Impacts of sand mining on beaches in Suriname

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Background

The goal of this report is to inform the Surinamese Government and Public on the impacts of sand mining on beaches in Suriname, based on the analysis of satellite images of the Suriname coast, and on ground observations on Braamspunt beach, and the necessity for conservation of beach sand budgets, beaches being a fundamental element of the coast of Suriname. The expertise proposed in the course of this work notably covers the following themes: (1) the Suriname coastal system and the role of sandy beaches in this system; (2) the importance of beaches as wave-energy buffers fundamental in coastal protection and as sites for the nesting of marine turtles; and (3) the impacts of sand removal on beaches and on the stability of the Suriname coast.

The work has been based on comprehensive facts, evaluations, and presentations drawn from: (1) personal expertise; (2) analysis of freely available satellite imagery covering the coast of Suriname; (3) a one-week field mission in Suriname in February 2016 devoted to ground data collection from Braamspunt beach; and (4) gathering of additional information, through consultation and exchanges with relevant agencies, interest groups and individuals. Convincing arguments for proscribing sand mining on beaches and conserving beach sediment budgets are presented via the following:

(1) A simple but thorough explanation on how the Suriname coast functions and the role of sandy beaches in the short- to long-term functioning of this coast. The report demonstrates how beaches (called ‘cheniers’ in the geological literature, and ‘rits’ in Suriname) are important in coastal protection on the Suriname coast within a framework of abundant but pulsed mud supply alongshore. This knowledge is based on nearly two decades of the expert’s research on the dynamics of the Amazon-Orinoco coast with several publications on the subject (see references with expert’s publications on the Guianas coast).

(2) A presentation of the morphodynamics and the fragility of the sediment budget of Suriname beaches and their exacerbated vulnerability as a result of beach sand mining.

(3) The deliverables have been in the form of: (a) PPT presentations on items 1 and 2, and (b) this final report. 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 setting up a coastal observatory, and adopting policies guided by Ecosystem-Based Management (EBM) that fully integrate short- to long-term perspectives of the future evolution of this coast as well as the importance of beach conservation.

The extensive empirical knowledge gathered over the last two decades from scientific research on the Guianas coast and culled from the literature has formed the basis for Part 1 of this report. The results presented in this report were also gathered from various sources and using a range of methods. These form the basis for Part 2. Finally, Part 3 proposes a framework for the establishment of a coastal observatory.
Abstract

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 mouth of the Orinoco River in Venezuela. 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. In inter-bank zones, higher incident wave energy leads to rapid erosion of the mangrove areas. This erosion can be strongly mitigated by beaches of sand and/or shells called “ritis” in Suriname or “cheniers” in the international literature that very efficient natural dissipaters of wave energy (many times more for the same width than a mangrove fringe). The relationship between mud banks, mangroves, cheniers, and the growth of the coastal plain is, thus, important in understanding the past, present and future state-of-health of the coast of Suriname. In addition to their role in coastal protection, cheniers provide cultural, recreational and ecological functions and services in Suriname. Topographically higher than the surrounding muddy deposits, cheniers are used as settlement sites and as roadways. Cheniers forming the present shoreline provide nesting sites for marine turtles, and habitat for shorebirds and other wildlife. They have also been mined extensively for aggregate for the road and building industry, although these activities should be prohibited on active shoreline cheniers and on cheniers near the present shoreline because of the limited and fragile sediment budget of these deposits.

Following the stabilization of the present sea level 5-6000 years ago and commencement of growth of the Young Coastal Plain, many cheniers were integrated in the growth of this plain. The latest period of growth of this plain (probably covering the last 1000 years) has been characterized by important muddy sedimentation and more limited chenier formation than during earlier periods. Active shoreline cheniers are presently relatively rare on the Suriname coast, due to blanketing of bedload (sand and shells) by mud. Commercial sand mining has been carried out in a number of areas along the Suriname coast, notably on Braams punt beach, a major turtle-nesting beach on the east bank of the Suriname River, constructed by waves essentially from sand supplied in the past by the Maroni River. Analysis of satellite images aimed at highlighting the shoreline changes between 1987 and 2016 that have affected the Suriname coast, notably under the overarching influence of mud banks, shows that Braams punt beach has significantly shortened. This process has resulted from much of the sand supply coming from the updrift part (east, from the Maroni) of the beach being integrated into a chenier driven landward by waves over mangroves and isolated from the present shoreline by a mud bank migrating between the Maroni and Suriname Rivers. Sand mining has essentially affected the downdrift (west) end of the beach which compromises successive spit recurves ending at the mouth of the Suriname River. These conditions, and the rarity of currently active cheniers, signify relatively fragile beach systems that have been strongly impacted by sand mining. This activity impairs the coastal protective role played by the rare subsisting beaches in Suriname, while also contributing to depriving Suriname of its already relatively rare, and therefore valuable, beach nesting sites for marine turtles. Beach sand mining in Suriname should therefore be completely proscribed and other sources of commercial aggregate should be explored, such as, in order of preference: inland river beds, bedload trapped behind dam reservoirs, the most inland cheniers, and estuarine sand shoals. In addition, a coastal observatory needs to be set up in order to monitor shoreline change and act as an interface with actors and stakeholders of the Suriname coast. The global change currently observed is deemed to generate accelerated coastal erosion and an increase in frequency and intensity of extreme weather events. Low tropical coasts such as the coast of Suriname are particularly vulnerable. Awareness of this
vulnerability should develop and should prompt recourse to the construction of an operational coastal observatory and the adoption of sound and sustainable Ecosystem-Based Management. The aims of these initiatives would be to characterize the coastal morphology of Suriname and to monitor the rhythms and mechanisms of evolution, adaptation and resilience of the coast in the face of sea-level rise and extreme climate and wave events (surges, strong swells...) and to forewarn on any initiatives that could engender coastal vulnerability, lower coastal resilience, and negatively impact on coastal sustainability. Based on this, appropriate defence and/or adaptation strategies, including pre-emptive strategies, can be developed and implemented.

Summary of Recommendations
• Beaches (cheniers) have played an important geological role in the building of the Young Coastal Plain in Suriname over the last 5-6000 years, and are the most important natural sources of coastal protection by buffering ocean waves. 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 cheniers, but also mud banks and mangroves, in the development and dynamics of the coast, need to be fostered.
• The implementation of Ecosystem-Based Management, following previous recommendations by various agencies and organizations on sound management of the Suriname coast, will need to be pursued with vigour.
• Beaches need to be conserved, and this entails proscription of mining activities that impair their roles as natural sources of coastal protection, recreational sites and sites for marine turtle nesting. This will necessitate the implementation and enforcement of a legal ban on beach sand mining.
• An observatory of the coast of Suriname needs to be set up, as there is an acute need for data on which to base coastal zone management decisions on this highly dynamic coast.
PART 1. THE ENVIRONMENT, CONTEXT AND FORMATION OF SANDY BEACHES IN SURINAME
1.1. Introduction

The coast of Suriname (Fig. 1) forms the present seaward fringe of a mud-dominated coastal plain on the Atlantic coast of northern South America between Amapá, in Brazil, and the Paria Peninsula in Venezuela. The coast forms the terminus of rivers draining the Andes, the Andean foreland, the Llanos, and the Brazil and Guiana Shields (Fig. 2). By far the most important of these rivers is the Amazon, which dominates the muddy fine-grained sediment dispersal and geological development of this coast. The resulting sediment accumulation pattern has seen significant coastal progradation (seaward coastal advance) along much of the 1500 km of coast from Amapá 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 coastal plain on which Paramaribo and other coastal towns in Suriname are built, has occurred through onshore welding of mud derived from mud banks that migrate from the Amazon (Fig. 3). In Suriname, the seaward fringe of this coastal plain shows three individual mud lobes between the four main rivers, each lobe ending in a mud cape (Fig. 1).

![Fig. 1. Google-earth image of the Suriname coast showing three individual mud capes between the four main rivers, and the location of Braamspunt beach at the terminus of the Maroni-Suriname mud cape.](image)

The hydrology and sediment fluxes of many of the smaller rivers, which essentially drain the crystalline rocks of the Guiana Shield, are still largely unknown. Even the catchment size of many of these rivers is not known with certainty. These rivers seem to be important suppliers of sand, thus contributing to a mixed sedimentary regime in which the Amazon mud supply
very largely dominates. Among these rivers are the Maroni (Marowijne), which forms the frontier between Suriname and French Guiana, and the Suriname, on the west bank of which Paramaribo has developed.

The Guianas coastal 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 Amazon is the world’s largest river system and has a drainage basin of $6.1 \times 10^6$ 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$^3$ per second (Martinez et al., 2009). Recent estimates of sediment discharge range from 754 to 1000 million tonnes a year (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 year, although the specific sediment yield of 190 tonnes per km$^2$ a year 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.

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, and the development and preservation of beaches, called “cheniers” in the international literature, and “rits” in Suriname.
The mud-bank system is associated with important ecological changes involving the development and destruction of mangrove forests (Anthony et al., 2010, 2014). 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.

**Fig. 3.** 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 Suriname coast is affected by trade winds from the northeast that are mainly active from January to May. 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 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 (Fig. 4). 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 Suriname coast is, thus, essentially a “wave-dominated coast”, characterized by a clear seasonal regime (Fig. 4). 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. The wave climate shows variations in wave height (which equates with wave energy) at timescales ranging from multi-annual, hinged on El Nino phases (Anthony et al., 2002), to multi-decadal, in association with large-scale atmosphere-ocean interactions in the North Atlantic (Walcker et al., 2015). Tides are semi-diurnal (i.e., there are two tides a day) and the spring tidal range (the largest range during the fortnightly tidal cycle) in Suriname is low to moderate (microtidal to low-mesotidal - about 1.5 to 3 m).

![Fig. 4](image_url). 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 distinctly seasonal, and 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.
The Guianas mud-bank system

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 (Moller 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 which drives the alongshore migration of the mud banks.

An unanswered question concerns how successive individual mud banks start forming 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 the succession of banks alongshore between the mouths of the Amazon and the Orinoco. 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 year (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.

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 (erosion) phases. By buffering wave energy, cheniers play a fundamental role in coastal protection in inter-bank areas. The duration of a bank or inter-bank phase at any point on the coast depends essentially on: (1) the size, morphology and rheology (mud characteristics) of a bank, (2) wave energy, and (3) the presence of river outflow. This combination of factors, plus local to regional factors such as shoreline orientation and morphology, signify 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 probably by meso-scale (decadal-to-multi-decadal) coupled atmospheric-oceanographic interactions involving changes in trade-wind intensity and their effect on the waves generated by these winds, as hypothesized 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 multi-decadal 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, and thus in wave characteristics, the NAO oscillations thus influence...
the rate at which mud banks migrate, and this has consequences on the dynamics of the coast and of cheniers, as shown in a subsequent section. Multi-annual wave variability associated with El Nino phases is also important in rates of bank migration or shoreline retreat (Anthony et al., 2002).

Once formed, the mud banks translate alongshore under a continuous process of recycling by waves (Fig. 7). Given the volume of mud contained in each mud bank, the alongshore migration process does not involve an ‘en masse’ movement, but rather resuspension and transport of mud by incident waves (Fig. 7) that reach the coast at an angle (obliquely-incident waves). This migration is assured by wave dissipation, and by wave- and wind-induced currents, notably longshore currents generated when waves impinge on the coast at an oblique angle. In Suriname, this angle can range from 10 to 45°, and the longshore drift potential of sediment (this occurs for both mud and sand) increases with the angle up to 45°. 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, especially, river mouths (Gardel and Gratiot 2005; Anthony et al., 2013).

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.

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” (e.g., the Maroni and
Suriname Rivers, discussed in section 1.5). 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 inducing 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 (Anthony and Gratiot, 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 colonized by mangroves, (3) trailing back) edge of mud bank undergoing erosion, and (4) a subtidal leading (front) edge sector. From Anthony et al. (2014).

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 (≥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.

Fig. 7. Schematic of a typical mud bank showing its dynamics combining wave reworking of the bank surface, shoreline accretion and erosion, chenier formation, and mangrove colonization and removal, all of which are embedded in the bank migration process. Wave breaking and dissipation lead to the mobilization 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 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, and especially the cheniers in such inter-bank areas, slow down this erosion process until the next bank phase. Modified after Anthony et al. (2014).

Over large parts of the bank surface, fluid mud pushed shoreward by breaking and dissipating waves during the fortnightly neap-to-spring and spring-to-neap tidal cycles 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 cyclic pressures generated by waves 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 satellite images, Light Detection And Ranging (LiDAR) data, and high-resolution
topographic surveys of bank surfaces 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 bar features generally occur as shore-parallel bodies in the
inner mud bank areas near the terrestrial shoreline, 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 fortnightly
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 colonize the mud banks.

1.3. Cheniers and chenier beaches: natural wave-energy buffers and ecosystems

Within the muddy coastal plain of the Guianas occur interspersed sandy beach deposits,
called “cheniers” in the international literature, and “rits” in Suriname. These deposits are
especially common in the vicinity of the larger river mouths, notably in Suriname and Guyana.
Their presence reflects an important contribution of sand by the Guiana Shield rivers, such as
the Maroni, to the coastal depositional system of the Guianas coast (Anthony et al., 2014), as
well as shelly material accumulated in the rich coastal and shallow-marine ecosystems of the
Guianas. Braamspunt beach, lying on the most westward part of the coast between the mouths
of the Maroni and the Suriname Rivers (Fig. 1), is the most recent of these beach deposits.

