works at the tail of a passing mud bank with the aim of postponing the transition from an accreting to an eroding coastline. A mud engine consists of artificial mobilization of fines aimed at enhancing sediment accretion.
3. Mud nourishment in critical coastal areas facing net erosion, and achieved by

mobilizing sediments from the seabed through dredging.

Apart from option 3, DELTARES (2009) recognised the importance of avoiding such accretion-enhancement solutions in inter-bank areas subject to strong erosion. This is compatible with the overarching control of inter-bank This condition also must be considered when implementing Sediment Trapping Units (STU, Fig. 30). These are being experimented in an eroding portion of the Weg Naar Zee area by the Faculty of Technology of Anton de Kom University of Suriname, under the leadership of Professor Sieuwnath Naipal. STUs are a good initiative reflecting the concern and the need to look for other solutions other than dykes. ***They are, however, labour-intensive. A factor that needs to be taken into account when implementing them is whether the experimental zone is in an eroding inter-bank area in which case, erosion is likely to continue during the high wave season).***

STUs use relatively permeable bamboo enclosures, and are similar to T-groynes perpendicular to the solution that have been deployed in recent years in eroding mangrove-fronted areas of the Mekong delta shoreline in Vietnam (Albers and Schmitt, 2015). In Suriname, such shore-perpendicular structures may interfere with longshore mud transport, as also recognised by DELTARES (2009). The T-groynes on the Mekong delta are apparently deployed in such a way that they more or less recreate the original coastline by connecting existing headlands with mangrove vegetation (Fig. 31), a design aimed at minimising interference of prevailing currents. Albers and Schitt (2015) reported that these permeable T-groynes decrease the longshore currents and dampen the incoming wave energy by up to 80 % (average 66 %). Such T-groynes may, however, be unsuccessful in sites with limited sediment supply, a constraint in Suriname during inter-bank phases, but, according to Albers and Schmitt (2015), this potential disadvantage must be viewed against the construction costs for these structures which are only about US$ 50–60 per metre in Vietnam, in contrast to US$ 2270 per metre for a 3.5 m high concrete dyke. Their lifespan in Vietnam is about 6-7 years. In Suriname, a cost-benefit analysis of STUs or similar 'soft' semi-permeable structures must consider their lifespan, which will be conditioned by a complex combination of inter-bank duration, position relative to bank migration, etc.

6. ICZM initiatives in Suriname in the face of sea-level rise

The Government of Suriname is charting out an ICZM course that will also envisage coastal protection options in a time of climate change and sea-level rise (Opdam et al., 2006; DELTARES, 2009; Christine Toppin-Allahar and Humphrey R. Shurman Consultants, 2009). These various reports, in addition to the evaluation conducted by Noordam et al. (2007), comprise recommendations regarding the absolute necessity of mangrove conservation. The present report fully supports these observations and recommendations, especially in the context of sea-level rise and climate change.

Fig. 30. Sediment trapping units (STU) being experimented in an eroding portion of the Weg Naar Zee area, October 2015. STUs are a good initiative reflecting the concern and the need to look for other solutions other than dykes. A necessary prior consideration is whether the experimental zone is in an eroding inter-bank area (in which case, erosion is likely to continue during the high wave season).

Fig. 31. Attempts at restoration of an eroded mangrove shoreline using bamboo T-groynes in Bac Lieu Province (Mekong Delta, Vietnam). The longshore elements close the eroded gap in the mangrove forest by connecting the remaining headlands (white arrows). From Albers and Schmitt (2015).

Is mangrove conservation viewed as desirable in the competition with urbanization? If so, this could be in terms, for instance, of the cost of enforcing, through government legislation, development and urbanization setback lines and the conservation of an adequate mangrove fringe, a recommendation proposed several years ago by DELTARES (2009). If dykes are considered, after all, as a viable option by the Government of Suriname, then their design will need to integrate sea-level rise (Fig. 32). If mangrove conservation is not viewed as a suitable option, then there will be a ned for a careful cost-benefit analysis of mangrove removal to the benefit of hard engineering protection to replace mangroves. The pursuit of rampant peri-urbanization north of Paramaribo reduces the protective role of mangroves while generating the idea that dykes will solve the

problem of potential marine inundation. If the practice of mangrove clearance for urbanization continues north of Paramaribo, then any future protection option without mangroves must be geared to: (1) assure protection for the land at the value at which it is presently being sold per hectare (i.e., US$283,000), plus the value of future housing, infrastructure and services! (2) integrate future sea-level rise scenarii in the cost-benefit analysis and design of dykes geared to such protection.

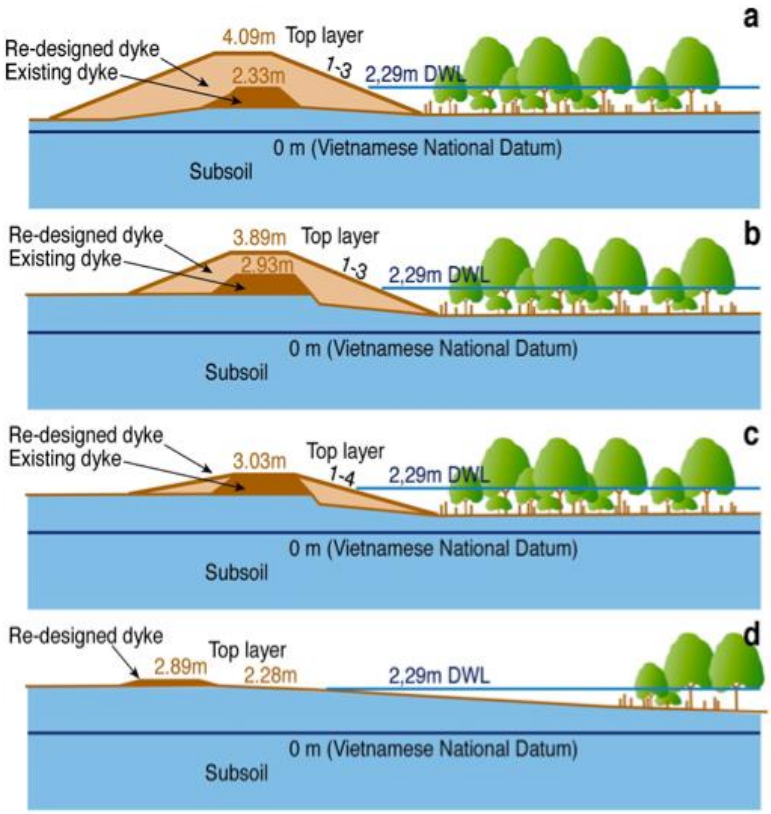

Fig. 32. The necessity of dyke redesigning in a time of sea-level rise: an example from the Mekong delta. From Albers and Scmitt (unpub. data).

The median value of projected sea level rise for the year 2100 is estimated range from 0.44 to 0.74 m for process-based projections, and 0.32 to 1.24 m for semi-empirical projections (IPCC, 2013). The behaviour of mangroves and coastal wetlands in the face of sea-level rise is becoming a hot scientific topic, and has been evaluated in a number of recent studies (e.g., Gedan et al., 2011; Arkema et al., 2013; Kirwan et al., 2013; Krauss et al., 2013; Lovelock et al., 2015). Sea-level rise can threaten the long-term sustainability of coastal communities and valuable ecosystems such as coral reefs, salt marshes and mangroves (Nicholls and Cazenave, 2010; Woodruff et al., 2012; Church et al., 2013; Record et al., 2012; Wong et al., 2014). However, mangrove forests can keep pace with sea-level rise and maintain wetland soil elevations suitable for plant growth that enable them to survive provided that there is sufficient vertical accretion of sediments (e.g. Kirwan and Menogal, 2013). Lovelock et al. (2015) have shown, for instance, that in the Indo-Pacific mangrove region, which holds most of the world's mangrove forests, the delivery of sediment is

declining, owing to anthropogenic activities such as damming of rivers.The authors predicted submergence of mangroves by 2070 in the Gulf of Thailand, the southeast coast of Sumatra, the north coasts of Java and Papua New Guinea and the Solomon Islands. In contrast, these authors showed that the outlook for the persistence ofmangroves into the future is more positive in east Africa, the Bay of Bengal, eastern Borneo and northwestern Australia, where there are relatively large tidal ranges and/or higher sediment supply. The sediment supply criterion is, thus, fundamental in future sea-level rise scenarii wherein mangroves are to play their role as ecological engineers in coastal protection.