The term “chenier” is used specifically in the geoscience literature to identify bodies of
wave-reworked sand resting stratigraphically on a muddy substrate (Fig. 8) (stratigraphy is the
branch of geology concerned with the order and relative position of sediments, deposited as
strata, and their relationship to the geological timescale). Cheniers are, thus, similar to any
other wave-formed beach, except that their dynamics are strongly embedded in reworking and
segregation of sand (or gravel and shells) from a muddy substrate over which the chenier also
develops. Cheniers are very commonly associated with river deltas such as the Mississippi,
where both mud and sand are supplied to the coast. The word ‘chenier’ is derived from the
French ‘chêne’, meaning oak, such tress being common in Louisiana (Cajun French settlers)
where they colonize linear sandy or shelly wave-formed beach deposits that are higher-lying
than the surrounding muddy deltaic plains of the Mississippi, and that thus serve as settlement
areas. Cheniers, in Suriname, as elsewhere, consist of local concentrations of fine to coarse
(0.05-2 mm or 50 to 2000 μm) sand, commonly with a variable, but locally significant amount
(5->50%) of whole or broken-up shells winnowed out from subtidal mud and/or transported
alongshore. Chenier sands also commonly include a small but variable amount of dark heavy minerals that form local concentrations on the beach face as a result of hydraulic segregation, as waves break on the beach, and in the course of longshore transport.

![Simplified stratigraphic sketch showing chenier sands](image)

**Fig. 8.** Simplified stratigraphic sketch showing cheniers composed of coarse sediment (sand, gravel, shells) resting on a fine-grained (muddy) substrate. Cheniers are reworked by waves into coherent bodies, and reflect grain-size segregation processes in wave-exposed coastal environments.

Cheniers are generally important on muddy coasts, including the Suriname coast, as they serve as settlement areas, while providing coast-parallel routes and aggregate for building materials in situations where this is not pernicious to their role in coastal protection. Indeed, on mud-rich coasts such as those of the Guianas, cheniers are an important economic and ecological asset. As deposits formed by wave runup on beach faces lying at higher elevations (2-4 m higher) than the level of the backshore muddy plains on which they also rest, cheniers can protect these low-lying areas against flooding. As open beaches, cheniers are fundamental in dissipating wave energy and, thus, in protecting backshore areas that are occupied by human settlements, farms, roads, and other infrastructure. This wave-energy buffering capacity is a paramount attribute of beaches, since, by virtue of their sedimentary framework composed of individual clasts (sand, gravel, shells), they adapt to fluctuations in wave energy by adopting the most optimal morphological configuration for energy buffering. Buffering wave energy is considered as the prime function of beaches in nature. **It is, therefore, not surprising that cheniers develop in inter-bank areas where wave energy is high. This highlights their fundamental role as the most efficient natural providers of coastal protection on mud-dominated coasts.** Cheniers are, for instance, much more efficient than mangroves in dissipating wave energy and in assuring backshore protection. Where a mangrove band up to 1000 m is needed to dissipate 90% of a 1 m high wave (e.g., Barbier et al., 2008), the same level of dissipation is rapidly assured on a beach by wave breaking and dissipation within a relatively narrow surf zone (the zone between wave breaking and the beach face) and a beach face only a few tens of metres wide. The rare perennial sandy beaches of the Guianas coast also provide recreation outlets for the coastal populations and are especially fundamental to the ecology of the protected marine turtles, *Lepidochelys olivacea, Chelonia mydas, Eretmochelys imbricata, Dermochelys coriacea* (Girondot et al., 2002; Kelle et al. 2007; Caut et al., 2007).
1.4. Bank and inter-bank phases, and inter-bank chenier development

The relationship between mud banks, mangroves, cheniers and the growth of the coastal plain is important in understanding the past, present and future state-of-health of the coast of Suriname. 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 as fluid mud is driven onshore during periods of stronger waves and at high (flood) tide. 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).

Along any stretch of alluvial coast, an inter-bank area always occurs in the wake of the trailing (back) 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 consolidated mud, and the shoreline is composed of either stiff consolidated mud bearing mangroves that may be rapidly eroded (Fig. 9), or cheniers (Fig. 10), where sand or shells are locally abundant and available. In the next section, 1.5, it will be shown that there is a second context wherein cheniers form: in the vicinity of the large river mouths where sand supply is most readily available.

Inter-bank dynamics are essentially driven by erosive wave activity, as opposed to the accretionary conditions associated with strong dissipation of wave energy over banks. The absence of a mud bank in inter-bank areas allows for significant wave energy incidence along the shore, but this effect is strongly modulated by the tide between low and high stages, and from neap to spring conditions. Notwithstanding the higher-energy status of inter-bank areas, inter-bank shorefaces (the offshore zone) are permanently muddy due to the pervasive influence of the Amazon muddy discharge, and as a result, the wave regime shows changes from spilling to solitary waves (Fig. 11) that are modulated by tides. Waves remain in the spilling domain up to the ‘terrestrial’ shore at high tide, whereas solitary wave behaviour expresses dissipation at low tide over the inner shoreface. Strong wave energy gradients occur in inter-bank areas during the course of the tidal excursion, with systematic wave-energy dampening by subtidal mud at low tide, and wave heights significantly increasing at high tide. High-tide hydrodynamic conditions are associated with a relatively narrow surf zone and energy concentration on the shore due to the marked topographic difference between the flat muddy shoreface and the relatively steep (erosional) concave inshore profile. This high-tide wave energy incidence can lead to the rapid erosion of consolidated shoreline mud and large-scale mangrove removal (Fig. 9).
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.

The relatively energetic wave conditions in interbank areas can lead to sediment sorting processes wherein sand, dominantly transported as bedload, becomes segregated from mud transported as either suspended particles or as mud clasts that undergo progressive attrition and breakdown. The sand has three basic sources: (1) the main source is fluvial quartz sand previously transported alongshore by wave-induced longshore drift and deposited on the shoreface during earlier inter-bank phases, (2) non-fluvial (marine) carbonate shells and shelly sand in the nearshore zone reworked onshore by waves and derived from the abundant skeletal remains of organisms that thrive in rich ecosystems associated with the Amazon-Orinoco mangrove system, one of the world’s most important, (3) sand reworked by waves from older earlier cheniers inland where coastal erosion has removed much of the sediment deposited during a previous mud bank phase (see section 1.6). The sediment segregation involving the separation of sand from mud is a paramount characteristic of wave-dominated coasts such as the Suriname coast. It also signifies that coherent sand bodies can be formed in spite of the overwhelmingly muddy environment. This is also an important criterion since the formation of such coherent sandy bodies represents an efficient way of further dissipating the high incident wave energy during inter-bank phases. Thus, where there is sufficient sand sorted out and concentrated by waves to form coherent intertidal sand bodies, cheniers develop.

Cuspat e bays, as shown in Fig. 10, are sometimes associated with sandy, and more or less abundant shell, concentrations, suggesting that either: (1) sediment sorting processes in the inshore area may be operating under higher incident wave energy in these zones, or (2) sand and shelly material is trapped in lower-energy embayed zones. The overall mechanisms underlying the mega-cuspat e morphology of inter-bank zones are, however, not known. Mega-cusp horns may correspond to mangrove ‘headlands’ lying on significantly over-consolidated mud. However, the regular alongshore spacing of these forms suggests the role of a driving mechanism, probably of hydrodynamic origin. These features are probably the mud-environment equivalents of sandy beach mega-cusps and bays associated with modifications in wave energy cascades (infragravity waves) or with self-organized patterns of coastal morphology. They may have developed from irregular initial alongshore variations in the resistance of over-consolidated shoreline mud to waves.
1.5. River mouths and chenier development

There appears to be a clear gradient in the degree of chenier formation over the last 5-6000 years between the Suriname-Guyana-Venezuela sectors of the Guianas coast, where chenier formation has been significant, resulting in the incorporation of numerous bands of cheniers in the prograded Holocene coastal plain, and the Brazil and French Guiana sectors where current chenier formation and fossil cheniers within the prograded muddy plain are relatively less developed. This alongshore gradient probably reflects the sand-supply influence of the much larger-sized rivers debouching from the granitic catchments from Suriname to Venezuela, including the large Orinoco delta.

The migrating mud banks tend to imprint a westward deflection of the mouths of the smaller river mouths on the coast. The deflection commonly forms a more or less prominent mud capes colonized by mangroves, reflecting the overarching influence of mud accumulation in transit from the Amazon. Such mud capes and their associated cheniers generally provide shelter for parts of the coast to the west from direct attack by ocean waves coming from the northeast. Paramaribo is niched on the west bank of such a cape deflection of the mouth of the Suriname River. It is important to note that this deflection is less expressed where large rivers debouch on the coast. Fine examples are provided by the two large rivers at the borders of Suriname, the Maroni and the Corantijn Rivers (Fig. 1). In the case of the Corantijn River, the mud cape appears to correspond to large-scale storage of mud on the east bank of the river associated with fluvial jet outflow effects that are described below.

The large liquid discharge of the bigger rivers (mean discharge of 1700 m$^3$ per second, for instance, for the Maroni River) appears to generate what can be called a “hydraulic-groyne effect” (Anthony et al., 2013; Gensac et al., 2016), 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 that may cause erosion 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 large estuarine sand banks (Fig. 12) that act as a fluvial sand supply reservoir for the construction of beaches adjacent to the river mouths and cheniers both updrift (eastward of the river mouths) and downdrift (westwards of the river mouths). The “hydraulic-groyne” effect may also be responsible for:

(1) persistent muddy accretion on coastal sectors updrift (east) of the large river mouths by slowing down the migration of mud, encouraging updrift mud concentration and, therefore, hindered muddy sedimentation downdrift (west). This is probably the case on the east bank of the Corantijn River which has shown significant persistent accretion over the last century;

(2) significant offshore deflection of mud banks in transit alongshore, as schematized in Fig. 12; this phenomenon thus goes with the formation of river-mouth mud capes for some of the small or moderately sized rivers such as the Suriname (Fig. 1);
Fig. 9. (a) Shoreline retreat in the course of an inter-bank phase in French Guiana, and (b) alternations of mega-cusps and bays 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, and especially cheniers (Fig. 10), play an important role by absorbing the pounding from the waves, thus slowing down the retreat process until the next bank comes along.
Fig. 10. Alongshore alternations of mega-cusps and bays in an inter-bank zone in French Guiana. Sand concentrations in the bays form cheniers.

Fig. 11. Inter-bank (c) and mud bank (e) profiles and schematic wave attenuation patterns. MWL is the Mean Water Level and MTR the Mean Tidal Range deduced from tidal signal series; (d), (f) associated sediment surface concentration profiles; the circle diameter is representative of the vertical error bar.

(3) temporary and partial liquefaction (disintegration) of mud banks as they go through the river mouth and are exposed to the fluvial outflow jet, especially during the high river discharge season;

(4) in turn, the hindered muddy sedimentation downdrift generally goes with more active sandy deposition, where a river supplies large quantities of sand, as the local absence of mud leads to individualization of sandy deposits and beaches and cheniers, a fine example being that of the west bank of the Maroni (Fig. 13);

(5) where fluvial sand supply is sequestered within the estuary of the river (the case of the smaller rivers with a smaller supply of sand), as in the case of the mouth of the Suriname, this effect can result in protracted inter-bank phases in the downdrift sectors of coast, such as in the Weg Naar Zee area north of Paramaribo, on the west bank of the mouth of the Suriname, with consequent potentially persistent erosion.
To summarize, therefore, cheniers can develop in inter-bank areas as a result of the winnowing of inherited fluvial, older chenier, and carbonate sand. There are numerous examples of such cheniers (type 1) interspersed throughout the muddy Guianas coastal plain and the Young Coastal Plain of Suriname. The shell-rich cheniers in the area of Paramaribo, and which served in providing building materials for some of the historic buildings in the city such as Fort Zeelandia, are thus formed in this way. Type 2 cheniers, described in this section, are those associated with direct river-mouth supply of sand. They are common in the vicinity of such river mouths throughout the Guianas coast, with the fine examples at the mouth of the Maroni (Fig. 13). These two types of cheniers differ radically from the rare, bedrock-bound embayed beaches in French Guiana (Cayenne and Kourou), which function as relatively classical beaches, albeit periodically mud-bound (Anthony et al., 2002, 2004).

**Fig. 12.** Schematic illustration of the “hydraulic-groyne effect” in river mouths on the Guianas coast, as exemplified by the mouth of the Maroni. The strong river jet outflow (2) acts just like a groyne, liquefying and diverting offshore the migrating mud bank (1), 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 further downdrift (towards the west) along the coast (3, 4) in inter-bank zones.

### 1.6. The Suriname Coastal Plain and long-term chenier development

Mud-bank migration involves spatio-temporal alternations of bank and inter-bank phases that imply periodic recycling by waves (at timescales of the order of years along any given stretch of shoreline) of muddy sediments, and reworking of the minor (relative to mud) component of chenier deposits. Each inter-bank phase results in the partial, or rarely, total removal, of the coastal stratigraphic package built during accretionary bank phases (Allison and Lee, 2004). Total removal of the stratigraphic package deposited during a bank phase can occur during a subsequent inter-bank phase characterized by particularly high wave-energy seasons such as during El Niño years (Gratiot et al., 2008). More commonly, removal is partial, signifying that there is a net coastal plain growth with each cycle (Allison and Lee, 2004).
The Young Coastal Plain is thus the net result of a progradational system wherein sediment accumulation during bank phases has strongly outstripped sediment removal during inter-bank phases. The Young Coastal Plain is of Holocene age (i.e., it is enfolded in the most recent epoch of the Earth’s history, the Holocene spanning the last 10,000 years). It started forming about 5,600 years when the Post-Glacial marine transgression resulted in sea level rising to about its present position. Sea level rose from a low stand of about -120 m below present at around 19,000 years BP (Before Present, i.e., before 1950).

Fig. 13. Bundles of sandy cheniers (in pink) at the mouth of the Maroni River estuary. The diversity in orientation, length, width and grouping of these cheniers reflect space- and time-varying bank and inter-bank dynamics (see discussion in section 2.1).