In their analysis of mangrove areal extent in French Guiana over the last 64 years, Walcker (2015) and Walcker et al. (2015) showed that fluctuations in such areal extent were not due to current sea-level rise (Fig. 33) nor to fluctuations in tidal components such as the 18.6 year nodal tidal cycle identified by Gratiot et al. (2008) as an important driver of coastal erosion and accretion in the Guianas. These more recent studies highlighted the pervasive role of NAO-driven multidecadal fluctuations in wave energy.

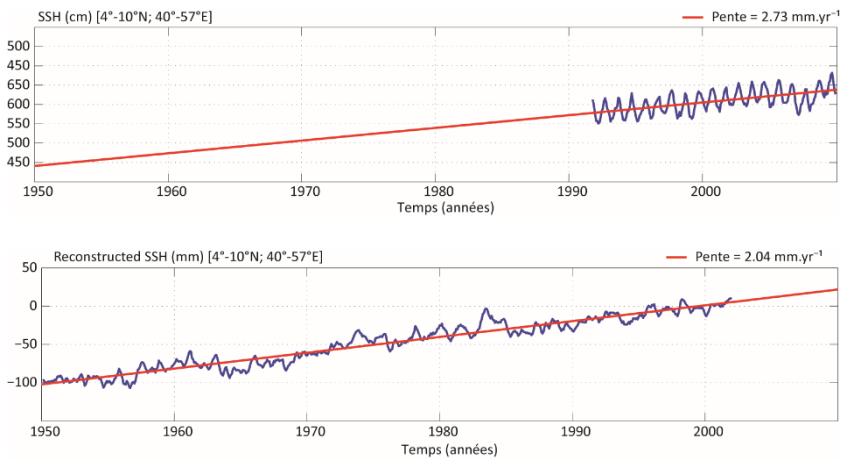

Fig. 33. Reconstruction of Sea Surface Heights (SSH) entre 1950 et 2001, following Church et al. (2004), and observed SSH from oceanic data off the Guianas coast [4°-10°N; 40°-57°E]. From Walcker (2015). Walcker et al. (2015) have shown that current trends in mangrove dynamics are not affected by sea-level rise, no doubt as a result of the high mud supply alongshore, such sediment supply being a fundamental criterion for the survival of mangrove ecsystems in the face of sea-level rise.

It is likely that mangroves in the Guianas will keep pace with all the future sea-level rise scenarii because of the pervasively high mud supply from the Amazon. ***The active ecosystem renewal evinced by the coexistence of dead and dying mangroves, and by rapid mangrove colonization and thriving on new substrates is a feature unique to the coast of the Guianas. This high mud supply criterion will be further reinforced by the unique capacity of mangroves in the Guianas to regenerate rapidly on fresh mud substrates through the twin processes of mud-bank migration and inter-bank erosion.*** Even under these high sediment supply conditions, large-scale mangrove degradation will inevitably

impair the role of these ecosystem engineers in coastal protection, as promoters of coastal sedimentation, and as fish nurseries.

7. Recommendations

- Mangroves have played an active geological role in the building of the Young Coastal Plain in Suriname over the last 5-6000 years. This role needs to be understood and highlighted as an important part of any future coastal zone management initiative in Suriname. A important aspect that needs to be developed is greater citizen awareness, and participatory involvement of all parties and local communities on the way the Suriname coast functions and the importance of mangroves in the development of the coast. ***The Mangrove Forum of Suriname (MAFOSUR) is, in this regard, a laudable initiative that needs to be strongly encouraged***.

- Mangroves are also important in coastal protection, acting as a rampart that slows down shoreline during inter-bank phases in Suriname. Preservation of mangroves is thus a way of "working with nature" as far as coastal protection in Suriname is concerned.

- In Paramaribo as elsewhere along the Suriname coast, mangrove conservation will necessitate the implementation and enforcement of setback lines beyond which urban development should be prohibited. The ongoing urbanization of the coastal plain north of Paramaribo is occurring at the expense of mangroves, which are being cleared, a process that signifies growing encroachment on low-lying areas of the coastal plain that will no longer be protected by mangroves.

- A dyke solution as coastal protection, nor even a mixed dyke-mangrove solution, are not recommended, as it makes no sense destroying mangroves to replace them with dykes that are very costly in the long run, while mangrove replanting in areas where dykes are emplaced and the foreshore eroded is only feasible at great coast. Dykes require adequate dimensioning that should take into account near-future scenarios of sea-level rise. They also require a careful cost-benefit analysis that includes regular maintenance. Dyke construction projects should also be stopped as they may give the impression that they offer long-term protection that encourages increasing urbanization seawards of coastal land in a perspective of future sea-level rise.
- There will also be a need for an ***Observatory of the coast of Suriname***. There is an acute need for more data on this highly dynamic coast, which, in fact, fostered the pioneer studies on the dynamics of the Guianas coast, as shown by the NEDECO (1968) and the fine pioneer study of Augustinus (1978).

8. References

ALBERS, T. & SCHMITT, K., 2015. Dyke design, floodplain restoration and mangrove co-management as parts of an area coastal protection strategy for the mud coasts of the Mekong Delta, Vietnam. *Wetlands Ecology and Management*, **23**, 991-1004.

ALLER, J.Y., ALLER, R.C., KEMP, P.F., CHRISTOSERDOV, A. & MADRID, V.M. 2010b. Fluidized muds: a novel setting for biosphere diversity through geological time. *Geobiology*, **8**, 169–178.

ALLER, R.C., HEILBRUN, C., PANZECA, C., ZHU, Z. & BALTZER, F. 2004. Coupling between sedimentary dynamics, early diagenetic processes, and biogeochemical cycling in the Amazon-Guianas mobile mud belt: coastal French Guiana. *Marine Geology*, **208**, 331–360.

ALLER, R.C., MADRID, V., CHRISTOSERDOV, A., ALLER, J.Y. & HEILBRUN, C. 2010a. Understanding diagenetic processes and sulfur biogeochemistry in tropical deltaic muds: implications for oceanic isotope cycles and the sedimentary record. *Geochimica et Cosmochimica Acta*, **74**, 4671–4692.

ALLISON, M.A. & LEE, M.T. 2004. Sediment exchange between Amazon mudbanks and fringing mangroves in French Guiana. *Marine Geology*, **208**, 169–190.

ALLISON, M.A., LEE, M.T., OGSTON, A.S. & ALLER, R.C. 2000. Origin of Amazon mudbanks along the northeastern coast of South America. *Marine Geology,* **163**, 241–256.

ALLISON, M.A., NITTROUER, C.A. & KINEKE, G.C. 1995. Seasonal sediment storage on mudflats adjacent to the Amazon River. *Marine Geology,* **125**, 303–328.

ANTHONY, E.J., BESSET, M., BRUNIER, G., GOICHOT, M., DUSSOUILLEZ, P. & NGUYEN, V.L., 2015. Linking rapid erosion of the Mekong River delta to human activities. *Scientific Reports,* 5:14745, DOI: 10.1038/srep14745.

ANTHONY, E.J., DOLIQUE, F., GARDEL, A., GRATIOT, N., PROISY, C. & POLIDORI, L. 2008. Nearshore intertidal topography and topographic-forcing mechanisms of an Amazon-derived mud bank in French Guiana. *Continental Shelf Research*, **28**, 813–822.

ANTHONY, E.J., GARDEL, A. & GRATIOT, N., 2014. Fluvial sediment supply, mud banks, cheniers and the morphodynamics of the coast of South America between the Amazon and Orinoco river mouths. *Geological Society, London, Special Publications*, **388**, 533–560.

ANTHONY, E.J., GARDEL, A, GRATIOT, N., PROISY, C., ALLISON, M.A., DOLIQUE, F. & FORMARD, F. 2010. The Amazon-influenced muddy coast of South America: A review of mud bank-shoreline. *Earth-Science Reviews*, **103**, 99–121.

ANTHONY, E.J., GARDEL, A., PROISY, C., FROMARD, F., GENSAC, E., PERON, C., WALCKER, R. & LESOURD, S. The role of fluvial sediment supply and river-mouth hydrology in the dynamics of the muddy, Amazon-dominated Amapá-Guianas coast, South America: A three-point research agenda, *Journal of South American Earth Sciences*, **44**, 18–24.

ANTHONY, E.J. & GRATIOT, N., 2012a. Comment on Protecting Brazil's Coastal Wetlands, http://comments.sciencemag.org/content/10.1126/science.335.6076.1571.

ANTHONY, E.J. & GRATIOT, N. 2012b. Coastal engineering and large-scale mangrove destruction in Guyana, South America: Averting an environmental catastrophe in the making. *Ecological Engineering*, **47**, 268–273.