Where sand has been locally available or concentrated by wave action, individual cheniers, or bands of cheniers in sand-rich contexts, especially the type 2 cheniers near river mouths (section 1.5), have been incorporated into the prograded coastal plain. The only exceptions to this progradational context are in parts of the French Guiana coast, notably in Cayenne and Kourou (Fig. 3a) where bedrock headlands with embayed beaches still prevail, and where mud-bank–inter-bank cycles have not resulted in coastal progradation but are expressed as marked spatio-temporal beach morphodynamic alternations (Anthony et al., 2010, 2011, 2014). *It is interesting to note, however, that the most recent to present Comowine deposits appear to have been characterized by much less chenier development, with the notable exception of the Maroni-sourced coast between the mouths of the Maroni and the Suriname, where the overall Young Coastal Plain is also narrower.* This is an important point as it points to changes in environmental conditions that are as yet, unexplained, but which have had an important influence on the availability of sand from the river catchments and from offshore for chenier formation.

Figure 14, adapted from Augustinus et al. (1989) and Augustinus (2004), shows an abundance of cheniers in the earlier sedimentation periods corresponding to the Wanica and Moleson deposits, especially between the Suriname and Coppename Rivers. This could reflect
a hiatus in mud supply from the Amazon mud-bank system as sea-level stabilized at about 5-6000 years ago, and/or more efficient winnowing of beach deposits, notably shelly material, from the shoreface. Interestingly, the fossil inland cheniers of the Young Coastal Plain between the Suriname and Coppename Rivers are very rich in shells, whereas the Suriname River does not seem to be a major supplier of sand for chenier formation, compared, for instance, to the Maroni River. This temporal variability suggests, in any case, that phases of sandy foreshore sedimentation alternated with large-scale muddy sedimentation, with a clear tendency towards more pervasive muddy coastal progradation and much less chenier development during the Comowine phase, especially between the Suriname and Corantijn Rivers. Several factors or combinations of factors may be invoked to explain the periodicity of bundles of cheniers. These include fluctuations in river discharge and larger mud banks subject to slower migration as a result of changes in wind parameters and wave energy and wave incidence angles.

Fig. 14. Sketch map of outcrops of the three sedimentation phases of the young Holocene Coronie Formation (< 6000 years BP) - comprising successively younger bands from inland to the sea of the Wanica, Moleson and Comowine deposits, and the main cheniers and chenier bundles (black strips) in Suriname. Modified from Augustinus (2004). It is interesting to note that the most recent to present Comowine deposits appear to have been characterized by much less chenier development, with the notable exception of the Maroni-sourced coast between the mouths of the Maroni and the Suriname, where the overall Young Coastal Plain is also narrower.

However, the growth of the coastal plain and its incorporated cheniers have been shown to have operated also during earlier epochs (notably the Pleistocene), according to work in Suriname (Wong et al., 2009), where the Coropina Formation largely constitutes the Old Coastal Plain (Fig. 15), formed during a previous sea-level phase similar to the present. Wong et al. (2009) have documented, from data culled from bauxite mining sites in Suriname, the depositional history of the Old Coastal Plain, which may be considered as a Pleistocene (and possibly older) analogue of the Young Coastal Plain. The Coropina Formation consists of the Para and Lelydorp Members, each comprising four units. The Para member is characterized by two transgressive cycles, both ranging upward from terrestrial towards chenier and coastal mudflat deposits reflecting sea-level changes of glacio-eustatic origin (i.e., sea-level variations
caused by changes in ice-cap formation and melt). The sandy sediments in this member represent fluvial and chenier deposits built from sediment supplied by rivers from the crystalline rocks of Suriname and to a lesser extent by westward longshore drift. This member also comprises clays largely derived from the Amazon River and transported alongshore over the shelf, probably as mud banks, to form extensive coastal mudflats. The Lelydorp Member represents a depositional system that is highly comparable to the modern lateral and vertical alternation of mudflat and chenier deposits formed over a period characterized by more or less constant sea level. Palaeomagnetic data suggest a Matuyama Chron (2.58–0.78 Ma) for the Para member, thus implying that the Coropina Formation is much older than hitherto assumed, and comprises one or more (long-term) hiatuses (related to sea-level change) that are not detected in the lithological succession (Wong et al. 2009).

![Fig. 15. Coastal geology of Surinam. (a) The Holocene Coronie formation and older deposits of the coastal plain of Pleistocene (Coropina) and older age. (b) Stratigraphy of the Pleistocene and Holocene deposits. (Modified from Wong et al. 2009).](image)

On-going geochronological dating of chenier deposits in French Guiana based on Optically Stimulated Luminescence (OSL) are also providing ages that span both the Holocene and the Pleistocene (the latter notably form the fine, very white (leached) sands seen along the road between Mana and Kourou in French Guiana). Although now lying adjacent to each other without an apparent morphological discontinuity, the Young and Old Coastal Plains (Fig. 14) are chronologically separated by a long phase of several tens of thousands of years during which sea level was much lower than present. As a result, the present rivers drained across the then subaerially exposed continental shelf to attain the Atlantic Ocean, depositing sand in their alluvial plains that are now drowned as sea level rose subsequently. Much of this sand is now
fossilized below Amazon mud on the shelf, thus shutting off the inner shelf sand-supply system that generally supplements fluvial and along-shore-derived sand for subsequent coastal progradation once sea-level stabilized 5-6000 years ago. Such a sand supply from the inner shelf has been important in the wave-building of sandy beach plains on other coasts (Fig. 16) where a mud supply system such as that of the Amazon is absent (e.g., parts of the east Atlantic coast of Brazil and the West African coast between Sierra Leone and the Niger River delta).

![Image](image_url)

**Fig. 16.** Aerial photograph and inset cross-sectional sketch of a massively prograded sandy beach-ridge strand plain in West Africa that contrasts with the massively prograded muddy Guianas coastal plain wherein sand has been largely fossilized by the pervasive mud supply from the Amazon, appearing interspersed on the muddy coastal plain as individual cheniers or bundles of cheniers (Figs. 13-15).

Two final important points need to be emphasized here. In the first place, large beaches such as those of Galibi at the mouth of the Maroni River are cheniers in the strict stratigraphic sense of the term, since the overall long-term Holocene progradation of the Suriname coast is hinged on successive stratigraphic packages of mud from net growth of the coastal plain resulting from the welding of mud banks, even though the mouths of some of the rivers, such as the Maroni, on which such large beaches form, may have held very stable positions since sea level reached its present high-stand 5-6000 years ago. In the second place, the periodicity of mud-bank migration signifies that, at some stage in time, such more or less large and widening beaches will be isolated from wave influence by mud banks, thus developing into the more classical ‘chenier’ forms commonly found locked within the muddy coastal plain. In Suriname, the mud-dominated three Holocene sedimentation phases and their bundles of cheniers (Fig. 14) are a clear testimony to this.
PART 2. RECENT SHORELINE CHANGES IN SURINAME: GENERAL MORPHODYNAMICS, METHODOLOGY AND RESULTS FOR BRAAMSPUNT BEACH
2.1. Chenier morphodynamics – cross-shore and longshore processes

As shoreline features exposed to wave action, cheniers can be characterized by wave processes acting over the beach face and eventually over the back-beach area (cross-shore transport orthogonal to the shoreline) and by longshore transport (parallel to the shoreline). Cheniers are associated with landward migration over mud (Fig. 17). This generally occurs by waves topping the beach (a process called overwash) and transferring the sediments (the transferred sediments form ‘washovers’) from the active beach face to the back-beach. As waves rich in temporarily suspended sediments overwash the beach, the transported water rapidly infiltrates into the beach, depositing lobes of sand or shells that form washovers. This is generally a situation typical of a limited supply of sand or shells, commonly associated also with supply-limited sandy ‘barrier islands’ as on the East Coast of the United States or parts of the North Sea, as beaches otherwise tend to build up their beach faces through active swash processes involving asymmetry between wave runup and rundown (water movements on the beach face linked to the uprush (or swash) and downwash of the wave after breaking). Since, in the case of cheniers, such sand remains segregated throughout by wave action from the ambient mud (i.e., mud on the foreshore, mud underlying the beach sand, and mud on the backshore in such situations of limited sand supply), these beach deposits tend to migrate landward over the muddy substrate, maintaining their integrity and shape across-shore and alongshore.

A type 1 chenier developing in an inter-bank area where sufficient sand and shells are winnowed out and segregated from mud by wave reworking can gain volume and eventually function as a ‘normal’ ocean beach with a well-developed surf and swash zone along which sediments are actively transported. Such large sandy beaches are characterized by typical beach foreshore behaviour dominated by swash processes, often with little or no overwash. These aspects of classical chenier morphodynamics are reiterated below. These large beaches are the most suitable ecotope on the Guianas coast for nesting marine turtles. As stated earlier, such relatively large beaches are more typical of the vicinity of river mouths where mud liquefaction occurs (type 2 cheniers). Cheniers subject to active landward migration through overwash by waves at high tide provide conditions that are not ideal for successful nesting by marine turtles, which require stable sandy beaches, beaches not subject to overwash and strong infiltration, and beaches free of mud and organic matter (Kelle et al. 2007; Caut et al. 2010).

Depending on the size and width of the sand body, and on the proximity of mud (typically a mud bank approaching from updrift), chenier morphodynamics can therefore range alongshore from beach sectors associated with large well-developed beach faces to sectors dominated by frequent overwash. Overwash commonly leads to sand migrating over mangroves that are progressively first asphyxiated, and then uprooted, leading to the accumulation of more or less significant amounts of drift wood, also called log jams. These accumulate notably on the upper beach. As coarse sediment migrates over the commonly poorly consolidated organic-rich muddy substrate, the increasing weight of the chenier body leads to muddy substrate consolidation and lowering that consequently leads to lowering of
the elevation of the chenier, thus further enhancing overwash processes (Fig. 17), a typical self-reinforcing morphodynamic feedback loop. On the lower beach and in some back-beach areas, this process is clearly manifested by the appearance of sandy beach deformation structures (Anthony and Dolique, 2006; Anthony et al., 2011). These structures are generated by dewatering and progressive consolidation of the mud substrate underlying cheniers. Although the development of these features is hinged on the marked grain-size and geotechnical differences between sand and mud, their formation is not due to hydraulic processes at the sand–mud interface, such as sand piping or undermining, nor to collapse of void space such as from encapsulated air within the sand body, since chenier and beach sands are often well packed. These features are most likely explained by hydraulic adjustment of the underlying mud to sand loading. Adjustment of the beach profile to sand loading in the intertidal zone occurs through mud dewatering via evaporation at low tide, when large areas of the foreshore are exposed, and to compaction of the underlying mud. These two processes generate accommodation space into which the overlying sand above the water exfiltration zone responds by forming subsiding packages of non-saturated sand delimited by cracks alongshore (Anthony and Dolique 2006). Piping processes are, however, well developed in the water exfiltration zone on the lower beach, and commonly generate additional deformation of the observed vertical collapse walls. These collapse features are generally ephemeral, as the sand on the lower beach is transferred alongshore by longshore currents and onshore through overwashing. As the chenier migrates inland, the subsisting consolidated muddy foreshore is exposed, commonly with remnant dead and dying mangroves undergoing uprooting by waves.

Fig. 17. Sketch of a deltaic setting showing shoreward chenier barrier migration over a muddy substrate. Overwash processes that lead to chenier migration also generate lowering of the chenier barrier as its weight results in consolidation of the underlying compressible, generally organic-rich mud. This results in a feedback effect that further enhances overwash. From Rosati et al., 2010.

Differences alongshore in overwash may also lead to spatial destructuring of a chenier and its eventual partial dismantling where local variations in incident wave energy occur. These variations are generally related to changes in local bathymetry or caused by anthropogenic structures such as sluice gates and groynes. Finally, it is important to note that aeolian dune
development on the Guianas cheniers and beaches is insignificant as a result of this common overwash regime and the mild wind speeds.

Cheniers, especially on the Suriname coast, are strongly influenced by strong longshore gradients in sand drift. On well-developed beach faces, the obliquely incident waves generate longshore currents that transport sand put into suspension in the wave breaking and surf zones. These processes are best expressed at high tide when waves are higher and break further up the beach, and in regimes where overwash processes are less well expressed, since these lead to dissipation of a portion of the wave energy over the overwashed beach through both water infiltration and flow towards the backshore in lieu of backwash down the beach. Mangrove trees and trunks in overwashed areas of beach also further dissipate wave energy, potentially diminishing the longshore component of such energy. In essence, therefore, sand sequestering through the overwash regime typical of active cheniers can deprive the beach longshore transport system of sand, thus further strengthening the downdrift propagation of the overwash chenier regime associated with limited sand supply. This morphodynamic feedback effect signifies, in fact, that the overwash chenier regime is important in locally dissipating incident wave energy by leading to a beach sand-trapping regime that propagates downdrift. This mechanism therefore enhances the coastal protection role played locally by chenier development. Overwash commonly generates in-situ sand sequestering on the upper beach and back-beach through the formation of more or less coalescing lobes of washovers. Such washovers may be nefarious to turtle eggs on the beach, as they are associated with enhanced water infiltration from the overwashing waves.

Bank phases lead to fossilization, and thus, sequestering, of sand bodies present on the shore by the large amount of ambient mud. This can lead to:

(1) inland isolation, within the prograded part of the muddy plain, of once active cheniers, well identified on aerial photographs and satellite images as linear strings of sand surrounded by marshes, and,

(2) the cutting off of any actively functional cheniers from potential supply of sand from updrift (commonly a river source, a reworked chenier or reworked nearshore deposits).

An approaching mud bank can thus lead to enhancement of the chenier overwash regime described above by curtailing the through-drift of sand from source zones. In contrast, under a prolonged inter-bank phase, and providing there is a sufficient or continuous supply of sand, type 2 cheniers can develop alongshore for several tens of kilometres. This is achieved through:

(a) thorough winnowing of sand (and sometimes shells) from the nearshore zone that may have been supplied by a river updrift and then fossilized (cut off) from the chenier downdrift by a bank phase,
(b) but more commonly by continuous downdrift supply of sand coming from an important updrift river mouth source (that contrasts with the classical chenier sequestering overwash regime). These two modes of chenier development have been characteristic of the recent (multi-decadal) history of Braamspunt beach (section 2.3).