ARKEMA, K. K., GUANNEL, G., VERUTES, G., WOOD, S.A., GUERRY, A., RUCKELSHAUS, M., KAREIVA, P., LACAYO, M. & SILVER, J.M., 2013. Coastal habitats shield people and property from sea-level rise and storms. *Nature Climate Change,* **3**, 913-918.

AUGUSTINUS, P.G.E.F. 1978. *The changing shoreline of Surinam (South America)*. Ph.D. thesis, University of Utrecht.

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

AUGUSTINUS, P.G.E.F., HAZELHOFF, L. & KROON, A. 1989. The chenier coast of Suriname: modern and geological development. *Marine Geology,* **90**, 269–281.

BALKE, T., BOUMA, T.J., HERMAN, P.M.J., HORSTMAN, E.M., SUDTONGKONG, C. & WEBB, E.L. 2013. Cross-shore gradients of physical disturbance in mangroves: implications for seedling establishment. Biogeosciences 10: 5411–5419. DOI:10.5194/bg-10-5411-2013.

BALKE, T & FRIESS, D.A., 2015. Geomorphic knowledge for mangrove restoration: a pan-tropical categorization. *Earth Surf. Process. Landforms*, DOI: 10.1002/esp.3841.

BAO, T.Q., 2011. Effect of mangrove forest structures on wave attenuation in coastal Vietnam. *Oceanologia*, **53**, 807–818.

BARBIER, E.B., KOCH, E.W., SILLIMAN, B.R., HACKER, S.D., WOLANSKI, E., PRIMAVERA, E.J., GRANEK, E.F., POLASKY, S., ASWANI, S., CRAMER, L.A., STOMS, D.M., KENNEDY, C.J., BAEL, D., KAPPEL, C.V., PERILLO, G.M.E. & REED, D., 2008. Coastal ecosystem based management with non-linear ecological functions and values. *Science*, **319**, 321.

BORSJE, B.W., VAN WESENBEECK, B.K., DEKKER, F., PAALVAST, P., BOUMA, T.J., VAN KATWIJK, M.M., & DE VRIES, M.B., 2011. How ecological engineering can serve in coastal protection. *Ecological Engineering*, **37**, 117-132.

BOSIRE, J.O., DAHDOUH-GUEBAS, F., WALTON, M., CRONA, B.I., LEWIS III, R.R., FIELD, C., KAIRO, J.G. & KOEDAM, N., 2008. Functionality of restored mangroves: A review. *Aquatic Botany*, **89**, 251-259.

BRANDER, L. M., WAGTENDONK, A.J., HUSSAIN, S.S., MCVITTIE, A., VERBURG, P.H., DE GROOT, R.S., & VAN DER PLOEG., S., 2012. Ecosystem service values for mangroves in Southeast Asia: a meta-analysis and value transfer application. *Ecosystem Services*, **1**, 62–69.

BRUNIER, G. 2015. Côtes sableuses-vaseuses sous influence deltaïque de l'Amazone et du Mékong: dynamique morphosédimentaire, stabilité, enjeux et aménagements. PhD thesis, Aix-Marseille Université.

CHRISTINE TOPPIN-ALLAHAR & HUMPHREY R. SHURMAN CONSULTANTS, 2009. Integrated Coastal Zone Management Plan Component II: Legal & Institutional Reforms. Final Report. Government of Suriname, Paramaribo, 21 pp.

CHURCH, J. A., WHITE N.J., COLEMAN, R., LAMBECK, K. & MITROOVICA, J.X., 2004. Estimates of the Regional Distribution of Sea Level Rise over the 1950–2000 Period. *Journal of Climate,* **17**, 2609–2625.

COSTANZA, R., DE GROOT, R., SUTTON, P., VAN DER PLOEG, S., ANDERSON, S.J., KUBISZEWSKI, I., FARBER, S. & TURNER, R.K., 2014. Changes in the global value of ecosystem services. *Global Environ. Change,* **26**, 152–158.

DELTARES, 2009. ICZM Plan Suriname – Implementation of a Pilot Plan for the Paramaribo/Wanica Region. Final Assessment Report.

DONATO, D.C., KAUFFMAN, J.B., MURDIYARSO, D., KURNIANTO, S., STIDHAM, M. & KUNNINEN, M., 2011. Mangroves among the most carbon-rich forests in the tropics. *Nature Geoscience*, **4**, 293-297.