In addition to the importance of cross-shore overwash processes, the foregoing points call for a consideration of the sand supply, transport and trapping dynamics in terms of sediment ‘cells’ driven by longshore gradients in wave energy. Such gradients arise from relatively steep angles between waves and the shoreline. Obliquity in wave approach alongshore generally occurs because the local bending of wave crests caused by the important process called refraction, which brings wave crests as parallel as possible to the shoreline, is not complete (Fig. 18). However, differential nearshore wave energy dampening related to the bathymetry can also cause gradients in alongshore wave energy (typically the case in the large-scale alignment of bank and inter-bank sectors alongshore).

A longshore sediment cell is defined as an entity, in the case of the Suriname coast, a beach, characterized by: (1) a sediment source zone updrift (river mouth, updrift sector of an inter-bank zone subject to wave winnowing of sand), (2) a variably long transport sector subject to active longshore drift, and (3) a commonly short downdrift terminus sector where sand is deposited. The cell structure corresponds to the alongshore distribution of wave energy, which has to be sufficiently strong in the source zone as to mobilize sediment. This is commonly assured across relatively deep nearshore bathymetry in front of beaches in the source zone, such as river mouths or inter-bank zones (where wave energy dissipation is thus less). These beaches (such as the present beaches in the Galibi sector of the Maroni River) serve as source zones where sand enters the beach transport system. Transport sectors are commonly dominated by equilibrium between the alongshore component of wave energy and its sand transport capacity. Note that this equilibrium can fluctuate over time with wave energy and wave incidence angles, and that phases of abundantly available sediment under high wave energy can lead to a dynamic equilibrium wherein the beach face grows but the alongshore transport capacity is maintained through adjustments, such as in beach slope. In depositional segments of the cell, wave energy gradients are such that transport can no longer be assured and the sediment is deposited. This can occur where wave energy density (the amount of energy per unit of shoreline) along the shoreline diminishes, commonly as a result of very strong refraction (the bending, tantamount to lengthening, of the wave crests to align with the bathymetry diminishes the wave energy density), but also dissipation due to massive sand accumulation. In river mouths, the outflowing river and tide-enhanced jet can also contribute to wave refraction, thus enhancing potential sedimentation.

River mouths, such as that of the Suriname, form estuaries that can act as significant bedload (sand) traps due to bottom salt wedge intrusion associated with the tide. Such river mouth areas also form re-entrants along the coast that can lead to strong bending of wave crests through refraction. In consequence, sand drifting alongshore through a well-defined transport cell formed by a beach can cease in the vicinity of such river mouths. This cessation of growth is commonly associated with the formation of spit recurves inward towards the
estuary that replicate the wave crest-bending process. *Braamspunt beach and its ancestral spit recurves into the mouth of the Suriname River provide a fine example of this situation* (see section 2.2).

**Fig.** 18. Sketch of the process of wave refraction by which wave crests bend (reorientate) to align with the bathymetric contours. From Davidson-Arnott, 2010. The process of alignment by which waves are ‘refracted’ is very commonly incomplete, leading to the generation of a longshore current (blue arrow) in the wave breaker zone that can transport mud, and sand cyclically suspended by wave breaking.

As a result of the foregoing range of morphodynamic conditions and processes, which can vary considerably both alongshore and in time, cheniers appear in all sizes on the Guianas coastal plain, are commonly discontinuous alongshore, and can be very variably wide (see Fig. 13, for instance). Their orientations also vary. In addition to the specific morphodynamic process variability imposed by the bank – inter-bank context, this diversity reflects various other factors, such as the availability of sand in inter-bank areas, the impact of previous bank phases in muting down sand-winnowing processes, local to regional sand availability and winnowing from the nearshore zone, but also the potential reworking of older inland cheniers by mobile river channels and their creek networks that recycle this sand into channel bed deposits. Such sand may eventually be re-injected on the shore where such creeks debouch. Over the decadal to multi-decadal timescales involved in bank-inter-bank cycles, changes in channel-mouth location can also occur as the mud capes diverting the smaller river mouths during bank phases are eroded. This leads to changes, in injection points on the coast, of sand brought down by rivers, or reworked from older sand bodies inland.

The formation of cheniers on the Guianas coast is, therefore, not primarily related to the simple temporal alternations between low wave energy conditions (muddy sedimentation) and high wave energy conditions (sand winnowing and chenie r formation) observed in many
of the world’s chenier coasts, but is hinged on the unique situation at the world scale wherein alongshore alternations of banks and inter-bank zones occur, engendering marked spatial and temporal variations in wave energy, in addition to the spatial heterogeneity generated by the presence of fixed river mouths that provide much of the sand for chenier formation (Anthony et al., 2014). Type 2 cheniers formed in the vicinity of such river mouths can also vary in orientation, from orthogonal relative to the regional shoreline where they line river banks as in the Galibi area on the west bank of the Maroni, to the more normal alongshore orientation as on the open coast between the Maroni and Suriname Rivers (Fig. 13).

2.1. The Maroni and Suriname river-mouth contexts and Braamspunt beach

Braamspunt beach (Fig. 1), in what may be considered as its ancestral version, prior to the ongoing changes in shoreline dynamics engendered by a mud bank approaching the mouth of the Suriname River (section 2.3 below), is a fine example of an open-coast chenier in the Guianas that developed between the mouths of two rivers, the Maroni and the Suriname. The former has acted as the primary sand source for the beach, whereas the latter, near which the presently subsisting remnant of the beach is situated (Fig. 1), has formed an important sink zone for this chenier. Supplementary sand for the beach is winnowed out from nearshore sources formed by shells. The source function of the Maroni is clearly expressed by the numerous isolated beaches at Galibi that mark the progressive incorporation of fluvial sand supplied by this river to the mud-dominated coastal system (Fig. 13). The sink situation corresponds to the downdrift segment of Braamspunt beach characterized by a number of spit recurves that reflect wave refraction engendered by the mouth of the Suriname River (see discussion below in section 2.5).

Estuary mouths are remarkable sediment traps that progressive tend to fill up with both fluvial and marine sediment where such sediment is available. Many estuaries on Earth have filled up over the last 5-6000 years to evolve into deltas (Fig. 19). This is not the case with the mouths of rivers in Suriname, which are still largely classically infilling estuarine systems characterized by major sand-trapping through the formation of estuary-mouth sand shoals and banks. These are well expressed in the mouth of the large Maroni estuary. Sand tends to be trapped at estuary mouths because of convergence between fluvial (freshwater) flow seaward and marine (seawater) flow inwards with the tidal excursion. The latter is particularly efficient in generating estuary-ward bedload (sand) transport through flood currents. The process may be enhanced by non-tidal (density) currents generated as a result of density stratification between estuary-ward flowing salt water at the bottom and seaward-flowing freshwater at the top of the water column. Estuary-ward trapping can also be enhanced where waves propagate inward, forming recurved spits, as in the Braamspunt case. Within the coastal progradation framework associated with bank phases, the oldest Braamspunt spit recurves have become isolated behind mangrove swamps, thus reflecting the permeating influence of mud in this environment. At the same time, estuarine ebb and flood currents associated with the tide, together with large incoming waves, rework the spit recurves, recycling the chenier sand into
the estuarine sand shoals and banks. Older spit recurves of this type in the mouth of the Suriname River are no longer visible as a result of this recycling.

Fig. 19. Prism showing a general coastal classification scheme based on inputs of rivers, waves and tidal processes and their variation in time (sea-level changes), with many estuaries developing, over the last 5-6000 years since global sea level stabilized, into deltas as their mouths become infilled with both river-borne and marine-derived sediment (a); and a cross-section through the prism showing deltas relative to other coastal landforms (b). Modified after Boyd et al. (1992).

Sand shoals and banks at estuary mouths can form sources of sand for adjacent beach deposits lining the banks of such estuaries, especially where sand supply has been high and has not been overwhelmed by mud from attached mud banks. This is the case of the Maroni, characterized by a large sand supply coupled with a strong seasonal fluvial jet outflow during the rainy season (Fig. 12), whereas the mouth of the Suriname reflects a much lower supply of sand and a more permeating mud influence from shore-attached banks over the last 5-6000 years.
2.2. Methodology: recent shoreline changes and evolution of Braamspunt beach

2.2.1. Mesoscale (multi-decadal changes)

In order to track the recent multi-decadal shoreline changes along the coast of Suriname, and hence determine the changing status of the ancestral and current forms of Braamspunt beach, fourteen Landsat 5 to 8 images from July 1987 to January 2016, acquired from the United States Geological Survey (USGS), were used. The image resolution is 30 m for the earliest L5 TM (1987) images and 15 or 30 m for the most recent L8 OLI-TIRS (2016) images (Table 1). The images were selected in order to avoid as much as possible cloud coverage. Images selected were only those of end-of-summer or autumn (dry season/lowest river discharge). The coordinate reference used for this study is the Universal Transverse Mercator (UTM) zone 21N, which comprises Suriname, associated with the Global Geodesic system WGS 1984 datum. Three items were identified on these images: (1) the shoreline and its changes, (2) beach surfaces, and (3) the outlines of mud banks.

Regarding shoreline discrimination and change, thirteen images of the dataset have good overlapping between them with their default georeferencing from USGS processing. However, an image from the 2009 dataset had inaccurate georeferencing which led to bad overlapping with the other images. The georeferencing of this image was further rectified using additional benchmark points from good images, such as cross-roads, bridges and buildings, and provided a Root Mean Square Error of the new georeferencing. The shoreline was digitized for each image using as a reference the external limit of vegetation.

Following this, cross-shore shoreline mobility was statistically analyzed using the ArcMap extension module Digital Shoreline Analysis System (DSAS), version 4.3, coupled with ArcGIS® v10.2.2 (Thieler et al., 2009). Long experience with the Guianas and other tropical coasts (such as those of the Mekong River delta) show that the mangrove fringe constitutes a good ‘shoreline’ marker. The shore-normal distance of the vegetation line relative to a base line for each two sets of dates was calculated every 250 m alongshore. This distance, chosen as a compromise between quality of the interpretation and total length of analysed shoreline (~350 km) was then divided by the time in years between two dates to generate a shoreline change rate, the End Point Rate (EPR) in DSAS 4.3, expressed in m a year:

\[
EPR = \frac{d_{1} - d_{0}}{t_{1} - t_{0}}
\]  

(1)

The annual error (E) of shoreline change rate was then defined from the following equation (Hapke et al., 2006):

\[
E = \frac{\sqrt{d_{1}^2 + d_{2}^2}}{T}
\]  

(2)
Table 1. Characteristics of LANDSAT images covering the Suriname coast and analyzed to highlight coastal change.

<table>
<thead>
<tr>
<th>Image number</th>
<th>Sensor</th>
<th>Resolution</th>
<th>Date</th>
<th>Georeferencing RMSE (optional)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LC82290562016019LGN00</td>
<td>Landsat 8</td>
<td>30 m/pixel (px); 15 m/px (panchromatic)</td>
<td>19/01/2016</td>
<td>-</td>
</tr>
<tr>
<td>LC82280562016012LGN00</td>
<td>Landsat 8</td>
<td>30 m/px; 15 m/px (panchromatic)</td>
<td>12/01/2016</td>
<td>-</td>
</tr>
<tr>
<td>LC82280562015297LGN00</td>
<td>Landsat 8</td>
<td>30 m/px; 15 m/px (panchromatic)</td>
<td>24/10/2015</td>
<td>-</td>
</tr>
<tr>
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<td>Landsat 8</td>
<td>30 m/px; 15 m/px (panchromatic)</td>
<td>15/10/2015</td>
<td>-</td>
</tr>
<tr>
<td>LC82300562015279LGN00</td>
<td>Landsat 8</td>
<td>30 m/px; 15 m/px (panchromatic)</td>
<td>06/10/2015</td>
<td>-</td>
</tr>
<tr>
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<td>28/09/2009</td>
<td>-</td>
</tr>
<tr>
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<td>Landsat 5</td>
<td>30 m/px</td>
<td>21/09/2009</td>
<td>-</td>
</tr>
<tr>
<td>LT52300562009246CUB01</td>
<td>Landsat 5</td>
<td>30 m/px</td>
<td>03/09/2009</td>
<td>-</td>
</tr>
<tr>
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<td>Landsat 7</td>
<td>30 m/px</td>
<td>02/07/2000</td>
<td>-</td>
</tr>
<tr>
<td>LE72280561999325EDC00</td>
<td>Landsat 7</td>
<td>30 m/px</td>
<td>21/11/1999</td>
<td>-</td>
</tr>
<tr>
<td>LE72290561999252EDC00</td>
<td>Landsat 7</td>
<td>30 m/px</td>
<td>09/09/1999</td>
<td>50 m</td>
</tr>
<tr>
<td>LT52300561988269CUB00</td>
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<td>30 m/px</td>
<td>23/09/1988</td>
<td>-</td>
</tr>
<tr>
<td>LT52290561987291XXX04</td>
<td>Landsat 5</td>
<td>30 m/px</td>
<td>18/10/1987</td>
<td>-</td>
</tr>
<tr>
<td>LT52280561987204XXX07</td>
<td>Landsat 5</td>
<td>30 m/px</td>
<td>23/07/1987</td>
<td>-</td>
</tr>
</tbody>
</table>
where \( d_1 \) and \( d_2 \) are the uncertainty estimates of shoreline position for the successive sets of images and \( T \) is the time in years between image sets. The uncertainty of shoreline position is defined by two times the pixel resolution in addition to georeferencing RMSE in the case of the rectified 2009 image. The obtained error \( E \) presents a range of 3.41 m a year to 8.5 m a year between 1987 and 2015, which we consider as an extremely cautious error range.

Coastal area variations (km\(^2\)) representing land losses or gains associated with changes in shoreline position can also be calculated from alongshore segments between two successive image dates by dividing area variation by the time in years between dates. This has not been done here as the focus is on Braamspunt beach, a linear shoreline feature. Such changes can, however, be calculated for gains and losses of mangrove areas associated with bank and interbank activity. The error \( (E_a) \) expressed in km\(^2\) a year is calculated using a method similar to that of shoreline change rate for each, say, 1 km segment, based on the following equation (Hapke et al., 2006):

\[
E_a = \sqrt{\frac{ShaE_{1973}^2 + ShaE_{2014}^2}{T}} \tag{3}
\]

where \( ShaE_{1987} \) and \( ShaE_{2015} \) (km\(^2\)) are the mean shoreline area error estimates for the successive sets of images and \( T \) is the time in decimal years between image sets. \( ShaE_{1973} \) and \( ShaE_{2014} \) are obtained from the mean square computation of surface errors for, in this case, every 1-km-longshore segment.

Identifying the limits and dimensions of mud banks on satellite images is a very delicate process, and generally only very vague outlines can be delineated because of the very high ambient mud concentrations on the Guianas coast. Mud banks are subtidal to intertidal features 10 to 60 km long and 10 to 30 km wide. Tidal limits and the shapes of the banks are, however, hard to differentiate from the sediment-charged waters on remote sensing images, although images taken in the dry season, when waters are less charged in sediment, are more suitable for differentiation of intertidal from subtidal zones, as are images taken at low tide. Baghdadi et al. (2004) also showed that radar images were more practical than optical images in delimiting the intertidal zone. Subtidal extensions of banks cannot be distinguished on images. Although banks can be mapped from field monitoring (e.g., Lefebvre et al. 2004; Anthony et al. 2008), this can only be practically done over small (< 1 km\(^2\)) surfaces. Mapping of larger surfaces at low tide requires airborne techniques (aircraft and LiDAR). Vantrepotte et al. (2013) showed from analysis of MODIS (moderate-resolution imaging spectroradiometer) satellite imagery that the highest values of suspended particulate matter (SPM >13 g m\(^{-3}\) approximately) are associated with the subtidal part of the banks. They also showed that the migration of the mud banks induces strong inter-annual changes in SPM of up to 6% year along the coastline of French Guiana.
2.2.2. Field surveys of the morphology and dynamics of Braamspunt beach

Two separate ground surveys were conducted on Braamspunt beach on February 9-10 and February 13-14, 2016, in order to observe the morphology and dynamics of the beach as well as measure aspects of the beach topography, beach grain size and carbonate percentage, wave conditions, and suspended sediment concentrations. These field experiments were designed to cover a spring-to-neap tidal cycle, i.e., a decreasing semi-fortnightly tidal cycle. Fortuitously, the experiments also coincided with variation in wave conditions between the two survey periods. These conditions will be described in section 2.3. The experiments were aimed at highlighting the morphodynamics and sand transport patterns that drive change on Braamspunt beach, and the beach sediment budget in the wake of sand mining over the last years. These field surveys also provided unique opportunities to discuss with, and disseminate basic knowledge on beach systems, and on the specific dynamics and morphological and sediment budget changes Braamspunt beach is undergoing, to WWF-Guianas staff, game wardens of the Nature Conservation Division of Suriname, a member of the Geological Mining Service of Suriname, and several 3rd year and Master’s students from Anton de Kom University of Suriname. This was also a two-way experience as the pertinent questions and past observations carried out by these various actors were also useful in helping elucidate the processes and changes observed. These aspects will need to be further strengthened within the framework of a coastal observatory (Part 3).

Accurate high-resolution topographic monitoring is increasingly employed to enhance our understanding of geomorphic processes in beach environments which are generally highly dynamic. Several techniques can be used to reconstruct the topography of a study site. These are ground surveying using total electronic stations, differential global positioning systems (DGPS), and terrestrial laser scanning (TLS), and airborne surveying using LiDAR, and photogrammetry. However, each of these techniques has operational constraints in term of cost/reproducibility, coverage, point density and accuracy, which render some of them inappropriate or too costly for very accurate monitoring of short-term changes affecting geomorphic features.

- Topographic surveys

High-resolution topographic surveys were conducted in the course of the two field missions using a Trimble R8 differential global positioning system (DGPS) in Real-Time Kinetics (RTK) mode. The system consists of a fixed station and a mobile station used to record the geographical coordinates and elevations of ground points. The two stations are linked by radio, which introduces a constraint since the radio signal can be lost over a distance of a couple of kilometres. The mobile unit comprises a GPS antenna and a computer that enabled acquisition and storage of data collected at 1 second-intervals over the beach. The mobile station was transported in a backpack most of the time by an operator carrying out the survey, but constraints imposed by time and tide also led us to use an all-terrain vehicle (Fig. 20a). The ‘trace’ covered by the acquisition on February 10 is depicted in Fig. 21. A total of 56,900 points were surveyed (23,050 on February 10 and 33,850 on February 13-14), giving an overall density
of 1 point for every 50 cm of beach. The two GPS receptors (fixed and mobile) position themselves relative to satellites. The base station compares its computed position to that given by the mobile operator and deduces corrections that are relayed to the mobile antenna which then applies these corrections and computes the position in x, y, z coordinates every second (hence the very high resolution beach coverage). In the absence of a topographic reference system and benchmarks at Braamspunt beach, we resorted to the Universal Transverse Mercator (UTM) zone 21N, which comprises Suriname, associated with the Global Geodesic system WGS 1984 datum. Elevation data were referenced to the world geoid EGM96 (Earth Gravitational Model) representing mean sea level. The constructor’s (Trimble Ltd) error margin is +/- 1 to 2 cm for the x and y coordinates and +/- 2 to 3 cm for the z coordinate. 2.5-m cell digital elevation models (DEM) of the gridded image were computed from the data using the Delaunay triangulation method. The comparison of the DEMs of the two surveys, named Differences of DEMs (DoD) images, highlighted short-term variations in the subaerial beach volume that coincided with the shift from spring to neap tides and the significant drop in incident wave energy observed over the week of the surveys.

(a) (b)

**Fig. 20.** (a): vehicle-mounted mode of GPS terrain survey; (b) preparation of the UAV used for the photogrammetric survey.
Fig. 21. ‘Trace’ of a total of 23,050 acquired GPS topographic points at Braamspunt beach on February 10, 2016.

- Aerial photogrammetry

In addition to high-resolution ground surveying, topographic details of the beach were also obtained from aerial photogrammetry using an unmanned aerial vehicle (UAV or drone) provided and operated (Fig. 20b) by the Nature Conservation Division of Suriname. Beaches composed of sand such as Braamspunt beach are commonly characterized by subtle morphological variations and by features ranging in elevation from a few cm to 1 m, such as beach erosion scarps and washover lobes. They are also characterized by essentially homogenous textures. These constraints imply that very high-resolution and accurate geomorphic mapping of these landforms cannot be optimally operated using classical survey with RTK-DGPS. Although this technique allows for repeated surveys, the distribution of field data points is generally relatively sparse because homogeneous and high-density surveys imply large time and cost constraints that are such that subtle morphologies cannot be accurate modelled in a short time window or before they undergo change. Consequently, only very high-resolution and high-density surveying methods provided by LiDAR, TLS, and aerial photogrammetry fulfill these conditions. However, the selected method must also withstand the constraint of frequent repetition in order to capture the medium-term dynamics, and this excludes expensive methods such as LiDAR, while TLS also suffers from deployment range constraints.

Photogrammetry is an old remote sensing technique notably used in the past to analyze aerial photographs and quantify various aspects such as landform changes. This once elaborate and laborious technique that necessitated specific expertise and analytical equipment has, over the last decade, undergone significant new developments related notably to the workflow technique called *Surface-from-Motion* (SfM) (Westoby et al., 2012). This innovation facilitates the utilization of this technique by non-specialists. SfM photogrammetry enables the production of high-resolution morphometric models and derived products such as digital surface models (DSMs) and orthophotographs. These new developments are allowing for the emergence of photogrammetry as a low-cost but high-resolution alternative to costly laser morphometry techniques or traditional topographic survey techniques (Gonçalves and Henriques, 2015). Photogrammetry is based on stereoscopic couples from image datasets of a feature. It allows reshaping the volume of this feature in a three-dimensional (3D) space from depth maps that generate cloud points. Initially, the alignment of stereoscopic couples of images was a tedious task, operated by the user himself/herself with a weak image resolution (50 cm ground pixel size). Furthermore, the derived digital elevation model had a lower density and accuracy than that of LiDAR (Ouédraogo et al., 2014). Advances in computer vision and image analysis have generated innovative developments and new software packages wherein SfM photogrammetry offers an automated method for the production of high-resolution DSMs with standard cameras (Fonstad et al., 2013; Hugenholtz et al., 2013; Javernick et al., 2014; Agisoft, 2015; Brunier et al., 2016a, 2016b). This low-cost method combines the reproducibility of RTK-DGPS with the density, the range and the accuracy of LiDAR.
SfM photogrammetry has been applied in the mapping of a beach under the influence of mud banks drifting alongshore from the mouth of the Amazon near Cayenne, in neighbouring French Guiana by our team (Brunier et al., 2016a), and we produced very high-resolution DSMs of 5 to 10 cm per pixel with an accuracy with +/- 10 cm, in addition to orthophotographs of the study site. The field protocol is very easy to organize and the powerful SfM workflow is operated using user-friendly software. The technique thus holds promise for rapid, repeated, and low-cost beach and coastal surveys in Suriname within the framework of a future coastal observatory (see Part 3).

The following field and data analytical protocol was applied to Braamspunt beach (same as that applied in French Guiana). First, we operated photograph collection. This phase combines the aerial photographic survey and ground operations. Several flights were operated over Braamspunt beach using the drone (Fig. 20b) and camera provided and operated by courtesy of the Nature Conservation Division of Suriname. The photographic material consisted of a pocket-size CANON Powershot S100 camera with a 12.1 MP 'high sensitivity' CMOS sensor installed in the drone. Particular attention needs to be paid to the camera parameters such as calibration and shutter speed, ISO camera sensitivity and diaphragm aperture as these were a source of difficulty and poor photographic capture during the early testing phases of our experiment. The drone flew close to the ground (< 100 m) in order to obtain a picture resolution less than or equal to 3.5 cm ground size pixel (GSD) and a scene size corresponding to a 120 x 80 m picture footprint. Indeed, the picture footprint needs to be carefully chosen in order to optimize parallax parameters for good stereography. We calibrated the parallax parameters using an overlap between pictures of about 85% end-lap in the lengthwise flight direction and about 50% side-lap between paths. Considering the scene size and the parallax parameters, we flew at a speed of 70 km/h in order to keep an end-lap ratio with shooting range of one picture per second. Moreover, we defined numerous parallel flight axes spaced tens of metres.

The stereopair alignment using SfM-photogrammetry is based on benchmark points deployed on the beach. During each implementation, we dropped off several targets of 40 x 40 cm which were accurately georeferenced using the Real Time Kinematic-Differential Global Positioning System (RTK-DGPS). These target points are named Ground Control Points (GCPs). Furthermore, we sampled, randomly and following specific morphologies, numerous topographic points, named Ground Truth Points (GTPs), in order to assess the quality of our DSMs.

The main improvement in photogrammetry and its increasingly widespread use nowadays result from the association of computer vision algorithms with those of traditional photogrammetry. This new paradigm does away with what was hitherto a tedious task wherein the operator had to find homologous points for aerotriangulation. This task is now automatically accomplished using the object recognition algorithm called *Scale Invariant Feature Transform* (SIFT) (Lowe, 2004). The SfM-photogrammetry workflow was operated using Agisoft Photoscan Professional software. We describe below the six main steps of the method:
- Picture quality assessment and masking of mobile objects. First, the picture dataset is imported into Photoscan. The pictures outside the area of interest, which was defined by the GCPs, are removed. Then, mobile objects are masked on each picture, such as people walking and water surfaces on the beach.

- Picture alignment. This is one of the most important procedures in the SfM protocol. At this stage PhotoScan uses a tracking algorithm to identify, match and monitor the movement of the features of the beach (Brunier et al., 2016a). This algorithm is based on an improved version of the SIFT object recognition system (Lowe, 2004). The software then determines the camera’s intrinsic orientation (focal length and lens distortion) and extrinsic parameters and the six exterior orientation parameters that define the image. It does so by reconstructing the optimal picture positions, and improves them with a bundle-adjustment algorithm (Javernick et al, 2014; Brunier et al., 2016a). SfM is innovative because, regarding scene reconstruction, it does not require 3D picture locations and orientations, unlike traditional photogrammetry. As a result, sparse point clouds - named SIFT clouds - and a set of picture positions in a relative coordinate system are formed. Following this, the first picture alignment (together with the SIFT cloud) must be transformed into an absolute spatial reference. To accomplish this, it is georeferenced and optimized with GCPs in the working geodetic system of the area. The GCPs are checked on each picture at infra-pixel scale. This estimation is made using image data alone, so there may be some errors in the final figures. The optimization process adjusts the picture alignment and allows enhancing the accuracy of GCP positions from 1 m to 1 cm.

- Dense points cloud and mesh model. This stage consists in building a dense point cloud using the algorithm, and then a mesh. Based on the estimated picture positions, the programme calculates depth information from correlation of each pair of images and then combines all of them into a single dense point cloud. This latter has the same density as a LiDAR point cloud with 200 to 300 points per m². The mesh surface model is created from triangulated networks between points.

- Digital surface model and orthophotograph. The final stage consists in exporting the mesh model to a TIFF raster file named the digital surface model (DSM). Photoscan allows for export with a resolution close to 2 times the GSD pixel size in cm, such as 7 cm for the beach. We chose to interpolate all of our DSM exports with respectively 10 and 5 cm resolution. This software also allows for export of cloud points and orthophotographs.

In the end, we assessed the quality of object reshaping. We based our protocol on a qualitative observation of morphology reconstruction in each case, and we conducted a quantitative assessment from the root mean square errors (RMSE) of GCP locations provided by Photoscan Professional software.