EISMA, D., AUGUSTINUS, P.G.E.F. & ALEXANDER, C.R. 1991. Recent and subrecent changes in the dispersal of Amazon mud. *Netherlands Journal of Sea Research*, **28**, 181–192.

ESIA, ESMP, 2015. 1. Environmental and Social Impact Assessment. 2. Environmental and Social Management Plan, Weg naar Zee, Consultant: P-all Pall Projects Supply Suriname.

FAO, 2007. The world's mangroves 1980-2005. *FAO Forestry Paper*, **153**, Forest Resources Division, FAO, Rome.

FIOT, J. & GRATIOT, N. 2006. Structural effects of tidal exposure on mudflats along the French Guiana coast. *Marine Geology,* **228**, 25–37.

FOWLER, J., 1989. Geotextile reinforced embankments on soft foundations. US Army Corps of Engineers, Geotechnical Laboratory, Washington DC http://www.dtic.mil/dtic/tr/fulltext/u2/a218009.pdf. Accessed 6 Nov. 2015.

FROMARD, F., PUIG, H., MOUGIN, E., MARTY, G., BETOULLE, J. L. & CADAMURO, L. 1998. Structure, above-ground biomass and dynamics of mangrove ecosystems: new data from French Guiana. *Oecologia*, **115**, 39–53.

FROMARD, F., VEGA, C. & PROISY, C. 2004. Half a century of dynamic coastal change affecting mangrove shorelines of French Guiana. A case study based on remote sensing data analyses and field surveys. *Marine Geology,* **208**, 265–280.

FURUKAWA, K., WOLANSKI, E. & MUELLER, H., 1997. Currents and sediment transport in mangrove forests. *Estuarine, Coastal and Shelf Science*, **44**, 301-310.

GARDEL, A. & GRATIOT, N. 2004. Monitoring of coastal dynamics in French Guiana from 16 years of SPOT images. *Journal of Coastal Research, Special Issue*, **39**, 1502–1505.

GARDEL, A. & GRATIOT, N. 2005. A satellite image-based method for estimating rates of mud bank migration, French Guiana, South America. *Journal of Coastal Research,* **21**, 720–728.

GARDEL, A., GENSAC, E., ANTHONY, E.J., LESOURD, S. & LOISEL, H. 2011. Wave-formed mud bars: their morphodynamics and role in opportunistic mangrove colonization. *Journal of Coastal Research, Special Issue*, **64**, 384–387.

GARDEL A., PROISY, C., LESOURD, S., PHILIPPE, S., CAILLAUD, J., GONTHARET, S., ANTHONY, E.J. & BRUTIER, L. 2009. A better understanding of mud cracking processes gained from in situ measurements on an intertidal mudflat in French Guiana. *Journal of Coastal Research, Special Issue*, **56**, 424–428.

GEDAN, K.B., KIRWAN, M.L., WOLANSKI, E., BARBIER, E.B. & SILLIMAN BR, 2011. The present and future role of coastal wetland vegetation in protecting shorelines: answering recent challenges to the paradigm. *Clim. Change*, **106**, 7–29.

GENSAC, E. 2012. *Dynamique morpho-sédimentaire du littoral sous influence amazonienne - Influence des forçages hydrométéorologiques sur la migration des bancs de vase et la mangrove côtière*. PhD thesis, Université du Littoral Côte d'Opale, Dunkerque.

GENSAC, E., GARDEL, A., LESOURD, S., ANTHONY, E.J., PROISY, C. & LOISEL, H. 2011. Short-term prediction of the evolution of mangrove surface areas: The example of the mud banks of

Kourou and Sinnamary, French Guiana. *Journal of Coastal Research, Special Issue*, **64**, 388–392.

GEYER, W.R., BEARDSLEY, R.C., LENTZ, S.J., CANDELA, J., LIMEBURNER, K., JOHNS, W.E., CASTRO, B.M. & SOARES, I.D. 1996. Physical oceanography of the Amazon shelf. *Continental Shelf Research*, **16**, 576–616.

GIRI, C., OCHIENG, E., TIESZEN, L. L., ZHU, Z., SINGH, A., LOVELAND, T., MASEK, J. & DUKE, N., 2011. Status and distribution of mangrove forests of the world using earth observation satellite data. *Global Ecology and Biogeography*, **20**, 154–159.