Successive DSMs can be used to establish temporal changes in beach sediment budget variations in the same way as DEMs can be used for this from high-resolution ground
topographic survey data. In the case of Braamspunt beach, a photogrammetry-based beach budget calculation has not been conducted because only one DSM of the beach was obtained in the course of the field survey.

• Wave and turbidity measurements in the breaker zone, and offshore model wave data

  In the course of both experiments, 2 to 3 NKE*-SP2T pressure sensors, some equipped with turbidity sensors, were deployed on the beach in its distal part near the tip of Braamspunt, and sampled continuously at 2 Hz. Sensor accuracy is 0.02 m. Wave heights and water levels under these values were neglected. We applied linear wave theory, considered a good first approximation for wind waves (e.g., Bradley and Houser, 2009). Wave spectra were calculated over periods, called ‘bursts’, of 20 minutes, using Fast Fourier Transforms with a Hanning window of 600 seconds and 75% overlap. All wave spectra calculated from our dataset show a clear 0.11 Hz limit between gravity and infra-gravity wave domains. We applied a correction factor, with a cutoff at 0.5 Hz to account for the non-hydrostatic pressure field. For each burst, significant wave height ($H_s$) and peak period ($T_p$) were calculated in the spectral window [0.11; 0.5] Hz. Turbidity values in NTU (nephelometric turbidity units) were derived.

  Offshore wave data during the study period were derived from the third-generation Wave Watch III (WWIII) database of the National Oceanic and Atmospheric Administration (NOAA) of the USA (http://polar.ncep.noaa.gov/waves/index2.shtml). WWIII is a spectral wave model that describes complex sea surface states based on wind data. WWIII calculates sea surface states every hour for regular spatial grids of half a degree of longitude and latitude. The model gives wave heights in metres (m), periods in seconds (s) and directions in degrees for each grid cell.

• Grain-size and carbonate determinations

  Finally, 20 sediment samples were collected from the beach in order to determine grain-size characteristics and the carbonate (shell) content of the beach sand relative to the dominant quartz fraction. The samples were analyzed using a Beckman Coulter laser grain-size type LS 13 320. Samples were analyzed in the aqueous phase and particles ranging in size from 40 to 2000 μm were determined. A single grain-size curve was used to describe the entire spectrum. The percentage of carbonates (shelly debris) in each sand sample was determined after passing the sample through hydrochloric acid to eliminate the organic fraction, leaving the residue of minerogenic sand.

2.3. Recent bank and inter-bank phases on the Suriname coast

  The number of mud banks in the analyzed LANDSAT images covering the Suriname coast ranges from one to two. Given the rates of mud bank migration deduced from the comparison of images, this suggests a succession of at least five banks over the 29-year period (1987-2016)
based on these images. From a larger database that also included MODIS images, which are appropriate for mud-bank identification, Gensac (2012) identified up to nine mud banks on the Suriname coast between 2006 and 2010 (Fig. 5).

2.3.1. The Maroni-Suriname sector (mud cape 1 in Fig. 1)

The alongshore continuity of a chenier between the mouths of the Maroni and the Suriname Rivers has been controlled by bank attachment episodes, the latest of which are brought out by the analyzed Landsat images between October 1987 and October 2015. Date-to-date comparisons of some of the images are depicted in Figs. 22 and 23. The successions of shoreline advance (bank) and retreat (inter-bank) and their progression along the coast also appear from the shoreline change rates which attain maximum values close to 150 m a year. In this bank-inter-bank framework, the continuity of Braamspunt beach as an open-coast beach, in lieu of a chenier migrating landward over a mangrove-colonized muddy substrate, has always varied. In essence, the only sector where Braamspunt has shown a semblance of perennial presence is in the sink zone near the mouth of the Suriname River, where the river’s fluvial jet has resulted in mud-bank liquefaction favorable to a clearly expressed beach with spit recurves, as shown by the Landsat images of 7 September 9, 1999 (Fig. 22b) and 15 October 2015 (Fig. 23b). As the current mud bank 1, shown in the October 2015 image, migrates westward, at an estimated rate of 1.6 km a year from a comparison of the leading edges of the mud banks in the two 2015 satellite images (Fig. 23b), Braamspunt beach has evolved from an open beach towards a more classical landward-migrating chenier. In other words, the open stretch of type 1 chenier beach has become progressively shorter, preceded by a landward-migrating chenier (Fig. 24), that, in turn, precedes the migrating mud bank. The beach ‘shortening’ shown in Table 2 suggests that the mud-bank migration rate of 1.6 km a year deduced from the satellite images is significantly outstripped by the real ‘ground’ migration rate at the very leading edge of the bank, where the mud bank is also less large, and subject to refracted, but still energetic incident waves, leading to a form of bank stretching.

Table 2. Field measurements of ‘shortening’ of Braamspunt beach resulting from impingement following westward-migration of the leading edge of a mud bank in 2015-2016 (courtesy of the Nature Conservation Division of Suriname).

<table>
<thead>
<tr>
<th>Date</th>
<th>Beach length</th>
</tr>
</thead>
<tbody>
<tr>
<td>January 2015</td>
<td>7.0 km</td>
</tr>
<tr>
<td>August 2015</td>
<td>5.6 km</td>
</tr>
<tr>
<td>January 2016</td>
<td>2.6 km</td>
</tr>
</tbody>
</table>
2.3.2. The Suriname-Coppename sector (mud cape 2 in Fig. 1)

This sector of the Suriname coast shows a more pervasive presence of mud, but with a very clear erosion hotspot that corresponds to the Weg Naar Zee area north of Paramaribo, where shoreline retreat has been persistent, but with a diminishing trend from 2009 to 2015 (Figs. 25, 26). Fig. 25 shows important shoreline erosion near the mouth of the Coppename River, succeeded westward by important muddy accretion. Muddy accretion has been rather pervasive along much of the coast between 1999 and 2009 (Fig. 26). These patterns appear to be associated with extremely important mud bank activity on this sector of the Suriname coast over the 29 year study period. Overall, notwithstanding the pervasive presence of mud, erosion hotspots seem to be associated with sectors of shoreline in the vicinity of the mouths of the Suriname and Coppename Rivers where fluvial jet outflow may be the overarching parameter in preventing mud from durably attaching onshore. The large muddy accretion trend also goes with a relative scarcity of beaches and cheniers on this sector of the coast.

2.3.2. The Coppename-Corantijn sector (mud cape 3 in Fig. 1)

The pattern on this sector of this coast is less clearly defined than in the previous two sectors, but the presence of mud is also pervasive (Figs. 27, 28). Erosion has been dominant west of the Corantijn River. Overall, shoreline change appears to have been more moderate than in the other two sectors but the quality of determination of mud bank areas is also less in this sector. The large changes that have affected this sector also go with a relative scarcity of beaches and cheniers. Several well-developed cheniers are, however, visible very near to the present shoreline.

2.4. Morphodynamics of Braamspunt beach

2.4.1. Offshore and nearshore hydrodynamic conditions

The tidal and wave conditions that prevailed during the February 2016 survey are depicted in Fig. 29. The tidal curves showing the semi-fortnightly variation in water level in the course of the survey period have been constructed from theoretical tidal data provided by the French Service Hydrographique et Océanographique de la Marine (SHOM). The water levels do not, therefore include oceanographic forcing effects such as ocean level setup by air pressure changes, and wind and wave forcing. The semi-diurnal tide suggests a mesotidal spring-tide range of about 2.2 to 3 m, and the tidal cycle showed a spring-neap variation between 09/02/16 and 16/02/16. *WWIII* deep water significant wave heights (designated Hs) ranged from about
2.2 m at the start of the experiment (09/02) to about 2 m at the end of the field experiment (14/02), with a maximum of 2.9 m attained on 10/02.

**Fig. 22.** Examples of Landsat images and graphs of analyzed shoreline changes between the Maroni and the Suriname Rivers (mud cape 1, October 1987 and September 1999),
showing the impact alongshore of migrating mud banks (muddy shoreline accretion) and inter-bank areas (shoreline erosion characterized by landward-migrating cheniers).

Fig. 23. Examples of Landsat images and graphs of analyzed shoreline changes between the Maroni and the Suriname Rivers (mud cape 1, from September 1999 to October
2015), showing the impact alongshore of migrating mud banks (muddy shoreline accretion) and inter-bank areas (shoreline erosion characterized by landward-migrating cheniers).

Fig. 24. Synthesis of analyzed shoreline changes between October 1987 and January 2016, in the Braamspunt beach sector showing the impact alongshore of migrating mud banks (muddy shoreline accretion) and inter-bank areas (shoreline erosion) and the latest phase of beach ‘shortening’ resulting from landward chenier migration.
Fig. 25. Examples of Landsat images and graphs of analyzed shoreline changes between the Suriname and the Coppename Rivers (mud cape 2, October 1987 and September 1999), showing the impact alongshore of migrating mud banks (muddy shoreline accretion) and persistent shoreline erosion in two erosion hotspots near the mouths of the Suriname (Weg Naar Zee) and Coppename Rivers. Note the relative scarcity of beaches (cheniers).
Fig. 26. Landsat images and graphs of analyzed shoreline changes between the Suriname and Coppenname Rivers (mud cape 2, from September 1999 to October 2015), showing still important muddy shoreline accretion towards the west and more rampant inter-bank shoreline erosion along the eastern sector of coast, within an overall context of very poor chenier formation.
Fig. 27. Examples of Landsat images and graphs of analyzed shoreline changes between the Coppename and Corantijn (Courantyne) Rivers (mud cape 3, October 1987-September 1989 and September 1999-July 2000), showing the impact alongshore of migrating mud banks (muddy shoreline accretion) and inter-bank areas (shoreline erosion characterized by landward-migrating cheniers).
Fig. 28. Landsat images and graphs of analyzed shoreline changes between the Coppenaice and Corantijn (Courantyne) Rivers (mud cape 3, September 2009 and October 2015), showing the impact alongshore of migrating mud banks (muddy shoreline accretion) and inter-bank areas (shoreline erosion characterized by landward-migrating cheniers).
These are relatively energetic wave conditions, reflecting a typical El Nino year of rougher waves than in modal conditions (most frequently occurring). The wave heights measured by the pressure sensors on the lower beach (Fig. 29) were, however, much lower, ranging from 0.5 to 0.8 m, thus reflecting a significant amount of dissipation by mud over the shoreface and dispersal of wave energy by refraction. About 60-80% of the deep water energy was lost by the time the waves broke on the beach. This still left a non-negligible amount of energy that led to important beach morphologic changes, as shown below. Wavewatch III wave periods were relatively uniform at about 9-10 s, reflecting the trade-wind regime responsible for generating these waves (see also Fig. 4). Beach measurements showed a wider spread of periods ranging from about 5 s to 20 s, reflecting a clear mix of both trade-wind waves (5-10 s) and longer swell waves from the Central Atlantic (12-16 s), and also possible infragravity waves (18-22 s) resulting from in-situ wave breaking conditions in the surf zone and beach. Deepwater Wavewatch III wave directions were from the northeast window, typical of the Guianas coast, and ranged from N 47-58°, indicating relative high angles of 32-43° relative to the beach. Beach observations show much lower, but still relatively high, angles of about 15-25°, following nearshore refraction.

![Fig. 29. Hydrodynamic conditions affecting Braamspunt beach from 9 to 14 February, 2016. From top to bottom: tidal variations depicted as water level, significant wave height (Hs), peak wave period (T) and deep water wave directions derived from the WAVEWATCH III model. Orthophotograph on the left is a drone-derived photogrammetric image of the beach showing the locations of the wave and turbidity sensors deployed on Braamspunt beach in the course of the two survey periods.](image)

The turbidity values (NTU) and significant wave heights (Hs) showed, in the case of sensor Cpt 4 PT, a clear relationship depicting temporary suspension of sand in the course of wave breaking (Fig. 30). Sensor cpt 3 PT did not function properly.
Fig. 30. Significant wave heights (Hs) and turbidity values (NTU), showing, in the case of sensor Cpt 4 PT, a clear relationship between wave height and sediment put into suspension in the course of wave breaking. Values given by sensor cpt 3 PT are not consistent.

2.4.2. Grain-size and sedimentology of Braamspunt beach

Braamspunt beach is characterized by well-sorted medium sand with median grain-size values of 400 to 560 μm (Fig. 31). The percentage of shelly material (carbonates) is highly variable, but locally significant, ranging from 4 to over 40%, reflecting preferential density sorting and concentration within the dominant quartz sand matrix.

2.4.3. Beach morphology from high-resolution field topographic surveying

The high-resolution topography of Braamspunt beach is depicted in three segments from the north to the south of the beach (Fig. 32a, b, c). Each segment comprises two digital elevation models DEMs (left: 10 February, centre: 14 February) a DoD (right) that shows the differential between DEMs, and representative profiles. The survey was incomplete for the northern part of the beach (Fig. 32a), mainly as a result of a poor radio signal on 10 February between the fixed and mobile GPS stations. The DoD and beach profiles show a narrow beach subject to significant erosion, involving nearly 5 m of retreat of a steep reflective beach face characterized by a well-developed berm. The central beach sector (Fig. 32b) exhibited a less steep (less reflective) beach profile and a beach that rather rapidly became larger from profile 2 southwards. The beach topography also showed better contrast with this widening. Erosion was dominant on the beach face but the berm and back-beach showed little change where the beach widened.
Fig. 31. Grain-size characteristics of sand from Braamspunt beach determined by laser analysis, and determination of the percentage of carbonates. Satellite image (top left) and photogrammetry orthophoto (bottom right) show sample locations. The grain-size curves show a clear concentration around median values of 400 to 560 μm, indicating well-sorted medium sand dominated by quartz. The percentage of shelly material (carbonates) is highly variable, but locally significant, ranging from 4 to over 40%, reflecting preferential density sorting and concentration.
Fig. 32. High-resolution GPS-derived topography of Braamspunt beach depicted in three segments from the north to the south of the beach (a, b, c). In the absence of local topographic benchmarks, elevation data are referenced to the world geoid EGM96 (Earth Gravitational Model) representing mean sea level. Each segment of beach comprises two digital elevation models DEMs (left: 10 February, centre: 14 February), a DoD (right) that shows the differential between DEMs, and representative profiles. The survey was incomplete for the northern part of the beach. The DEMs, DoD and profiles show a progressive change from a steep narrow reflective beach in the north with a well defined berm on the beach face (profile 1) to a wider bermed (profile 3) beach that becomes lower (profile 4) as it ends in the current spit recurve of Braamspunt beach. Much of the topographic change derived from the DoDs concerned the active beach face. Change was much less intense over the top and back of the beach. The spit sector shows interesting alongshore alternations of erosion and accretion that represent
mobilized sand bodies migrating downdrift under the strong longshore drift conditions that prevail on this beach.