GRATIOT, N., ANTHONY, E.J., GARDEL, A., GAUCHEREL, C., PROISY, C. & WELLS, J.T. 2008. Significant contribution of the 18.6 year tidal cycle to regional coastal changes. *Nature Geoscience*, **1**, 169–172.

GRATIOT, N., GARDEL, A. & ANTHONY, E.J. 2007. Trade-wind waves and mud dynamics on the French Guiana coast, South America: input from ERA-40 wave data and field investigations. *Marine Geology,* **236**, 15–26.

HARTLÉN, J., 1996. Methods of construction. In: HARTLÉN, J, WOLSKI, W. (eds.), Embankment on organic soils. *Development in Geotechnical Engineering*, **80**. Elsevier Science, Amsterdam, pp. 240–248.

IPCC (Intergovernmental Panel on Climate Change), 2013. Sea level change. In: STOCKER, T.F., QIN, D., PLATTNER, G-K., TIGNOR, M., ALLEN, S.K., BOSCHUNG, J., NAUELS, A., XIA, Y., BEX, V. & MIDGLEY, P.M. (eds) Climate change 2013: the physical science basis. Contribution of working group I to the fifth assessment report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge.

KAMALI, B. & HASHIM, R., 2011. Mangrove restoration without planting. *Ecological Engineering*, **37**, 387-391.

KIRWAN, M.L. & MEGONIGAL, J.P., 2013. Tidal wetland stability in the face of human impacts and sea-level rise. *Nature*, **504**, 53–60.

KRAUSS, K.W., MCKEE, K.L., LOVELOCK, C.E., CAHOON, D.R., SAINTILAN, N., REEF, R. & CHEN, L., 2013. How mangrove forests adjust to rising sea level. *New Phytology*, **202**, 19–34.

LEE S.Y., PRIMAVERA J.H., DAHDOUH-GUEBAS F., MCKEE K., BOSIRE J.O., CANNICCI S., DIELE K., FROMARD F., KOEDAM N., MARCHAND C., MENDELSSOHN I., MUKHERJEE N., & RECORD S., 2014. Ecological role and services of tropical mangrove ecosystems: A reassessment. *Global Ecology and Biogeography*, **23**, 726–743.

LEFEBVRE J.P., DOLIQUE F., & GRATIOT N., 2004. Geomorphic evolution of a coastal mudflat under oceanic influences: An example from the dynamic shoreline of French Guiana. *Marine Geology*, **208**, 191–205.

LEWIS III, R.R., 2005. Ecological engineering for successful management and restoration of mangrove forests. *Ecological Engineering*, **24**, 403-418.

LOVELOCK, C.E., CAHOON, D.R., FRIESS, D.A., GUNTENSPERGEN, G.R., KRAUSS, K.W., REEF, R., ROGERS, K., SAUNDERS, M.L., SIDIK, F., SWALES, A., SAINTILAN, N., THUYEN, L.X., & TRIET, T., 2015. The vulnerability of Indo-Pacific mangrove forests to sea-level rise. *Nature*, **526**, 559-563.

MARTINEZ, J.M., GUYOT, J.L., FILIZOLA, N. & SONDAG, F. 2009. Increase in sediment discharge of the Amazon River assessed by monitoring network and satellite data. *Catena*, **79**, 257–264.

MILLIMAN, J.D. & FARNSWORTH, K.L. 2011. *River Discharge to the Coastal Ocean*. Cambridge University Press, Cambridge.

MOLLERI, G.S.F., DE NOVO, M.L. & KAMPEL, M. 2010. Space-time variability of the Amazon River plume based on satellite ocean color. *Continental Shelf Research*, **30**, 342–352.

NIJBROEK, R.P., 2014. Mangroves, mudbanks and seawalls: whose environmental knowledge counts when adapting to sea level rise in Suriname? *Journal of Political Ecology*, **21**, 533-550.

NEDECO, 1968. Surinam Transportation Study: Report on Hydraulic Investigation. Netherlands Development Company, NEDECO, Den Haag, 293 pp.

NICHOLLS, R. J. & CAZENAVE, A., 2010. Sea-level rise and its impact on coastal zones. *Science*, **328**, 1517–1520.