The wide southern sector of Braamspunt beach (Fig. 32c) corresponds to the current spit recurve towards the Suriname River estuary. The back-beach topography in this sector shows significant variations that reflect overwash processes, overall beach surface lowering towards the back-beach lagoon, but also no doubt inherited sand mining pits dug just prior to the ministerial moratorium on sand mining taken in December 2015. Much of the topographic change derived from the DoDs concerned the active beach face. Change was much less intense over the top and back of the beach. This spit sector shows interesting alongshore alternations of beach face erosion and accretion that represent mobilized sand ‘waves’ migrating downdrift under the strong longshore drift conditions that prevail on this beach.

2.4.4. Beach morphology from photogrammetric surveying

The orthophotographs and Digital Surface Models (DSMs) yielded by the photogrammetric survey and obtained using the analytical procedure based on the SfM protocol described earlier in section 2.2.2. are shown in Fig. 33. Both the orthophotographs and the DSMs clearly highlight the morphodynamics of the beach and the cross-shore and longshore sediment transfer mechanisms. Fine-scale variations in beach topography, and especially various large-scale morphological features such as spit recurves at the approaches to the Suriname River mouth, but also smaller-scale features such as beach scarps, log jams, overwash fans are clearly identified in the photographs. Interesting, there is a clear convergence in the topography of the beach between the products of SfM photograph and the lower resolution topographic data generated by the GPS surveys. Unfortunately, no DoDs were drawn up from SfM photogrammetry because only one photogrammetric survey was possible in the course of the week of the field surveys. This method holds great promise for very high-accuracy, repeated, low-cost surveys of the Suriname coast, and has the significant extra advantage of generating orthophotographs of the coast.

2.4.5. Sediment budget of Braamspunt beach and budget change over the survey period

The overall context during the survey period was one of net erosion of Braamspunt beach, as shown by the digital elevation models generated from the RTK DGPS surveys and the examples of cross-shore profiles (Fig. 28). A net budget of the beach obtained from the overall DoDs is shown in Fig. 34. **The overall estimated sand stock of Braamspunt beach from the topographic survey, and using an absolute beach base at -0.5 m, is about 570,000 m³ of sand.** This is a conservative estimate since the true absolute sandy base of the beach above ambient mud is probably lower than this value as a result of consolidation and lowering of the mud substrate and, especially as the spit impinges on deep waters at the approach to the Suriname estuary. However, even allowing for a comfortable error margin of +20-30%, this volume represents a moderate amount of sand that can be rapidly depleted if sand mining were to continue unabated.
Fig. 33. Two very high-resolution and high-density orthophotograph assemblages (left) and Digital Surface Models (right) of Braamspunt beach obtained from SFM photogrammetry in February 2016. Both the orthophotos and the DSM clearly depict variations in beach topography, and especially various large-scale morphological
features such as spit recurves at the approaches to the Suriname River mouth and smaller-scale features such as beach scarps, log jams, overwash fans.

Fig. 34. Sediment budget of Braamspunt beach based on a beach base of -0.5 m relative to absolute datum. The budget concerns the volume of intertidal beach sand above this elevation. Partial budgets are shown for various sectors of the beach. These budgets highlight the net differential between a dominantly eroding beach along much of its length and a short spit recurve that serves as a sink for some of the sand eroded further updrift and transported to this spit sector by longshore currents. The net overall budget shows a substantial loss, over only 3-4 days, of 4200 m$^3$ that also reflects the erosive effects of a combination of relatively high waves and large tides in the course of the survey. These partial and global sediment budgets highlight the fragility of Braamspunt beach.

Net budget differentials for four sectors of Braamspunt beach over the 3-4 days separating the two GPS topographic surveys are depicted in Fig. 34. They bring out an overall loss of 4200 m$^3$ of sand for what corresponds to a very short period of time, and a short stretch of beach (2.5 km). This highlights the fragile sediment budget of this beach. The important loss of sand could reflect updrift sequestering under mud, but more likely infill of holes caused in the subtidal beach by sand mining operations, this zone not having been covered by the surveys. The differentials also show the clear propensity for downdrift transport of sand, dominantly as propagating sand waves as we saw earlier (Fig. 30), and its final deposition in the large spit sector which forms an accreting sink from which sand is then progressively
transferred towards the estuarine depths. However, it was also clear in the course of the week that the spate of erosion observed and measured between the two GPS surveys was essentially driven by large waves that coincided with large spring tides. These are the conditions most favourable to overwashing by waves, scarping, strong downdrift longshore transport, and overall rapid erosion of the beach.

2.4.6. Morphodynamic synthesis of Braamspunt beach

During the field survey in February, 2016, Braamspunt beach showed a clear updrift-downdrift gradient in morphology and dynamics (Figs. 32-34) that mainly reflected alongshore wave energy and longshore drift variations between a ‘source’ zone in the northeastern part of the beach and a ‘sink’ zone in its southwestern extremity of spit recuces. This gradient is related to different updrift (approaching mud bank) and downdrift (approaches to the Suriname estuary) contexts. These differences are depicted in the 12 January 2016 Landsat 8 image. For simplicity, three sectors are distinguished (Fig. 35):

Fig. 35. A synthesis of the morphodynamics and sediment transfer conditions at Braamspunt beach superimposed on a 2016 Landsat image.
(1) The northern sector, which comprises two elements:

the leading edge of the mud bank where the existing chenier (former open beach) has been isolated from the sea by mud and fossilized inland, and the ‘terrestrial’ shoreline junction with the leading edge of the mud bank. The former has been rapidly migrating westwards, resulting in the shortening of the beach (Table 2). The latter consists of a narrow 150 m-long sandy chenier migrating landward (Fig. 36). As the chenier migrates inland over back-beach stands of *Avicennia germinans* mangroves, it leaves in its wake a muddy foreshore with subsisting mangroves that were part of the muddy mangrove-colonized muddy plain.

*Fig. 36. View of the limit between the advancing leading edge of the mud bank (high mangrove fringe in the background) and the developing landward-migrating chenier (foreground with game warden) that forms the present updrift sector of Braamspunt beach. Migration of the mud bank is leading to shortening of the beach. Landward chenier migration leads to the exposure, on the beach foreshore, of more or less consolidated former back-beach mud rich in mangrove remains.*

(2) The southern sector, also with two segments:

a narrow 1.7 km-long reflective beach, and a relatively large 0.6 km-long downdrift beach segment. The former segment is a strongly eroding one, the process being materialized by beach scarping and the constitution of log jams on the beach from uprooted mangroves. Scarping by waves occurs at high tide, and is particularly favoured by spring tides such as at the start of the survey. Large washover lobes of sand were also being transferred towards the back-beach, the typical signature of chenier migration (Fig. 37). Some of the sand removed by scarping is transferred alongshore by the strong longshore drift, thus accounting for the
considerable narrowing of the beach and the net budget deficit over the survey period (Fig. 34). In addition to the role of these processes, beach narrowing and the budget deficit may also result from partial fossilization of sand under the stretched advancing mud-bank leading edge.

The large waves and strong longshore drift that cannot be balanced (dissipated) by the sand volume of the beach to maintain stability. The narrow reflective portion of Braamspunt beach also shows small-scale alongshore morphological variability related to numerous zones of driftwood debris. The second segment forms the transition zone towards the present Braamspunt beach recurve zone into the Suriname River estuary (Fig. 38). This sector also shows some scarping and rarer washover lobes associated with the alongshore alternations of depositional sand waves being transferred downdrift and erosional zones between these sand waves (Fig. 28c). Overall, this spit recurve sector constitutes the downdrift sink for sand transferred alongshore, hence the net positive sediment budget here (Fig. 34).

(3) The estuarine sector with older spit recurves zone, where waves are nearly completely refracted.

Fig. 37. Ground photographs of the eroding updrift sector of Braamspunt beach. Top left: pronounced beach scarp; bottom left: log jam (drift wood) on the beach face from mangroves uprooted as the chenier migrates inland. Top right: a large sector of overwash; bottom right: view towards the back beach showing washover sand encroaching on *Avicennia* g. mangroves and burying their pneumatophores (breathing root network), leading to asphyxia and death of the plants.
Fig. 38. Downdrift sand transport terminus and partial sink where Braamspunt beach forms a spit recurve in response to wave refraction caused by the Suriname River mouth re-entrant. The refracting wave front is visible in the right background. Darker shades of sand on the beach correspond to heavy minerals (black sands) deposited in this area of relatively lower wave energy as a result of refraction, and further concentrated by mild wind sorting of the beach sand. Debris lines on the right mark the limit of swash at high tide during the lower neap tides at the end of the survey. Washover lobes inherited from the higher spring tides at the start of the survey are present in the left background.

2.5. Overall assessment of the stability of Braamspunt beach and the impacts of sand mining on coastal protection and turtle nesting

The multi-decadal to recent evolution of Braamspunt beach shows a classical chenier beach that depends essentially on sand supply from updrift. *This is a first factor of beach fragility*. This sand comes from the Maroni, but transport is not direct and continuous as one would expect on a classical open-ocean beach because the sand from the Maroni source transported alongshore by wave-induced drift is partially sequestered over more or less long periods of time (multi-decadal) by mud banks migrating westward towards Guyana. Sand availability is, thus, neither constant nor perennial on Braamspunt beach. In other words, Braamspunt beach does not function as a classical through-put source-to-sink (Maroni-Suriname) sediment cell, but as a potentially fragmented temporally and alongshore-variable cell. This has serious implications for the overall sediment budget of the beach and its sustainability.

As a result of the foregoing, Braamspunt beach is an essentially reflective beach the morphodynamics of which essentially hinge on sand reworked alongshore, and only during
inter-bank phases. Such reworking also enables the concentration of shelly material from offshore that supplements the beach sand budget. Reworking is basically dominated by what may be termed as a form of ‘self-cannibalization’, a process common in gravel beach systems, but also in sandy beach systems where sand-supply stress conditions prevail. In the case of Braamspunt beach, cannibalization is generated by updrift sand sequestering in the advancing leading edge of mud banks during bank phases, a process that, in turn, generates a chain reaction involving a switch in beach behaviour in the immediate vicinity of the bank’s leading edge to an increasingly more landward-migrating chenier mode associated with beach overwash that further deprives the downdrift beach of sand. As this occurs, beach scarping and lowering occur further downdrift to balance an under-saturated wave and longshore transport system, engendering a downdrift migrating wave of erosion as the system translates downdrift. The subsisting beach may be preserved in its most downdrift sector (a few hundred metres at most) at the mouth of the Suriname where mud is liquefied by the river’s outflow jet. This preservation outcome may be considered as a form of coastal self-organization involving morphodynamic negative feedback adjustment effect between beach and river mouth and without which Braamspunt beach would cease to exist. Here, preservation of the beach is essential in turn in dissipating waves impinging on the east bank of the river mouth, thus protecting the back-beach mangrove wetlands and maintaining the mild cape morphology on this bank. These effects have a bearing on the availability of the beach or sectors therefore, as pristine grounds for sustained turtle nesting, and also on the role of Braamspunt beach in coastal protection.

Overwash processes are nefarious to turtle nests as they involve water infiltration and sand loading on the upper beach. Scarping and beach narrowing lower the available space for turtle nesting while generating a vertical beach face that may hinder turtle access to the beach. The important driftwood accumulation associated with the chain of processes and the beach morphodynamic effects described above also generates obstacles to turtle landing, while organic material from abundant driftwood can be nefarious to nests by altering temperatures during decomposition.

In consequence, under these conditions, sand mining can only be deleterious to the integrity of the subsisting beach since it not only lowers available nesting beach space but also the beach’s sediment budget, and hence its wave buffering capacity. Braamspunt beach and its ancestral forms between the Maroni and the Suriname have always played an important role in protecting the Young Coastal Plain from exacerbated retreat during inter-bank phases by dissipating wave energy. Together with mangroves, they play this role in inter-bank areas, except that mangroves, while being extremely important energy-buffering agents on the Guianas coast, are much less efficient than sandy beaches in this role. Beaches also evince ‘threshold’ functioning’. This implies that large-scale sand removal by mining can lead to a threshold point wherein an already strongly depleted beach can, in the face of repeated spates of high wave episodes (such as would be expected in the present El Nino years), completely collapse through massive washover and wave recycling of sand into the Suriname estuarine sink. The total collapse of Braamspunt beach could have very damaging feedback effects (irreversible change, with no possibility for resilience), wherein the east bank cape at the mouth
of the Suriname River can be severely eroded several kilometres back during inter-bank phases thus exposing the estuary and the water-front of Paramaribo to incident Atlantic waves.
PART 3. THE NECESSITY OF A COASTAL OBSERVATORY IN SURINAME
3.1. Introduction

The coastal zone is a theatre of interest to a multitude of actors and stakeholders. The concept of ‘integrated coastal zone management’ (ICZM), now largely superseded by Ecosystem-Based Management (EBM), embodies a need for collective action geared towards natural and societal processes that may pose a threat to sustainable environmental quality and coastal activities. A necessary preamble to the efficient management of the coastal zone, however, is a sound knowledge of the way this zone functions and evolves in time. Significant increase in anthropogenic pressure, large tracts of low-lying mangrove wetlands, limited stretches of sandy beaches, and, as result, exacerbated vulnerability to climate change, sea-level rise, and high-energy events, are a number of constraints facing Suriname. Accelerated sea-level rise as well (IPCC, 2013), as modification of numerous physical and biogeochemical processes such as the acidification of oceans, the increase in ocean surface temperatures, changes in oceanic circulation, in wave climates and in salinity are now well documented (Doney et al., 2009; Mori et al., 2010). These changes will have important impacts on tropical coastal ecosystems such as mangroves, but also on adjacent or related coastal morphosedimentary systems lying at elevations close to sea level, such as lagoons, beaches and cheniers. The management of tropical coasts will need to integrate over short to medium timescales the evolution of dynamic parameters characterized by random phases of respite and erosion that will become accentuated in the future in response to climate change (Nicholls et al., 2007). Tropical coasts could be particularly vulnerable to climate change in the future, although marked differences will be expected between those with high rocky coasts and those, more vulnerable, with low depositional coasts, such as the Guianas coast and Suriname. It is therefore necessary, for decision-makers, managers, and the scientific community, to monitor and quantify the reactions of coasts to the consequences of climate change. The understanding gained on the functional mechanisms and resilience of coastal systems constitutes a key contributory element in attempts to identify vulnerability levels in order to implement improved coastal management and risk evaluation plans (UNESCO, 2003; Boruff et al., 2005; Romieu et al., 2010).