NOORDAM, D., 2007. Promotion of sustainable livelihood within the coastal zone of Suriname, with emphasis on Greater Paramaribo and the immediate region. Netherlands Country Assistance Program, Phase 2 (NCAP-2).

OPDAM, H.J., MONBALIU, J., VAN MAREN M., NAIPAL, S., DEL PRADO, N., MOHADIN, K., WIERSMA, F., & TOORMAN, E., 2006. Towards ICZM in Suriname – Final Report. Terms of Reference - Integrated Coastal Zone Management Plan, Suriname and Pilot Project, Inter-American Development Bank.

ORGANIZATION OF AMERICAN STATES, 2005. Integrated and Sustainable Management of Transboundary Water Resources in the Amazon River Basin. *Water Project Series*, **8**. World Wide Web Address: http://www.oas.org/osde

PHAN, S.K., VAN THIEL DE VRIES, J.S.M. & STIVE, M.J.F., 2015. Coastal mangrove squeeze in the Mekong Delta. *Journal of Coastal Research* **31**, 233-243.

PLAZIAT, J.C. & AUGUSTINUS, P.G.E .F. 2004. Evolution of progradation/erosion along the French Guiana mangrove coast: a comparison of mapped shorelines since the 18th century with Holocene data. *Marine Geology*, **208**, 127–143.

PROISY, C., GRATIOT, N. ANTHONY, E.J., GARDEL, A., FROMARD, F. & HEURET, P. 2009. Mud bank colonization by opportunistic mangroves: a case study from French Guiana using lidar data. *Continental Shelf Research*, **29**, 632–641.

RAO, N.S., GHERMANDI, A., PORTELA, R. & WANG, X., 2015. Global values of coastal ecosystem services: A spatial economic analysis of shoreline protection values. *Ecosystem Services*, **11**, 95-105.

RECORD, S., CHARNEY, N. D., ZAKARIA, R. M. & ELLISON, A. M., 2013. Projecting global mangrove species and community distributions under climate change. *Ecosphere*, **4**, 1–23.

TEMMERMAN, S., MEIRE, P., BOUMA, T.J., HERMAN, P.M.J., YSEBAERT, T. & DE VRIEND, H.J., 2013. Ecosystem-based coastal defence in the face of global change. *Nature*, **504**, 79–83.

VAN LEDDEN M., VAUGHN G., LANSEN J., WIERSMA F., & AMSTERDAM M., 2009. Extreme wave event along the Guyana coastline in October 2005. *Continental Shelf Research*, **29**, 352–361.

WALCKER, R. 2015. *Dynamique spatiale des mangroves de Guyanz entre 1950 et 2014 : forçage atmosphérique et consequence pour le stock de carbone côtier.* PhD thesis, Université de Toulouse.

WALCKER, R., ANTHONY, E.J., CASSOU, C., ALLER, R.C., GARDEL, A., PROISY, C., MARTINEZ, J.M. & FROMARD, F., 2015. Fluctuations in the extent of mangroves driven by multi-decadal changes in north atlantic waves. *Journal of Biogeography*, **42**, 2209-2219.

WINTERWERP, J. C., ERFTEMEIJER, P.L.A., SURYADIPUTRA, N., VAN EIJK, P. & ZHANG, L. 2013. Defining eco-morphodynamic requirements for rehabilitating eroding mangrove-mud coasts. *Wetlands*, **33**, 515-526.

WITTMANN, H., VON BLACKENBERG, F., MAURICE, L., GUYOT, J.L., FILIZOLA, N. & KUBIK, P.W. 2011. Sediment production and delivery in the Amazon River basin quantified by in-situ-produced cosmogenic nuclides and recent river loads. *Geological Society of America Bulletin*, **123**, 934–950.

WONG P.P., LOSADA I.J., GATTUSSO J.P., HINKEL J., KHATTABI A., MCINNES K., SAITO Y., & SALLENGER A., 2014. Coastal systems and low-lying areas. *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*.

WONG, TH., E., DE KRAMER, R., DE BOER, P.L., LANGEREIS, C. & SEW-A-TJON, J. 2009. The influence of sea level changes on tropical coastal wetlands: the Pleistocene Coropina formation, Suriname. *Sedimentary Geology*, **216**, 127–137.

WOODRUFF, J.D., IRISH, J. L. & CAMARGO, S. J., 2013. Coastal flooding by tropical cyclones and sea-level rise. *Nature,* **504**, 44–52.