The low-lying coastal plain of Suriname is characterized by a diversified morphology comprising beaches (cheniers) and mangroves subject to increasing pressure from strong demographic and urban growth. 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). Caught up in a context of such strong demographic growth, the coastal zone of Suriname has been subject to increasing anthropogenic pressures, especially the Paramaribo urban area, since these early pioneer studies. These pressures bear on the quality and sustainability of the coastal landforms of Suriname. The mangrove system exhibits important signs of degradation and is considered today as highly endangered from urban growth north of Paramaribo (Anthony, 2015). Pressure on some of the rare beaches of Suriname, which act as coastal protection barriers that buffer Atlantic waves, and serve as sites for protected marine turtles, has also come from multi-decadal sand mining for building and industrial purposes. The effects of anthropogenic pressure
exacerbate those of climate change and impair the resilience of these mangrove and beach systems in the face of both natural and human perturbations.

Awareness of these challenges should prompt the construction of an operational observatory on the coastal dynamics of Suriname. The rationale for the setting up of such an observatory and the aims, structure and organisation of this observatory are presented, together with the necessary coastal monitoring methodology presented in part 2 of this report, that could provide a better framework for future coastal conservation and management. Such an observatory is currently being developed in neighbouring French Guiana (Observatoire de la Dynamique Côtière de Guyane, under the auspices of the DEAL (Direction de l’Aménagement et de l’Logement: http://www.guyane.developpement-du...).

3.2. Rationale and goals of a coastal observatory in Suriname

Over the last few years, calls have come from the Suriname administrative authorities and environmental conservation entities for an integration of development planning within a viable and sustainable economic strategy. The Government of Suriname is charting out an ICZM/EBM 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.

The dilemma raised by the conflict between the sensible maintenance of the natural mangrove system that has contributed to the multi-millennial growth of the Young Coastal Plain of Suriname (Anthony, 2015), and calls for the replacement of this mangrove system by costly dykes and seawalls that will exacerbate coastal degradation in the future, as they have done in neighbouring Guyana, are increasingly bringing pressure to bear on local and national authorities regarding the necessity of setting up and implementing a sound policy of integrated and sustainable coastal management. The successful implementation of projects aimed at environmental conservation and a preserved Suriname coast need to be supported by a fine understanding of the functional dynamics of the coast, which imply a certain degree of interactivity between ‘natural’ (morphosedimentary processes) and anthropogenic factors (human activities and land use in the coastal zone) where urban development is spreading, as in Paramaribo. Under these conditions, the establishment of an operational network, in the form of a coastal observatory, for monitoring the coastal zone, becomes obvious and necessary in order to reinforce observational and analytical capacities. The idea of setting up of this observatory was initiated by discussions with WWF-Guianas and various actors in Suriname involved in environmental issues, and their relayed action with Suriname ministries in charge of the environment.
The twin goals of the observatory are: (1) to enhance our understanding of the particularly complex functioning of the coast of Suriname and its resilience relative to climate change, and (2) to translate the acquired information into a framework liable to inform the general public, researchers, and decision-makers, with a view towards the implementation of decisions aimed at rational coastal management and conservation. This observatory, which should also be an instrument of coastal surveillance, comprises three major tasks: (1) the constitution of a data bank on the state of the Suriname coast, (2) the observation, measurement and characterization of the coast and coastal changes at various temporal and spatial scales based on the acquisition of field data, (3) the analysis and integration of the generated data into user-friendly tools accessible to decision-makers, the general public and scientists. Within a local framework of strong socio-economic and demographic pressures, and a more global context of environmental change, this observatory should lead to a better understanding and prediction of the morphodynamics of the coast of Suriname, while providing data to the public at large, to researchers, and to stakeholders involved in decision-making in the face of the major and rapid environmental and socio-economic changes liable to affect the fragile mangrove systems and beaches and cheniers.

Closely linked with the idea of an observatory, the notions of management and controlled development of the coastal zone should be central themes in the establishment of a Management and Sustainable Development Plan (MSDP) for Suriname that should define the main orientations and the management policy of the coast (and environment in Suriname) for the decades to come. The rationale for these initiatives is reinforced by the fact that Suriname is a keen actor in global change issues and an active COP member.

3.3. Methodological basis and running of a coastal observatory in Suriname

Although the overall morphosedimentary and dynamic framework of the coast of Suriname are known (see Parts 1 and 2), the present state of the coast in terms, notably, of a fine determination of the overarching bank and inter-bank zones and their recent phasing, are still rather not well identified (see Figs. 22-28, for instance), and will require observations, monitoring and measurements from a variety of satellite image sources, and from which may eventually be derived conceptual and deterministic models of local to regional (sectoral) behaviour that can be fed into management schemes. The roadmap of a coastal observatory should include a preliminary characterization of Suriname’s coastal geomorphology, enabling the identification of both eroding and vulnerable sites as a function of bank and inter-bank phases, the dynamics of which are far from being linear in space and time. An observatory approach requires determination of threshold levels, sensitivity to adaptation, and the processes and rhythms of resilience of mangroves and sandy beaches (cheniers). The protocol for achieving these objectives should therefore be based on an initiated observatory programme covering various aspects such as monitoring of waves and currents, mapping of alongshore distribution and longshore and cross-shore dynamics of beaches and longer-term (bank-inter-bank) cycles of formation, erosion, and inland isolation, and mangrove surface area.
variations. The methodology used for the evaluation of the impacts of sand mining on beaches in Suriname, and presented in section 2.2., should serve as a basis for monitoring and surveillance of the coast. Notwithstanding the non-linearity of bank and inter-bank phases and sectors, these are large-scale elements, with spatial and temporal scales that can be well covered by currently available observation and photogrammetric techniques. Beyond fieldwork and data collection, a fundamental element of this surveillance network should reside in the constitution of a data bank on the coast. This will necessitate the implementation of a Geographical Information System (GIS) enabling the diffusion and exploitation of data collected by the observatory. The observatory requires having as a functional framework a GIS that integrates various field measurements and observations conducted on the coastal forms, on the basis of a predefined protocol and methodology. Elements of such a methodology, and the training it requires, could be based on the description in section 2.3 of this report. Field monitoring could include hydrodynamic measurements, topographic surveys, and observations, and these should be coupled with the analysis of satellite images, and especially aerial orthophotographs obtained from low-cost and repeatable photogrammetric surveys using UAVs (drones). Such UAV surveys are already being carried out by the Nature Conservation Division of Suriname which is gradually acquiring expertise in this field. Output from photogrammetry can then be combined with regional wave and meteorological data in order to gain a better understanding of the coastal morphology and of its spatio-temporal evolution in terms of bank and inter-bank phases. The results fed into the observatory and analysed through the GIS should provide interactive maps of the coastal landforms and their evolution and dynamics over various timescales. The methodological basis for a coastal observatory in Suriname and the data expected to be generated by such a structure no doubt call for a full implication of the scientific actors of the country, notably researches and students of Anton de Kom University of Suriname.

It is expected that an established monitoring structure should throw light, for instance, on the precise area covered by mangroves along the coast, the locations, dimensions and changing dynamics of cheniers, mud-bank and inter-bank areas, the sediment budget of any given beach (chenier), alongshore and temporal differences in beach (chenier) behavioural modes ranging from stretching, overwash, scarping, distal widening and spit development, response to fluvial hydraulic jets outflow, characterization of mangrove dynamics in the leading and trailing edges of mud banks, in chenier overwash sectors, and, especially, in retreating inter-bank areas, and, of course, following intense wave episodes. Such elements should contribute in the first place to a better knowledge of what the Suriname coast is, its specificities, and how it functions from local to regional scales, and to better anticipation and/or definition of response strategies and to the evaluation of the financial costs facing the local stakeholder communities in their efforts at ensuring better protection and management of urban growth zones, tourist infrastructure, and fish resources, in the context of strong demographic growth. The choice of field sites monitored within the framework of the observatory should concern both the muddy and sandy coastal morphotypes representative of the diversity of the Suriname coast: mangroves, sandy beaches (cheniers), and strongly human-modified shores. The implementation of the observation network could start with selected sites of in situ
measurement along the coast, and these sites should be bench-marked with reference to the Suriname geodetic system. Additional benchmarks should be established further inland for each site as a precautionary measure in the event of the destruction or disappearance of the initial benchmarks resulting from severe inter-bank erosion.

By collecting, archiving, standardizing and diffusing data generated by the coastal observatory surveillance network, the GIS should fulfill several other objectives, including:

- bringing together under a common framework for various organizations and initiatives interested in coast matters in Suriname;
- pooling of efforts aimed at data acquisition and development of protocols of data collection and treatment;
- development of tools aimed at visualizing and anticipating present and future coastal evolution trends and providing aid in decisions taken by coastal managers.

Plans should be made also for devolving the running of the observatory to an organism (Nature Conservation Division or similar body). Access to data and data diffusion stand out as two essential elements in the eventual success of a coastal observatory regarding good management practice. The results and field observations collected by the surveillance network should be integrated into the GIS as downloadable files. The GIS should be available to local management and environmental-oriented organs, and updatable as new data are acquired. Finally, data diffusion by the GIS and the observatory should contribute to knowledge acquisition and sharing with existing observation networks involved in coastal matters, such as the Coral Reef Observatories and the Marine Turtles Observatories, and observatories in neighbouring states such as in French Guiana and the Caribbean.

The observatory should address the needs of local, regional and national stakeholders involved in coastal planning and management. The database should subsequently improve coastal hazard mapping and contribute as a support to decisions on protection and adaptation necessary to sound coastal management planning within a framework of sustainable development. The interest elicited among political and management actors by the research work undertaken on the beaches and mangroves of Suriname (this, and the Weg Naar Zee report, Anthony, 2015) suggests that the tools eventually developed by the observatory will be useful to the management and conservation of the coast. The observatory should favour interaction between scientists of Anton de Kom university and civil actors by improving information diffusion and communication towards local coastal managers through the organization of technical seminars and through the GIS, including the provision of a regularly updated website and interactive maps. The observatory should also propose actions aimed at informing and educating the public, and in enhancing public awareness of the stakes involved in sustainable coastal management, as is presently done by the Mangrove Forum of Suriname. Recommendations to stake holders should be an important short-term goal of the observatory. Articles in journals and magazines and the organization of conferences are also initiatives that should get underway. It is imperative that the public is fully involved in the initiatives of the observatory through partnerships, such as with local associations, and through participative
grassroots management ventures as well as through local governance of the coast. Participative actions and awareness initiatives regarding conservation of the environmental legacy constitute, in this regard, a necessary preamble to efficient operational mobilization.
Recommendations of this report

The beaches of Suriname essentially function as cheniers supplied in sediment by rivers and by wave reworking of shells and sand from the nearshore zone. These cheniers have played an important geological role in the building of the Young Coastal Plain in Suriname over the last 5-6000 years, and are the most important natural source of coastal protection by buffering waves. 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 cheniers, but also mud banks and mangroves, in the development and dynamics of the coast, need to be fostered.

Analysis of satellite images aimed at highlighting the shoreline changes between 1987 and 2016 that have affected the Suriname coast, notably under the overarching influence of mud banks, shows that beaches are a rare resource on this coast, and this situation has probably been more prevalent over the last 1000 years of the geological history of the coastal plain than in earlier periods. The work conducted on Braamspunt beach also clearly shows the drastic changes that have resulted in significant shortening of the beach over the last few years. This process has resulted from much of the sand supply coming from the updrift part (east, from the Maroni) of the beach being integrated into a chenier driven landward by waves over mangroves and isolated from the present shoreline by a mud bank migrating between the Maroni and Suriname Rivers. Sand mining has essentially affected the downdrift (west) end of the beach which comprises successive spit recurves ending at the mouth of the Suriname River. These conditions, and the rarity of currently active cheniers, signify relatively fragile beach systems that have been strongly impacted by sand mining. This activity impairs the coastal protective role played by the rare subsisting beaches in Suriname, while also contributing to depriving Suriname of its already relatively rare, and therefore valuable, beach nesting sites for marine turtles. Beach sand mining in Suriname should therefore be completely proscribed and other sources of commercial aggregate should be explored, such as, in order of preference: inland river beds, bedload trapped behind dam reservoirs, the most inland cheniers, and estuarine sand shoals. This will necessitate the implementation and enforcement of a legal ban on beach sand mining.

An observatory of the coast of Suriname needs to be set up, as there is an acute need for data on which to base coastal zone management decisions on this highly dynamic coast. The observatory should also address the needs of local, regional and national stakeholders involved in coastal planning and management. The database should subsequently improve coastal hazard mapping and contribute as a support to decisions on protection and adaptation necessary to sound coastal management planning within a framework of sustainable development.
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